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Chloride induced corrosion behaviour of mild steel rebars: A case study of calcined Clay Pozzolan containing concrete

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ABSTRACT

The partial replacement of 5 – 30 % by mass of ordinary Portland cement with clay pozzolana in concrete, gives impressive chemical characteristics to the resulting material. Corrosion behavior of reinforcement steel in two types of concrete mixtures: Ordinary Portland Cement (OPC) containing concrete and 30 % clay pozzolana cement (PPC) containing concrete are studied. These concretes were exposed to 3 % and 5 % (w/v) solutions of NaCl as corrosion acceleration media. Electrochemical polarization measurements were performed for 3, 7, 15, and 23 days. The corrosion rate obtained from the polarization curves revealed that samples exposed to 5 %(w/v) NaCl had higher corrosion rates than those exposed to 3 %(w/v) NaCl. The addition of 30 % clay pozzolan as a partial replacement for OPC in concrete resulted in an average reduction in the corrosion rate of approximately 90 % in 3 %(w/v) NaCl and 74 % in 5 %(w/v) NaCl over 23 days.

Introduction

Steel-reinforced concrete remains a cornerstone material in construction due to its exceptional ability to withstand mechanical loads and protect steel reinforcements from corrosion. This durability stems from the protective environment provided by the alkalinity of concrete, which forms a passive oxide layer on the steel surface. However, this protective mechanism can be disrupted under specific environmental conditions, leading to premature deterioration of reinforced concrete structures. Such deterioration is not only associated with the high cost of maintenance and repairs but also results in consequential financial losses due to structural failures and reduced service life [1,2]. Among these environmental factors, chloride-containing environments are particularly aggressive. Chloride ions diffuse into the concrete matrix and induce localized corrosion of steel rebars [3]. This process progressively weakens the bond strength between the concrete and steel reinforcement, leading to the formation of cracks, spalling, and the eventual loss of compressive strength of the reinforcing steel itself. For more detailed discussions on how corrosion affects the mechanical properties of steel rebars, see [4,5].

The challenges posed by chloride-induced corrosion have prompted extensive research into effective mitigation techniques to enhance the service life of reinforced concrete. Some advanced methods include coating steel rebars with protective materials like zinc through the hot-dip galvanization process, where a zinc layer acts as a barrier against corrosive agents [1,6,7]. Similarly, cathodic

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protection techniques, which involve the application of an electrical current to the reinforcement, have gained traction as a means of minimizing corrosion [8,9]. Another promising area of research is the use of organic compounds as corrosion inhibitors, which act by forming a protective film over the steel surface [10,11]. While these techniques are effective, their relatively high costs and implementation challenges make them less suitable for widespread adoption in cost-sensitive applications. Therefore, there is significant interest in exploring simpler, cost-effective approaches such as optimizing cement types and admixture compositions to enhance the corrosion resistance of reinforced concrete. Studies such as [12–14] have demonstrated that incorporating pozzolanic materials, either as additives or as partial replacements for ordinary Portland cement (OPC), can improve concrete's resistance to chloride-induced corrosion. This growing body of evidence has increased the demand for pozzolans as a constituent in sustainable construction practices.

Pozzolans, predominantly composed of reactive glassy materials such as fly ash, micro-silica, silica fume, and calcined clay, have been utilized in construction for thousands of years. Their technical advantages include low heat requirements for hydration and the promotion of secondary chemical reactions that result in higher quantities of calcium silicate hydrate (CSH), the primary strength-giving phase in cementitious materials. These reactions also diminish the presence of calcium hydroxide ($Ca(OH)_2$), which is less effective in resisting aggressive chemical environments [15]. Specifically, calcined clay pozzolan has been identified as a particularly beneficial additive due to its fine particle size and high reactivity. In Ghana, studies have shown that replacing 5–30 % of OPC with calcined clay pozzolan produces Portland pozzolana cement (PPC) with compressive strengths suitable for both load-bearing and non-load-bearing structural applications [16]. This has made calcined clay pozzolan an attractive material for sustainable construction, particularly in regions where economic and environmental factors necessitate alternatives to traditional OPC.

