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Integrated Methodological Framework for Chloride-Induced Corrosion Assessment in Geopolymer Concrete: A Systematic Secondary-Data Study

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Abstract

Background: Chloride-induced reinforcement corrosion threatens the durability of reinforced concrete, while existing methods for assessing chloride transport and reinforcement corrosion in geopolymer concrete remain fragmented.
Objective: This study aims to characterize the distribution of assessment methods, identify methodological gaps, and develop an integrated framework linking material characteristics, chloride transport, electrochemical responses, and reinforcement damage.
Methods: A quantitative-descriptive systematic secondary-data approach was employed, incorporating Scopus-based literature screening and methodological coding. Of the 1,792 records identified, 973 duplicates were removed, leaving 819 records for screening. Following eligibility assessment and final quality control, 139 reports were retained, including 88 unique core methodological studies that were analyzed using 20 binary indicators.
Results: Compressive strength was assessed in 65 studies (73.9%), scanning electron microscopy (SEM) or field-emission scanning electron microscopy (FESEM) in 55 (62.5%), chloride profiling or diffusion analysis in 36 (40.9%), half-cell potential (HCP) or open-circuit potential (OCP) measurements in 25 (28.4%), and linear polarization resistance (LPR) or corrosion current density ((I_{\mathrm{corr}})) measurements in 20 (22.7%). Reinforcement mass loss was measured in only 9 studies (10.2%). Comparisons with ordinary Portland cement (OPC)-based concrete were reported in 31 studies (35.2%), whereas numerical values for concrete cover thickness were documented in only 16 (18.2%). These findings reveal substantial methodological fragmentation, particularly in the integration of electrochemical monitoring with physical damage validation.
Conclusion: The proposed framework integrates precursor chemistry, alkali activation, microstructural characteristics, chloride transport, steel depassivation, electrochemical responses, reinforcement mass loss, and mechanical degradation. It provides a structured basis for improving methodological consistency and experimental comparability, although further experimental validation is required.

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INTRODUCTION

Chloride-induced corrosion of steel reinforcement is one of the most important deterioration mechanisms affecting reinforced concrete infrastructure exposed to marine aerosols, seawater, saline groundwater, and other chloride-bearing environments. The deterioration process is not a single event but rather a sequence of stages in which chloride ions enter the concrete cover, migrate through the pore network, accumulate near the steel–concrete interface, disrupt the passive state of the steel, initiate electrochemical corrosion, and ultimately

cause cracking, concrete spalling, bond loss, and a reduction in the reinforcement cross-sectional area. Because each stage is governed by different material and environmental mechanisms, reliable durability assessment requires multiple complementary indicators. Tests that measure only chloride transport, corrosion potential, or compressive strength cannot independently explain the complete pathway from chloride exposure to actual damage to the reinforcing steel. Globally, the economic burden of corrosion is substantial. The NACE International IMPACT study estimated the annual cost of corrosion at approximately US$2.5 trillion, equivalent to about 3.4% of global gross domestic product (GDP), with reinforced concrete infrastructure, including bridges, marine structures, and buildings, representing a major share of this cost (Koch et al., 2016).

Geopolymer concrete and related alkali-activated materials are increasingly being investigated as alternatives to Ordinary Portland Cement (OPC) concrete, particularly because they can reduce reliance on clinker-based binders. The durability of these materials cannot be assessed simply by transferring assumptions applicable to OPC concrete, because precursor chemistry, calcium content, activator concentration, silicate availability, reaction products, pore-solution alkalinity, and pore structure can differ significantly. These differences can affect chloride transport and the electrochemical environment surrounding embedded reinforcing steel.

Long-term studies and marine exposure investigations have demonstrated that chloride penetration and reinforcement corrosion behavior can be monitored in geopolymer concrete. However, the reported findings are strongly influenced by binder composition, curing conditions, exposure procedures, specimen geometry, and the electrochemical methods employed (Babaee & Castel, 2016; Chindaprasirt & Chalee, 2014; Gunasekara et al., 2019; Noushini et al., 2020; Pasupathy et al., 2021; Tennakoon et al., 2017).

Another methodological challenge arises when conventional chloride test methods are applied directly to alkali-activated systems. Rapid electrical testing is attractive because it is relatively simple and fast; however, the measured electrical charge or conductivity reflects the ionic characteristics of the pore solution as well as pore connectivity. Inconsistencies in rapid chloride permeability testing (RCPT) of geopolymer concrete indicate that binder chemistry can influence the electrical response. Calcium content, alkali concentration, chloride binding, pore structure, and pore-solution characteristics interact to govern chloride transport in alkali-activated materials. Chloride resistance must therefore be interpreted using methods that can distinguish actual transport behavior from the effects of electrical conductivity (Duży et al., 2022; El Moustapha et al., 2023; Mostazid et al., 2026; Wan et al., 2023).

The same methodological concern applies to the assessment of reinforcement corrosion. Half-cell potential (HCP) and open-circuit potential (OCP) measurements can provide useful nondestructive information about the probability of corrosion and changes in electrochemical conditions over time. In contrast, linear polarization resistance (LPR), corrosion current density measurements, electrochemical impedance spectroscopy (EIS), and other polarization methods provide additional information about corrosion kinetics and interfacial behavior. These electrochemical techniques do not directly quantify the loss of steel cross-sectional area. In geopolymer systems, the relationship between electrochemical potential and damage that is visible or measurable through gravimetric analysis may also differ from conventional interpretations developed for OPC concrete. Potential measurements should therefore be interpreted cautiously when conventional thresholds are applied to geopolymer concrete. In addition, pore-solution alkalinity and the chloride-to-hydroxide concentration ratio influence corrosion initiation in alkali-activated concrete (Babaee & Castel, 2018; Ekaputri et al., 2017; Ichimiya et al., 2024; P. Mangat & Lambert, 2016; Morla et al., 2021).

Previous literature has established many useful methods but has not yet produced a consistent methodological sequence. Some studies focus on precursor chemistry, activator concentration, compressive strength, and microstructure without incorporating embedded reinforcing steel. Other studies investigate chloride transport without directly validating corrosion. Corrosion studies may rely on potential or current measurements without verifying steel mass loss, while comparisons with OPC concrete may involve different curing conditions, strength classes, exposure conditions, or specimen geometries. The primary problem is not the absence of individual techniques but the fragmentation of methods that should logically represent

sequential stages of the same deterioration process. Each approach has a specific limitation: studies focused on precursors and mechanical strength characterize material behavior but omit embedded steel; transport-only studies quantify chloride ingress without confirming corrosion; and electrochemical studies infer corrosion activity without gravimetric verification of steel loss. Consequently, no single approach necessarily validates the complete pathway from chloride exposure to physical damage (Wasim et al., 2021; Zhang et al., 2021).