In Ghana, OPC remains the preferred choice for concrete due to its widespread availability and long-standing familiarity within the construction industry. However, recent campaigns by the Council for Scientific and Industrial Research – Building and Road Research Institute (CSIR–BRRI) have highlighted the technical, economic, and environmental benefits of clay pozzolans, leading to an increase in their use as a partial replacement for OPC in concrete. Despite this growing interest, the impact of calcined clay pozzolans on the corrosion resistance of reinforced concrete, particularly under chloride-rich conditions, remains poorly understood. This knowledge gap is significant, as chloride-induced corrosion is one of the leading causes of structural degradation in marine and industrial environments.

This study seeks to address this gap by investigating the corrosion resistance of steel reinforcements embedded in concrete containing calcined clay pozzolan compared to those in conventional OPC concrete. The primary focus is to evaluate the behavior of these materials under accelerated corrosion conditions using sodium chloride (NaCl) solutions of varying concentrations. The hypothesis driving this study is that calcined clay pozzolan, when used as a partial replacement for OPC, enhances the durability and corrosion resistance of concrete by reducing its permeability to chloride ions and by chemically binding free chloride ions. This dual mechanism is expected to significantly reduce the rate of chloride-induced corrosion in reinforced concrete.

The findings of this study have broader implications for sustainable construction practices. By promoting the use of PPC as a cost-effective and environmentally friendly alternative to OPC, this research contributes to ongoing efforts to improve the longevity and structural integrity of reinforced concrete structures. In addition to its technical benefits, the adoption of PPC can help reduce the carbon footprint of the construction industry by lowering the demand for OPC production, which is a major source of greenhouse gas emissions. These advantages make calcined clay pozzolan a promising material for the development of more resilient and sustainable infrastructure, particularly in regions prone to aggressive environmental conditions.

Materials and methods

Materials and specimen design

Calcined clay pozzolan branded commercially as pozzolana cement in Ghana (PPC) and Ordinary Portland cement (OPC) was used in this study. The chemical compositions of the pozzolan and the binder are listed in Table 1. Other materials used to prepare the concrete included sand, 2.36 mm – 4.75 mm sized coarse aggregate, and deionized water. Two concrete mixes were prepared for this study with the mix proportions presented in Table 2. The first concrete mix was prepared with ordinary Portland cement (OPC), and the other contained 30 wt% clay pozzolan (PPC) as a partial replacement for ordinary Portland cement.

Table 1
Chemical composition (Wt.%) of oxides in Ordinary Portland and Clay Pozzolana cements.

Ordinary Portland Cement (OPC)		Clay Pozzolan	
Oxide	Composition (%)	Oxide/element	Composition (%)
CaO	65	SiO_2+ Al_2O_3+ Fe_2O_3	70
SiO_2	21.5	$SiO_{2,}$ Min	23.05
Al_2O_3	5	Reactive $SiO_{2,}$ Min	–
Fe_2O_3	3.5	MgO	2.5
MgO	2	S in SiO_3	2.5
Na_2O	0.5	Na_2O	1.9
K_2O	0.5	Cl	0.05
SO_3	2	–	–

Cubic concrete specimens with dimensions of 100 mm were fabricated. Each contained 10 mm diameter high-tensile steel embedded in concrete cubes. The mechanical properties and chemical composition of the steel rebar are listed in Tables 3 and 4 respectively. The rods were sourced from a freshly manufactured batch and washed with acetone before being embedded in the concrete. The length of the steel-embedded portion of the steel rod was 90 mm, which is nine times the diameter of the steel bar. This was done to ensure that bond-slip failure dominates other types of failure, such as the yielding of the steel reinforcement. The unembedded part of the steel rod, 20 mm long, was sealed in epoxy to prevent contact with the corrosive environment. The reinforced concrete cubes were wholly immersed in deionized water at a temperature of $(21 \pm 2)^{\mathbf{o}}\mathrm{C}\ ^{\circ}\mathrm{C}$ for the first seven days, and then kept in a curing room with a humidity corresponding to $(22 \pm 2)^{\mathbf{o}}\mathrm{C}$ for the following 21 days.