This study addresses this gap through a systematic secondary-data analysis focused on research methodologies rather than solely on the stated objectives of individual articles. A structured evidence matrix was developed from the screened literature, and each core study was coded according to material characterization, activation design, specimen and exposure variables, chloride transport methods, corrosion assessment methods, microstructural and mechanical validation, concrete cover thickness, and OPC benchmarking. The analysis evaluates the distribution of methods, identifies important validation relationships that remain unaddressed, and reorganizes the identified methods into a more coherent research architecture.

The academic contribution of this study is the development of an integrated methodological framework that links precursor chemistry and alkali activation with microstructure, chloride transport, steel depassivation, electrochemical response, actual reinforcement mass loss, and mechanical performance degradation following exposure. The framework has international relevance because chloride-induced deterioration is a global infrastructure problem, and comparable methodological reporting is essential for transferring findings across material systems, laboratories, and exposure conditions. The novelty of this study does not lie in proposing a new individual test method; rather, it lies in establishing methodological relationships among existing indicators along the concrete deterioration pathway, positioning each method as a means of validating the subsequent stage.

Accordingly, the objectives of this study are explicitly formulated as follows: (1) to identify and quantify the distribution of material characterization, chloride transport, electrochemical, and physical damage assessment methods used in research on chloride-induced corrosion in geopolymer concrete; (2) to determine which methodological combinations and validation relationships are most frequently absent; and (3) to develop an integrated methodological framework linking precursor chemistry, alkali activation, microstructure, chloride transport, steel depassivation, electrochemical response, reinforcement mass loss, and mechanical performance degradation. Academically, this study clarifies how fragmented methods can be reorganized into a mutually validating causal sequence. Practically, it provides researchers with a transparent basis for designing resource-efficient and reproducible durability experiments on geopolymer concrete and other low-clinker binder systems.

METHODS

This study employed a quantitative-descriptive secondary-data design involving systematic evidence identification, methodological coding, and cross-study synthesis. Scopus was the primary bibliographic database documented in the research protocol. The documented search vocabulary included *geopolymer concrete*, *fly ash*, *metakaolin*, *ordinary Portland cement* (OPC), *reinforcement corrosion*, *chloride attack*, *half-cell potential*, *rebar mass loss*, *compressive strength*, *X-ray fluorescence* (XRF), *chloride penetration*, and *scanning electron microscopy* (SEM). Targeted query groups combined terms related to geopolymer or alkali-activated concrete with NaOH concentration, Na_2SiO_3/NaOH ratio, chloride penetration or ingress, NaCl exposure or marine environments, and chloride test methods, including rapid chloride permeability testing (RCPT), diffusion, migration, and NT BUILD 492. The documented targeted-query matrix was updated through June 5, 2026. Articles that passed the screening and methodological assessment processes were subsequently classified according to their contributions to the research methods. Studies included in the core methodological group constituted the quantitative dataset and were coded using 20 binary indicators covering material characterization, mechanical testing, chloride transport, reinforcement corrosion assessment, mass-loss validation, OPC benchmarking, concrete cover thickness, and NaCl or marine exposure. The complete identities and coding results of all core studies were stored in a separate research evidence matrix, which served as an audit trail for the analysis and could be provided as a

supplementary file upon request from the editor or reviewers. The frequency and percentage of each indicator were calculated, and article–method mapping using a heatmap was performed to identify patterns of method use, combinations of methods that had not been integrated, and methodological fragmentation. The quantitative results were subsequently synthesized qualitatively to identify methodological gaps and construct a research framework linking material characteristics, activation, microstructure, chloride transport, electrochemical response, physical reinforcement damage, and changes in mechanical performance. A meta-analysis was not performed because of heterogeneity in mixture composition, curing conditions, specimen geometry, exposure conditions, and outcome parameters across the included studies. This study used secondary data and involved neither human participants nor animals; therefore, ethical approval was not required. The identification, screening, eligibility, and inclusion stages followed the PRISMA 2020 guidelines for reporting systematic reviews to ensure transparency and reproducibility of the study selection process. The corresponding flow of records is summarized in Figure 1 (Page et al., 2021). Because this study constituted a methodological systematic review rather than a hypothesis-testing statistical model, no inferential path hypotheses were specified. Instead, the relationships examined corresponded to the sequential stages of the proposed framework, while indicators not central to the causal chain were also examined to reveal methodological fragmentation.

To ensure coding reliability, the 20 indicators were defined *a priori* based on established durability and corrosion-assessment literature, using explicit binary decision rules. The coding scheme was pilot-tested on a random subset of studies, after which the indicators were applied by the first author and verified by the co-authors. Coding disagreements were reconciled through consensus, and ambiguous cases were resolved by reexamining the full texts.

To facilitate replication, the documented search vocabulary and targeted query groups were consolidated into a representative Scopus search expression. This reconstructed expression summarized the documented search strategy and was not intended to represent the exact final syntax originally exported from Scopus. The documented search terms covered geopolymer and alkali-activated concrete, precursor materials, chloride exposure, reinforcement corrosion, and relevant transport and corrosion-assessment methods. The available search documentation had been updated through June 5, 2026.

RESULTS AND DISCUSSION

Results

Study Selection and Evidence Dataset

The source search log contained 1,792 records. After 973 duplicates were removed before screening, 819 records remained for title and abstract evaluation, of which 669 were excluded. The remaining 150 full-text reports then underwent final quality control. At this stage, two additional duplicate records were identified, reducing the dataset to 148 unique full-text reports. Nine reports were excluded following methodological assessment. Thus, the final evidence map contained 139 retained reports, consisting of 88 unique core methodological studies, 32 complementary-method studies, and 19 background or review studies. The 88 core studies formed the quantitative dataset used in the subsequent analysis.