Accelerated chloride exposure

An accelerated chloride ion exposure test was conducted using different chlorides 3 % and 5 % (W/V) by weight of NaCl to solutions modelled after an earlier study [17]. To prepare the solutions, 825 ± 0.001 g of NaCl solute was dissolved in $27,500 \pm 5$ mL of deionized water to produce a 3 % (w/v) NaCl solution, whereas 1375 ± 0.001 g of NaCl solute was dissolved in $27,500 \pm 5$ mL of deionized water to produce 5 % (W/V) of NaCl solution. These solutions serve as electrolytes and different media for accelerating corrosion. Reinforced concrete specimens were placed in the chloride solution for accelerated corrosion measurements after 3, 10, 15, and 23 days. The specimens were submerged at the top of the concrete immediately below the solution surface. The top and bottom portions of the steel rebar were adequately insulated with epoxy coating to prevent direct contact with the chloride solution. Each specimen was placed in a large amount of solution to minimize diffusion effects or depletion of the solution concentration during the period of exposure.

Polarization curves

The current – voltage characteristics of the rebars were studied to ascertain their corrosion behavior. During the study, the current was passed at varying potential differences across the reinforcement steel rod as they remained in solution, and a Tafel plot was generated from the current – voltage characteristic. The measurements were performed using a NOVA – Metrohm Autolab ultramodern machine (NMAUM) and software, and the setup was aligned such that the reinforcing steel was the anode (working electrode), whereas an immersed graphite rod acted as the counter electrode, with its associated calomel reference electrode serving as the cathode. A linear polarization test was performed using a scanning potential range of $-1000\ \mathrm{mV} \leq V \leq 100\ \mathrm{mV}$, at a scanning rate of 10 mV /s. Data were obtained for 2 h at room temperature. MATLAB codes were used to extrapolate the corrosion current density $\mathrm{I_{corr}}$ (μA/cm^2) from the Tafel plots and the corrosion rates calculated using Eq. (1) [18].

$$\text{Corrosion Rate} \left(\frac{\text{mils}}{\text{yr}}\right) = \frac{0.13\ W}{\rho A} I_{Corr} \tag{1}$$

where W is the atomic weight of the steel (56 for iron), ρ is the density of the steel (7.85 g/cm^3) and A is the surface area. The weight loss due to corrosion in grams was calculated using ASTM Standards G1 – 90 (1990), as shown in Eq. (2).

$$\text{Corrosion Rate} \left(\frac{\text{mils}}{\text{yr}}\right) = \frac{3.45\ \times 10^6\ \Delta W}{\rho A\ \Delta t} I_{Corr}, \tag{2}$$

where the constant is consistent with the density measurement in gm/cm^3, surface area A in cm^2 and the time of exposure Δt measured in hours.

Results and discussion

Effect of concrete composition and chloride ion composition on corrosion rate of rebar

Figs. 1,2,3,4 illustrate the polarization curves generated from electrochemical measurements on steel rebars embedded in concrete mixes and exposed to accelerated chloride environments (3 % and 5 % NaCl). These curves provide insights into the electrochemical behavior of the steel reinforcements over time. The corrosion current density (I_{corr}) and corrosion potential (E_{corr}) values were derived

Table 2
Mix proportions of concrete and compressive strengths.

Concrete Mix Number	De-ionised water (kg/m^3)	PPC (kg/m^3)	OPC (kg/m^3)	Sand (kg/m^3)	4.75 mm Gravel (kg/m^3)	2.36 mm Chippings (kg/m^3)	Average Weight (kg)	Compressive Strength after curing (MPa)
1	187	–	340	775	605.4	403.6	2.274	21
2	187	53	287	775	605.4	403.6	2.293	20.5

Table 3
Mechanical properties of high tensile steel.

Type	Yield Load (N)	Tensile Load (N)	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young Modulus (GPa)
TMT	31,133	41,043	416.81	549.48	200

Table 4
Chemical composition of high tensile steel (Wt.%).