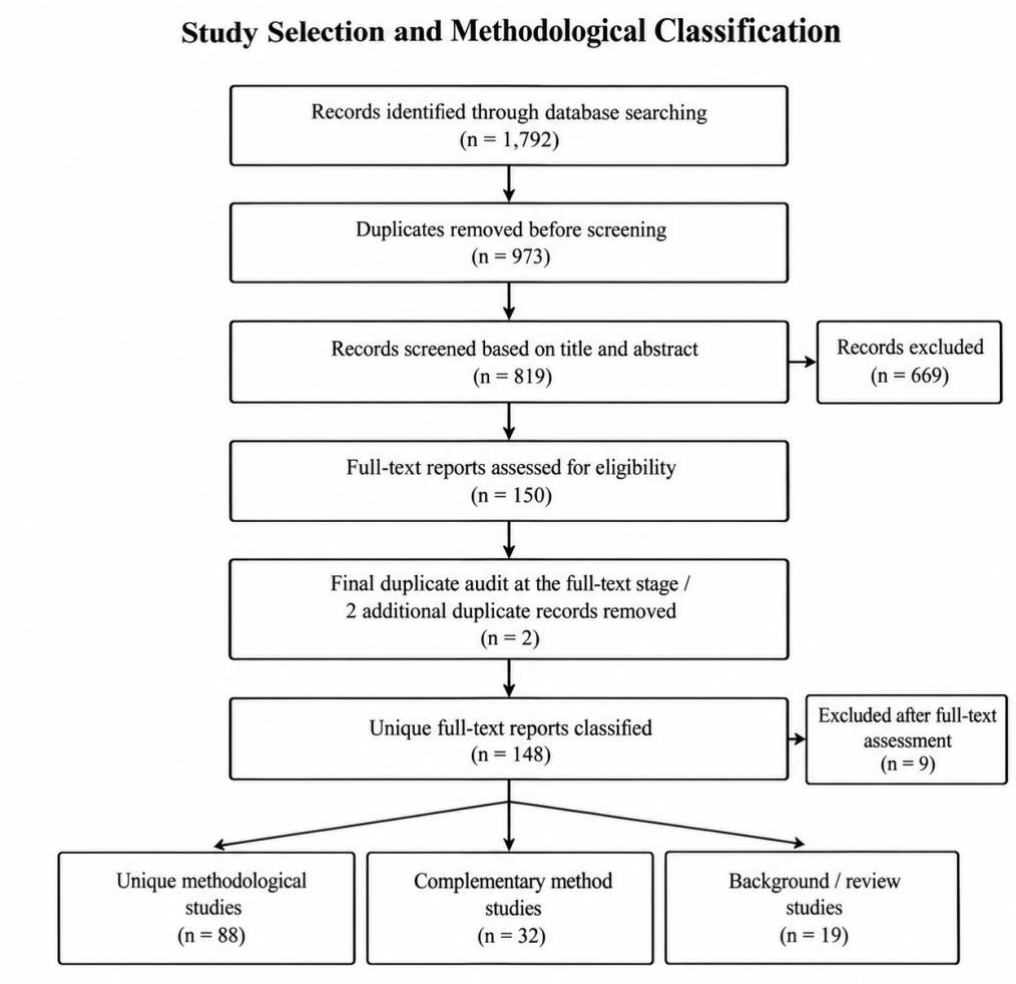


Figure 1. Study selection, final duplicate audit, and methodological classification.

Table 1
Distribution of methodological indicators coded across 88 unique core studies

No.	Methodological indicator	Studies (n)	Percentage
1	Compressive strength	65	73.9%
2	SEM/FESEM	55	62.5%
3	Chloride profiling/diffusion	36	40.9%
4	XRD	34	38.6%
5	OPC benchmark	31	35.2%
6	HCP/OCP	25	28.4%
7	LPR/Icorr	20	22.7%
8	EDS/EDX	19	21.6%
9	XRF	16	18.2%
10	Sorptivity/absorption	16	18.2%
11	Numerical concrete cover thickness	16	18.2%
12	RCPT	14	15.9%
13	RCM/NT Build 492	14	15.9%
14	FTIR	14	15.9%
15	Potentiodynamic/Tafel	13	14.8%
16	MIP	9	10.2%
17	Reinforcement mass	9	10.2%

	loss		
18	Accelerated corrosion	7	8.0%
19	EIS	6	6.8%
20	NaCl/seawater exposure	84	95.5%

Table 1 shows that NaCl or seawater exposure predominated in the core dataset (84/88; 95.5%). Compressive strength was the most frequently reported performance test (65/88; 73.9%), followed by SEM/FESEM (55/88; 62.5%). Direct approaches involving chloride profiling or diffusion-related methods appeared in 36 studies (40.9%), whereas HCP/OCP was used in 25 studies (28.4%), LPR/Icorr in 20 studies (22.7%), and reinforcement mass loss in only 9 studies (10.2%). An explicit OPC benchmark was reported in 31 studies (35.2%), whereas numerical concrete cover thickness could be coded consistently in only 16 studies (18.2%). All results are reported as descriptive frequencies and percentages. No null hypothesis significance testing was performed; therefore, no p values are reported. Probabilistic terms, such as corrosion "probability," refer only to their conventional electrochemical interpretation and do not imply statistical inference from the coded frequencies.

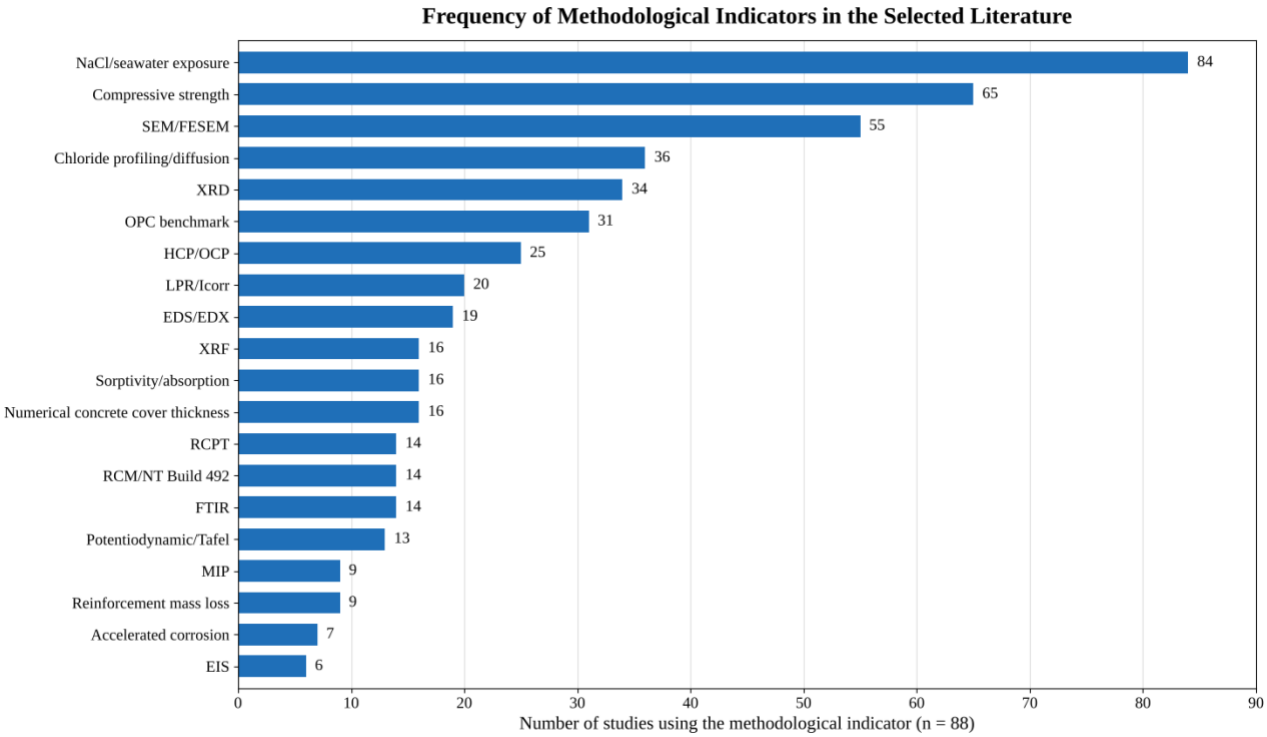


Figure 2. Frequency of methodological indicators across 88 unique core studies

Material Characterization and Activation Methods

Material characterization data indicate a greater emphasis on microstructural imaging than on comprehensive chemical characterization and pore structure analysis. SEM/FESEM was coded in 55 studies (62.5%), XRD in 34 studies (38.6%), EDS/EDX in 19 studies (21.6%), XRF in 16 studies (18.2%), FTIR in 14 studies (15.9%), and MIP in 9 studies (10.2%). These methods were often combined with compressive strength testing, which was reported in 65 studies (73.9%). Thus, the dataset contains substantial evidence on morphology and mechanical response, but fewer studies quantitatively characterize precursor oxide composition and pore-size distribution.

Within the fly ash–metakaolin group, A fly ash-to-metakaolin (FA:MK) ratio of 70:30 has been investigated in studies evaluating compressive strength and microstructure, whereas other studies have examined the performance and characteristics of fly ash–metakaolin pastes under various mixture compositions and activation conditions. Studies examining chloride content, sulfate

concentration, and the microstructure of geopolymer concrete further underscore the importance of early-stage material characterization. These studies make valuable methodological contributions but do not yet provide a comprehensive assessment of corrosion in embedded reinforcing steel (Barbhuiya & Pang, 2022; Kumar et al., 2024; Qiao et al., 2024).

Exposure, Concrete Cover Thickness, and Chloride Transport Methods

Chloride or seawater exposure was reported in 84 of the 88 core studies, but the exposure designs varied substantially. The coded studies included external immersion in NaCl solutions, seawater exposure, wet–dry cycles, the addition of chloride to fresh mixtures, field exposure in marine environments, and accelerated impressed-current procedures. Numerical concrete cover thickness could be explicitly and consistently identified in only 16 core studies. This finding indicates that most studies address chloride durability without reporting cover thickness in a form that can be directly compared across the dataset. Variation in exposure design is also evident in studies evaluating the corrosion-related performance of recycled aggregate geopolymer concrete (Gopalakrishna & Dinakar, 2024).

The transport methods used were also heterogeneous. Chloride profiling, penetration depth measurements, or diffusion-related approaches were coded in 36 studies (40.9%), whereas the rapid chloride permeability test (RCPT) and rapid chloride migration (RCM) methods, including NT BUILD 492, were each coded in 14 studies (15.9%). Sorptivity or absorption indicators appeared in 16 studies (18.2%). Thus, direct and indirect transport indicators are distributed across different experimental approaches and have not converged on a single, uniformly applied standard method.

Reinforcement Corrosion Assessment Methods and Physical Validation

Electrochemical techniques were used more frequently than direct measurements of physical steel damage. HCP/OCP was coded in 25 studies (28.4%), LPR/Icorr in 20 studies (22.7%), potentiodynamic or Tafel polarization in 13 studies (14.8%), EIS in 6 studies (6.8%), and accelerated corrosion testing in 7 studies (8.0%). Reinforcement mass loss was reported in only 9 studies (10.2%). The quantitative difference between the 25 studies monitoring potential and the 9 studies measuring mass loss is one of the main empirical patterns in the dataset. Studies of passive-film behavior also emphasize the importance of the alkaline pore environment in determining the passivation conditions of reinforcing steel (Jin et al., 2022).

The heatmap of the 88 core studies also shows that the main methodological indicators rarely occur together in a complete sequence. Studies employing transport methods do not always examine embedded reinforcing steel, and studies using electrochemical corrosion assessment methods do not consistently include gravimetric validation. Likewise, SEM and compressive strength testing are frequently used but may not be directly linked to chloride measurements or steel damage assessments.

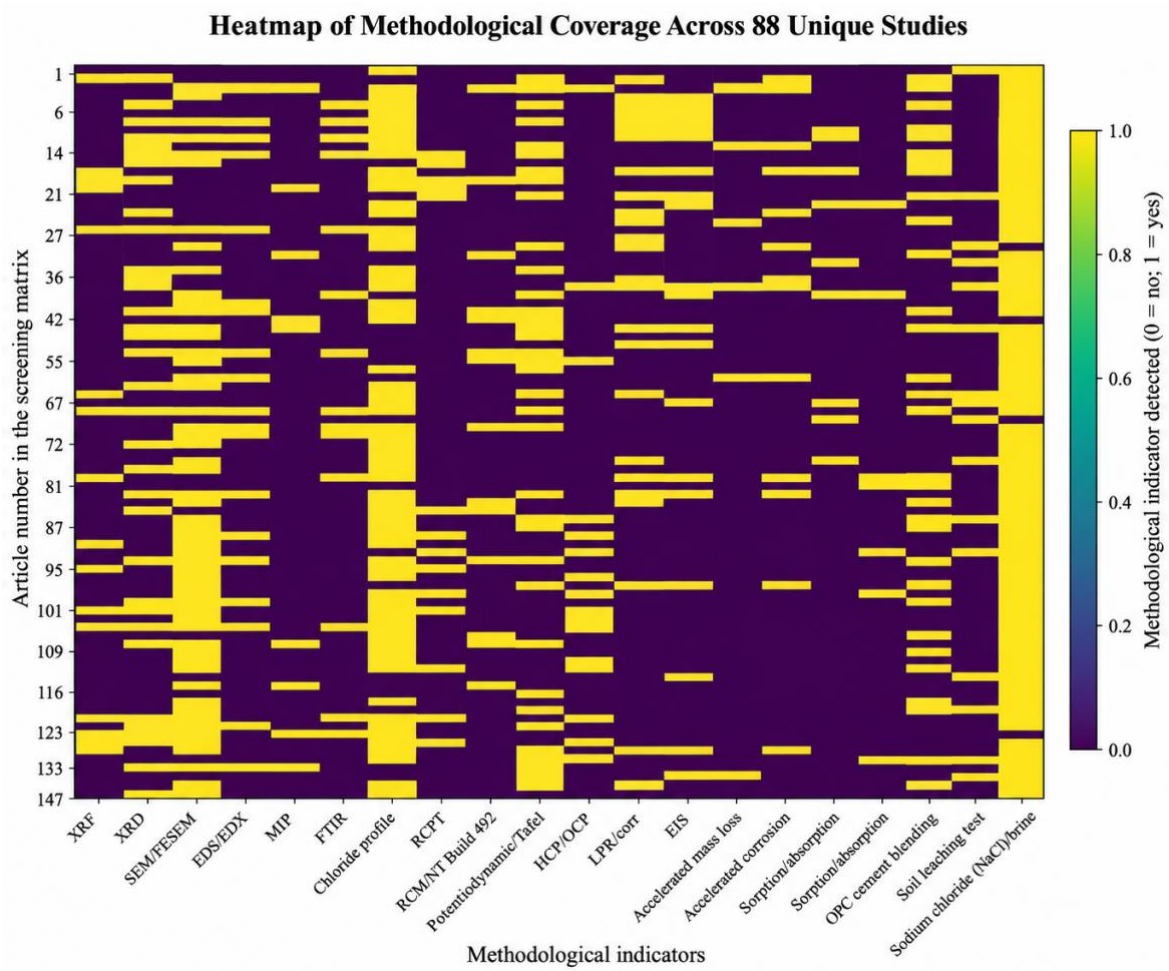


Figure 3. Heatmap of methodological coverage across 88 unique core studies based on 20 coded indicators.