Elements	C	Si	Mn	P	S	Sn	Cr	Cu	Fe
Wt.%	0.693	0.321	0.885	0.028	0.03	0.024	0.541	0.246	97.232

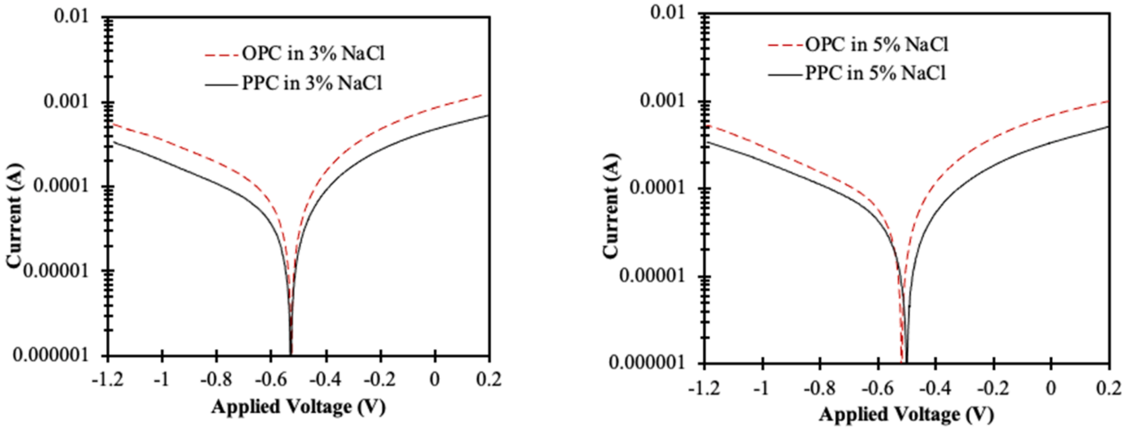

Fig. 1. Polarization curves of reinforcing steel rods concrete mix 1 (OPC) and mix 2 (PPC) the two NaCl accelerated media for 3 days.

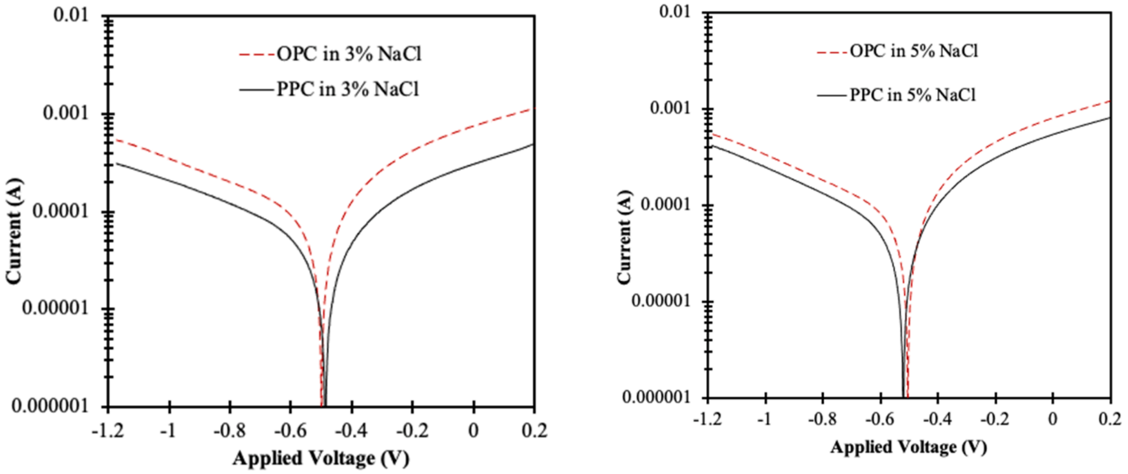

Fig. 2. Polarization curves of reinforcing steel rods concrete mix 1 (OPC) and mix 2 (PPC) the two NaCl accelerated media for 10 days.

using MATLAB scripts, ensuring precision and minimizing the risk of human error. These parameters, listed in Tables 5 and 6, highlight the impact of chloride ion concentration and concrete composition on corrosion performance.

The corrosion rates, calculated from I_{corr} values using Eq. (2), are summarized in Fig. 5. These rates consistently increased with exposure time, indicating the progressive degradation of the steel surface. However, the rates were significantly lower for Mix 2 (PPC), which incorporated 30 % calcined clay pozzolan as a partial replacement for OPC. The reduced corrosion rates in Mix 2 demonstrate the material's superior resistance to chloride-induced corrosion.