OPC Comparison and Methodological Integration

Only 31 of the 88 core studies (35.2%) explicitly included an OPC benchmark. The remaining studies evaluated geopolymer or alkali-activated materials without a directly comparable conventional concrete benchmark. In addition, only a small proportion of the dataset included modeling, cross-method correlations, or an integrated interpretation stage that explicitly linked material chemistry, transport, electrochemical response, and physical damage. This descriptive evidence indicates that integration, rather than the availability of individual methods, is the least represented methodological feature.

Discussion

The secondary data analysis shows that the research field already possesses most of the techniques needed to investigate chloride-induced corrosion in geopolymer concrete. What remains lacking is a consistent methodological framework for combining these techniques. This distinction is important because novelty should not be claimed merely because XRF, SEM, chloride migration testing, HCP, LPR, EIS, mass-loss measurements, or compressive strength testing are included. These methods are well established. The methodological contribution lies in explaining how each method represents a different stage of the deterioration process and how the results from these stages should be used to validate one another. One plausible explanation for the observed patterns is methodological inheritance: research on geopolymer durability has largely adopted the testing repertoire developed for OPC concrete, in which compressive strength testing and microstructural imaging are routine, whereas destructive gravimetric validation and long-term electrochemical monitoring are resource-intensive and therefore less frequently used. This inheritance, rather than any material-specific necessity, may help explain the observed frequencies. Throughout this discussion, empirical findings (the coded frequencies), theoretical

interpretations (the causal roles of individual methods in the degradation process), and possible explanations (contextual factors such as methodological inheritance) are clearly distinguished. The latter are presented as hypotheses rather than established facts.

From Precursor Chemistry to Transport: The Importance of Early-Stage Characterization

The first methodological implication concerns the relationship among precursor chemistry, alkali activation, pore structure, and chloride transport. The dataset shows that SEM and compressive strength testing are used much more frequently than XRF and MIP. This pattern can create an interpretive gap. SEM can reveal an apparently dense matrix, while compressive strength testing can characterize the development of mechanical properties. However, neither measurement can independently explain why a particular binder resists or permits chloride transport. XRF characterizes the elemental composition of the precursor materials and can be used to determine their oxide composition. Activation variables influence precursor dissolution and reaction-product formation, whereas pore structure analysis provides evidence of the pathways through which aggressive ions can migrate. When these data are unavailable, chloride transport performance may be described without a sufficiently traceable explanation of the underlying material mechanisms.

This issue is particularly relevant to fly ash–metakaolin systems. An FA ratio of 70:30 has been evaluated in terms of compressive strength and microstructure, while variations in mixture composition and activation conditions have been shown to affect the characteristics of fly ash–metakaolin pastes. This early-stage evidence provides a mechanistic basis for understanding material behavior but becomes considerably more valuable when the same material is subsequently evaluated for chloride transport and reinforcement corrosion. Future research frameworks should therefore position precursor and activation characterization as the starting point for durability analysis rather than treating it as a standalone material investigation (Qiao et al., 2024).

Why Chloride Test Method Selection Requires Binder-Specific Interpretation

The second implication concerns chloride transport. The relatively lower frequency of RCPT compared with direct profiling or diffusion-related methods does not mean that RCPT lacks value; rather, it highlights the need to distinguish what each method actually measures. RCPT results are strongly influenced by electrical conductivity because the test measures the electrical charge passed through a specimen under an applied potential difference. In OPC concrete, this test can serve as a useful empirical durability index. However, the pore solutions of alkali-activated systems may differ in ionic composition, concentration, and mobility. The literature indicates inconsistencies in the application and interpretation of rapid chloride permeability testing for geopolymer concrete, as well as interactions among the chemical and physical factors governing chloride transport in alkali-activated materials (Mostazid et al., 2026; Wan et al., 2023).

A defensible research framework should prioritize direct chloride concentration profiling, penetration-depth measurements, diffusion tests, or chloride migration methods when the research objective is to explain chloride transport and availability near reinforcing steel. RCPT can still be used as a supporting electrical indicator, particularly for comparative screening, but its results should not automatically be interpreted as direct measurements of chloride diffusion. This distinction has international relevance because test methods developed for conventional cementitious systems are often applied to alternative binders. Without binder-specific interpretation, numerical comparisons may reflect differences in pore-solution chemistry and electrical conductivity rather than differences in chloride transport resistance alone.

Electrochemical Monitoring Must Be Validated Against Actual Steel Damage

The most pronounced quantitative methodological gap is the imbalance between the use of HCP/OCP and measurements of reinforcement mass loss. HCP/OCP was used in 25 core studies, whereas reinforcement mass loss was reported in only 9 studies. This distinction is important because corrosion potential is not a measurement of corrosion rate and does not directly quantify steel cross-sectional loss. HCP is nevertheless valuable because it is nondestructive and can be measured repeatedly over time, but its interpretation should remain probabilistic and should

account for the test conditions and applicable reference criteria. In geopolymer systems, applying conventional OPC-derived potential thresholds can be more complex because of differences in pore-solution chemistry and reinforcement passivation behavior. The practical consequence is that corrosion conclusions in a substantial proportion of the literature rely on potential readings that, by themselves, cannot confirm whether steel cross-sectional loss has occurred or quantify its extent. Interpretations of reinforcement corrosion in geopolymer concrete that are not supported by gravimetric measurements or equivalent physical validation should therefore be regarded as provisional.

Highly negative corrosion potentials in geopolymer concrete do not always correspond directly to visible corrosion when interpreted using conventional criteria. Alkalinity and the Cl^-/OH^- ratio also influence reinforcement corrosion in alkali-activated concrete. These findings support a triangulation approach. HCP/OCP should be used to monitor potential trends and assess the likelihood of depassivation; LPR-derived corrosion current density (Icorr) or EIS can be added when information on corrosion kinetics is required; and mass-loss measurements at the end of testing should be used to verify whether the electrochemical response corresponds to physical steel damage (P. S. Mangat & Ojedokun, 2024).

This combination also improves interpretation when indicators appear to conflict. A specimen may exhibit a negative corrosion potential but limited mass loss, or a moderate potential while localized damage has developed. Without gravimetric or other physical verification, such conditions may be misclassified. Cross-method validation therefore reduces the risk of applying OPC-derived thresholds to alkali-activated systems without evidence that those thresholds correspond to comparable levels of physical damage.

Concrete Cover Thickness and Exposure Time as Controlling Variables

The limited reporting of numerical concrete cover thickness in the dataset represents another important gap. Concrete cover is not merely a geometric detail; it determines the transport distance between the exposed concrete surface and the reinforcing steel. A concrete matrix with high chloride resistance may still allow chloride ions to reach the steel relatively quickly if the cover is inadequate, whereas a more permeable matrix may exhibit a longer initiation period when the cover thickness is increased. Treating cover thickness as a controlled experimental variable makes it possible to distinguish more clearly between the protective effects of material chemistry and those of specimen geometry.

Exposure duration creates a similar interpretive problem. The literature includes accelerated tests lasting several hours or days, laboratory immersion lasting months, and field exposure lasting years. These protocols do not necessarily represent equivalent stages of the corrosion process. A framework intended to improve experimental comparability should establish defined observation ages and maintain consistent exposure mechanisms across the material groups being compared. Long-term external chloride exposure studies demonstrate the methodological value of observing transport and reinforcement responses over a defined period rather than bypassing the transport mechanism by adding chloride at the outset or using excessively aggressive impressed-current conditions (Asmara et al., 2016; Pasupathy et al., 2021; Tennakoon et al., 2017).

The Role of an OPC Benchmark under Equivalent Exposure Conditions

Only about one-third of the core studies explicitly used an OPC benchmark. This limits the strength of general claims that geopolymer concrete is superior or inferior to conventional concrete. Including a benchmark is not sufficient in itself; the benchmark must be tested using the same specimen geometry, cover thickness, exposure conditions, monitoring schedule, and final validation procedures. If curing conditions, target compressive strength, or chloride exposure differ between binders, the observed performance differences cannot be convincingly attributed solely to binder chemistry. When a benchmark is absent or tested under nonequivalent conditions, claims that geopolymer concrete outperforms or underperforms conventional concrete are methodologically weak because the observed differences may result from unequal curing conditions, strength classes, cover thicknesses, or exposure conditions rather than binder chemistry. The limited and inconsistent use of OPC benchmarks in the dataset therefore constrains

the strength of comparative durability conclusions across the field.

An OPC benchmark tested under equivalent exposure conditions serves two functions. First, it provides a familiar reference for assessing the magnitude of chloride transport and corrosion responses. Second, it helps determine whether interpretive thresholds developed for OPC concrete produce comparable responses in geopolymer systems. This is particularly important for HCP/OCP measurements and electrically based chloride transport tests. Using the same testing sequence therefore improves both scientific comparability and practical relevance.

Proposed Integrated Methodological Framework and Novelty

The proposed framework synthesizes these findings into a sequential chain of evidence. Precursor chemistry is characterized first because it defines the raw-material system. Alkali activation is then controlled because activator concentration and silicate availability influence the geopolymerization process. The resulting microstructure and pore network subsequently govern chloride transport through the concrete cover. Chloride transport and the potential for chloride accumulation near the steel are then evaluated alongside electrochemical monitoring, with HCP/OCP serving as a nondestructive indicator of corrosion potential and the likelihood of depassivation. At the final stage, reinforcement mass loss provides direct physical validation of steel damage, while post-exposure compressive strength testing and selected microstructural observations help explain the accompanying changes in material performance.

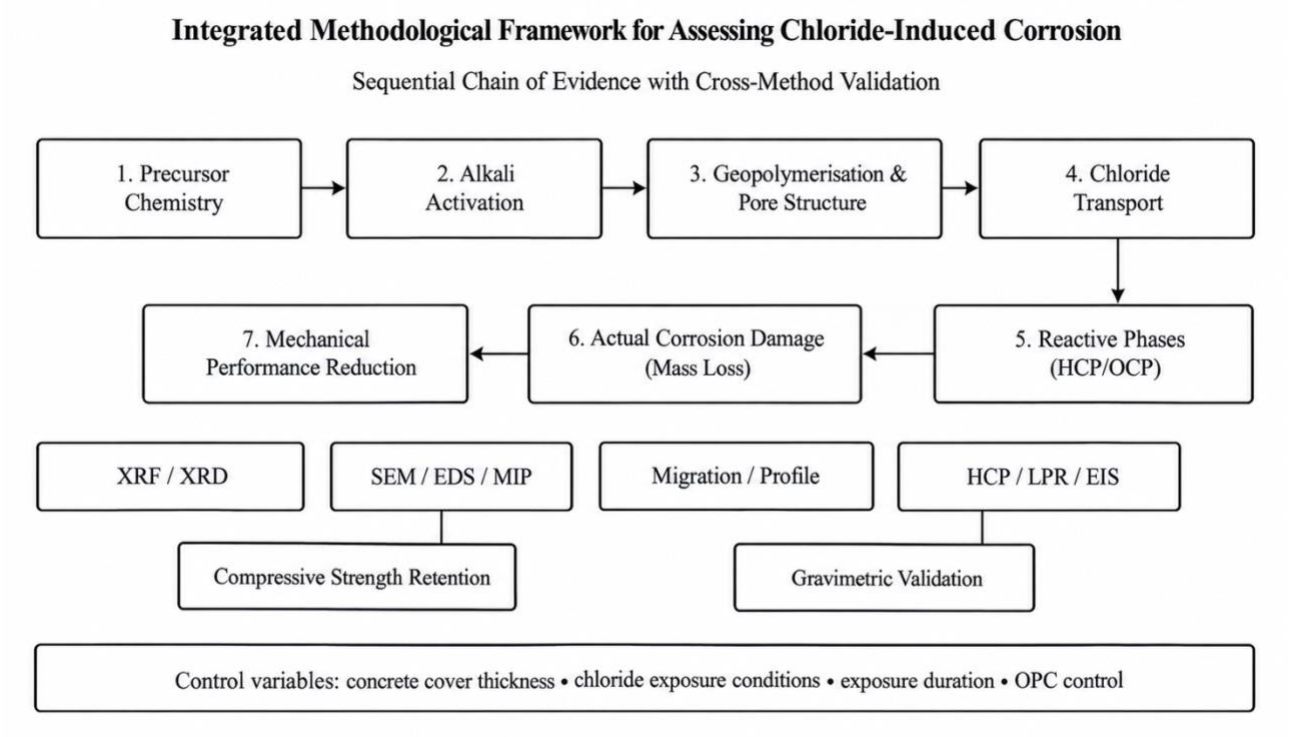


Figure 4. Proposed integrated methodological framework for assessing chloride-induced corrosion in geopolymer concrete.

The framework should be understood as an evidence architecture rather than an obligation to use every available technique. Researchers working with limited resources can select one robust method at each critical stage. For example, XRF can characterize precursor oxide composition; controlled activator variables can define the mixture design; direct chloride migration or chloride profiling methods can quantify transport; HCP/OCP can provide repeated electrochemical monitoring; mass-loss measurements can validate actual steel damage; and SEM and compressive strength testing can explain microstructural and mechanical consequences. Where higher resolution or more detailed mechanistic evidence is required, XRD, MIP, LPR, EIS, or polarization methods can be added.

The novelty of the study lies in methodological integration. The framework transforms a fragmented body of literature into a causal sequence in which each result has a defined

interpretive role and a validation relationship with subsequent stages. This approach addresses the main weakness identified in the heatmap: individual studies often include several useful tests but rarely cover the entire chain from material characteristics to physical damage. The proposed architecture also makes negative or inconsistent results scientifically valuable because discrepancies among chloride transport indicators, HCP/OCP readings, and mass-loss measurements can be investigated rather than concealed through reliance on a single index. Theoretically, the sequence is directional and causal rather than merely associative: precursor chemistry and activation influence pore structure; pore structure governs chloride transport; transport determines the chloride exposure experienced by the reinforcing steel; chloride exposure can promote depassivation and alter the electrochemical response; and subsequent corrosion may produce mass loss and mechanical degradation. These latter outcomes provide evidence of physical damage against which earlier indicators can be evaluated. Each link in Figure 4 therefore represents a testable relationship between an upstream factor and a downstream response, although the strength and direction of these relationships must ultimately be established empirically.

Theoretical, Practical, and International Implications

The theoretical implication of this study is that chloride-induced corrosion in geopolymer concrete should be understood as an integrated material–transport–electrochemical process. Precursor chemistry and activator design are not merely mixture variables; they are upstream factors that influence the pore environment through which chloride ions migrate and the chemical conditions surrounding the reinforcing steel. The framework therefore connects materials science and corrosion science within a single interpretive sequence. This approach can help explain apparently inconsistent findings in the literature by examining whether different studies measure different stages of deterioration rather than assuming that all durability indicators represent the same phenomenon.

The practical implication is a more defensible experimental design. Researchers can use this framework to explain the rationale for each method, avoid repetitive testing without additional interpretive value, and determine the minimum validation required to characterize reinforcement corrosion. Laboratories with limited equipment can still apply the core logic by combining precursor characterization, direct chloride transport methods, HCP/OCP measurements, mass-loss measurements, and selected microstructural or mechanical assessments. The framework is also suitable for staged research programs in which advanced electrochemical or pore-structure methods are applied only to representative mixtures.

In an international context, methodological comparability is particularly important because geopolymer precursors vary by region. Fly ash composition, metakaolin purity, slag calcium content, and activator chemistry can differ substantially across countries and industrial sources. A framework that reports precursor chemistry, exposure geometry, chloride transport methods, electrochemical responses, and physical steel damage in a standardized sequence allows results from different regions to be compared more meaningfully. The same approach can also be applied to other low-clinker binders and alternative cementitious materials for which assumptions derived from OPC concrete may not be directly applicable.

Study Limitations

This study has several limitations. First, it is a method-oriented secondary-data synthesis rather than a meta-analysis of material performance. The analyzed studies are highly heterogeneous in terms of precursor systems, activator compositions, curing conditions, specimen geometry, chloride exposure, and reported outcomes; therefore, combining numerical performance values would require additional normalization. Second, the frequency analysis depends on whether a method was explicitly reported in the screening matrix. Accordingly, the absence of a coded method should be interpreted as indicating that the method was not identified in the extracted record, rather than as evidence that it was not used. Third, the available search documentation identifies Scopus as the primary database, records the main search vocabulary and targeted query groups, and documents an update dated June 5, 2026, but does not retain a single final exported search string. Therefore, the search expression presented in the Methods section

represents a reconstruction of the documented search strategy rather than the exact original exported query. Fourth, two duplicate pairs were identified during final full-text quality control. These duplicate records were excluded from the quantitative synthesis and reported transparently in the study-selection flow.

CONCLUSION

This systematic secondary-data study shows that research on chloride-related durability and reinforcement corrosion in geopolymer concrete employs a diverse range of experimental methods, but these methods have not yet been consistently integrated. Among the 88 unique core methodological studies, compressive strength testing and SEM/FESEM are commonly used, direct chloride profiling or diffusion-related methods are used with moderate frequency, electrochemical monitoring is less frequent, and gravimetric reinforcement mass-loss measurements remain relatively rare. The clearest methodological imbalance is between HCP/OCP, reported in 25 studies, and reinforcement mass loss, reported in only 9 studies, indicating that potential-based assessments are often not validated against actual steel damage. The explicit use of OPC benchmarks and the numerical reporting of concrete cover thickness are also limited. Based on these patterns, the study proposes a sequential evidence framework linking precursor chemistry, alkali activation, microstructure and pore development, chloride transport, steel depassivation, electrochemical response, actual reinforcement mass loss, and mechanical performance degradation, with cover thickness, exposure duration, and OPC benchmarking serving as controlling variables. The principal contribution is therefore the organization of established methods into a mutually validating causal architecture rather than the introduction of new individual testing techniques.

In direct response to the study objectives, the principal limitation identified in the field is integrative rather than technical. The proposed framework specifies the measurements needed to validate the successive stages of the chloride-induced degradation process and provides a basis for designing more comparable and reproducible experiments on corrosion in geopolymer concrete. Because the framework was derived from a systematic synthesis of secondary data and has not yet been experimentally validated as an integrated sequence, its conclusions are limited to methodological organization rather than validated material performance. Future experimental research should therefore operationalize the framework under controlled, long-term chloride exposure, particularly by combining electrochemical monitoring with end-of-test gravimetric validation to evaluate its predictive value.

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AUTHOR CONTRIBUTION STATEMENT

Tira Roesdiana was responsible for the conceptualization and methodological development of the study, systematic literature identification and screening, secondary data collection and processing, methodological indicator coding, data analysis and interpretation, development of the integrated methodological framework, visualization of research findings, and preparation of the original manuscript draft. Antonius contributed to the supervision of the study, validation of the methodological indicator coding and data analysis, and critical review and editing of the manuscript. Abdul Rochim contributed to the supervision of the study, validation of the integrated methodological framework, and critical review and editing of the manuscript. All authors have read and approved the final version of the manuscript and take responsibility for its content.

REFERENCES

Asmara, Y. P., Siregar, J. P., & Nurlisa, W. (2016). Long Term Corrosion Experiment of Steel Rebar

in Fly Ash-Based Geopolymer Concrete in NaCl Solution. *International Journal of Corrosion*. https://doi.org/10.1155/2016/3853045

Babaee, M., & Castel, A. (2016). Chloride-induced corrosion of reinforcement in low-calcium fly ash-based geopolymer concrete. *Cement and Concrete Research*, *88*, 96–107. https://doi.org/10.1016/j.cemconres.2016.05.012

Babaee, M., & Castel, A. (2018). Chloride diffusivity, chloride threshold, and corrosion initiation in reinforced alkali-activated mortars: Role of calcium, alkali, and silicate content. *Cement and Concrete Research*, *111*, 56–71. https://doi.org/10.1016/j.cemconres.2018.06.009

Barbhuiya, S., & Pang, E. (2022). Strength and Microstructure of Geopolymer Based on Fly Ash and Metakaolin. *Materials*, *15*(10), 3732. https://doi.org/10.3390/ma15103732

Chindaprasirt, P., & Chalee, W. (2014). Effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash-based geopolymer concrete under marine site. *Construction and Building Materials*, *63*, 303–310. https://doi.org/10.1016/j.conbuildmat.2014.04.010

Duży, P., Choińska, M., & Hager, I. (2022). Mechanical Strength and Chloride Ions' Penetration of Alkali-Activated Concretes with Blended Precursor. *Materials*, *15*, 4475. https://doi.org/10.3390/ma15134475

Ekaputri, J. J., Mutiara, I. S., Nurminarsih, S., Chanh, N. V, Maekawa, K., & Setiamarga, D. H. E. (2017). The Effect of Steam Curing on Chloride Penetration in Geopolymer Concrete. *Matec Web of Conferences*, *138*, 1019. https://doi.org/10.1051/matecconf/201713801019

El Moustapha, B., Bonnet, S., Khelidj, A., Maranzana, N., Froelich, D., Khalifa, A., & Ahmedou Babah, I. (2023). Effects of microencapsulated phase change materials on chloride ion transport properties of geopolymers incorporating slag and, metakaolin, and cement-based mortars. *Journal of Building Engineering*, *74*, 106887. https://doi.org/10.1016/j.jobe.2023.106887

Gopalakrishna, B., & Dinakar, P. (2024). The evaluation of the life cycle and corrosion properties of recycled aggregate geopolymer concrete incorporating fly ash and GGBS. *Journal of Building Engineering*, *94*, 109977. https://doi.org/10.1016/j.jobe.2024.109977

Gunasekara, C., Law, D., Bhuiyan, S., Setunge, S., & Ward, L. (2019). Chloride induced corrosion in different fly ash based geopolymer concretes. *Construction and Building Materials*, *200*, 502–513. https://doi.org/10.1016/j.conbuildmat.2018.12.168

Ichimiya, K., Yamamoto, R., Nguyen, Q. D., Castel, A., & Ikeda, K. (2024). A New Performance-Based Test for Assessing Chloride-Induced Reinforcement Corrosion Resistance of Geopolymer Mortars. *Materials*, *17*(21), 5162. https://doi.org/10.3390/ma17215162

Jin, Z., Zhao, X., & Du, Y. (2022). Comprehensive properties of passive film formed in simulated pore solution of alkali-activated concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2021.126142

Koch, G., Varney, J., Thompson, N., Moghissi, O., Gould, M., & Payer, J. (2016). International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) Study. Houston, TX: NACE International.

Kumar, S., Maradani, L. S. R., Mohapatra, A. K., & Pradhan, B. (2024). Effect of mix parameters on chloride content, sulfate ion concentration, and microstructure of geopolymer concrete. *Construction and Building Materials*, *435*, 136864. https://doi.org/10.1016/j.conbuildmat.2024.136864

Mangat, P., & Lambert, P. (2016). 18 - Sustainability of alkali-activated cementitious materials and geopolymers. In J. M. B. T.-S. of C. M. (Second E. Khatib (Ed.), *Woodhead Publishing Series in Civil and Structural Engineering* (pp. 459–476). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100370-1.00018-4

Mangat, P. S., & Ojedokun, O. O. (2024). Alkalinity and Cl-/OH- Affecting Reinforcement Corrosion in Alkali Activated Concrete. *Proceedings of the International Conference on Sustainable Construction Materials and Technologies*. https://doi.org/10.18552/2024/scmt/233

Morla, P., Gupta, R., Azarsa, P., & Sharma, A. (2021). Corrosion Evaluation of Geopolymer Concrete Made With Fly Ash and Bottom Ash. *Sustainability*, *13*(1), 398. https://doi.org/10.3390/su13010398

Mostazid, M. I., Kim, T., Foster, S., Ben, B., Asadi, H., & Hajimohammadi, A. (2026). Inconsistencies in rapid chloride permeability testing of geopolymer concrete: Insights into binder

chemistry, pore structure, and test cell configuration. *Cement and Concrete Composites*, *165*, 106340. https://doi.org/10.1016/j.cemconcomp.2025.106340

Noushini, A., Castel, A., Aldred, J., & Rawal, A. (2020). Chloride diffusion resistance and chloride binding capacity of fly ash-based geopolymer concrete. *Cement and Concrete Composites*, *105*, 103290. https://doi.org/10.1016/j.cemconcomp.2019.04.006

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71

Pasupathy, K., Sanjayan, J., Rajeev, P., & Law, D. W. (2021). The effect of chloride ingress in reinforced geopolymer concrete exposed in the marine environment. *Journal of Building Engineering*, *39*, 102281. https://doi.org/10.1016/j.jobe.2021.102281

Qiao, J., Lv, Y., Peng, H., Han, W., Pan, B., & Zhang, B. (2024). Performance and characterization of fly ash-metakaolin-based geopolymer pastes. *Materials Today Communications*, *41*, 110293. https://doi.org/10.1016/j.mtcomm.2024.110293

Tennakoon, C., Shayan, A., Sanjayan, J. G., & Xu, A. (2017). Chloride ingress and steel corrosion in geopolymer concrete based on long term tests. *Materials & Design*, *116*, 287–299. https://doi.org/10.1016/j.matdes.2016.12.030

Wan, X., Cui, Y., Jin, Z., & Gao, L. (2023). Chloride Transport and Related Influencing Factors of Alkali-Activated Materials: A Review. *Materials*, *16*(11), 3979. https://doi.org/10.3390/ma16113979

Wasim, M., Ngo, T. D., & Law, D. (2021). A state-of-the-art review on the durability of geopolymer concrete for sustainable structures and infrastructure. Construction and Building Materials, 291, 123381. https://doi.org/10.1016/j.conbuildmat.2021.123381

Zhang, F., Xi, X., & Yang, S. (2021). Research progress in corrosion mechanism of reinforced alkali-activated concrete structures. Corrosion and Materials Degradation, 2(4), 641-656. https://doi.org/10.3390/cmd2040034

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