The enhanced performance of PPC concrete can be attributed to several key mechanisms. The incorporation of calcined clay pozzolan increases the density of the concrete matrix, as shown in Fig. 6. This densification reduces the permeability of the matrix,

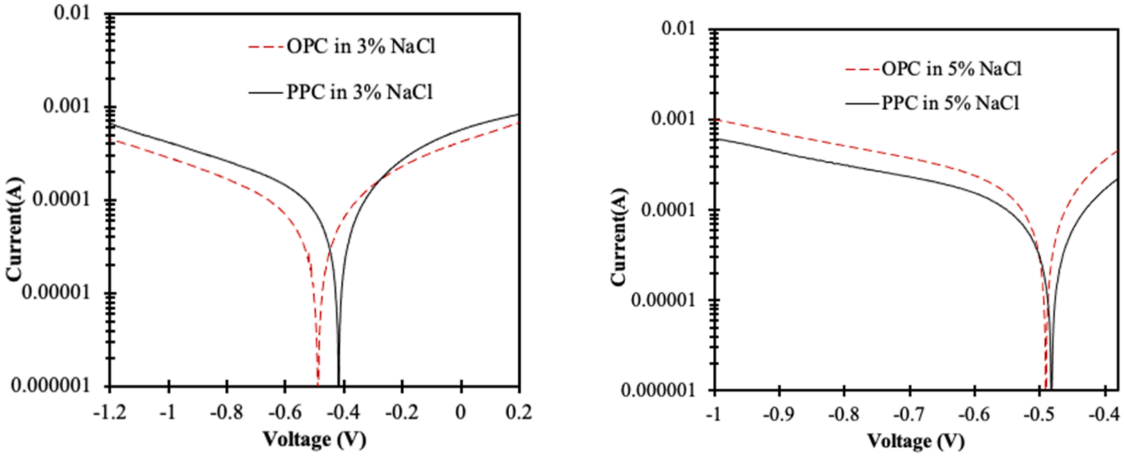

Fig. 3. Polarization curves of reinforcing steel rods concrete mix 1 (OPC) and mix 2 (PPC) the two NaCl accelerated media for 15 days.

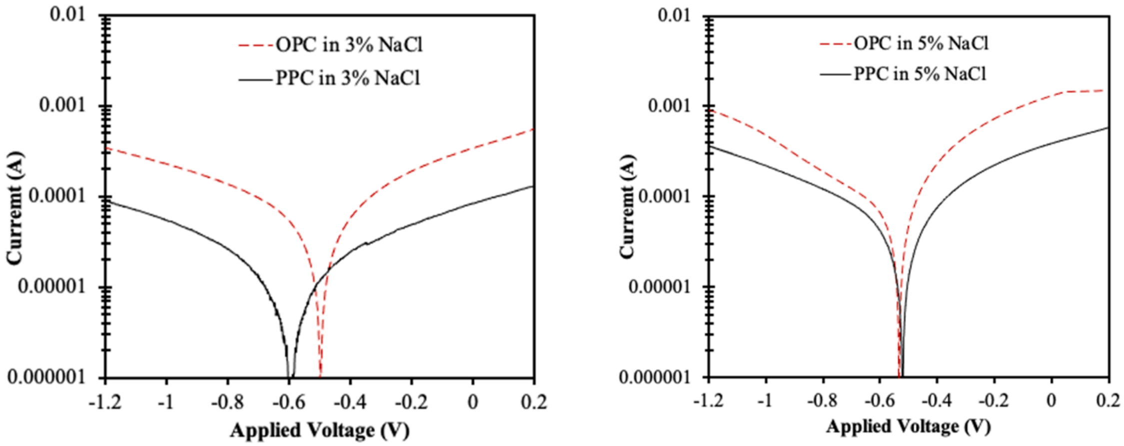

Fig. 4. Polarization curves of reinforcing steel rods concrete mix 1 (OPC) and mix 2 (PPC) the two NaCl accelerated media for 23 days.

Table 5
Corrosion rates of reinforcing steel rods embedded in concrete mix 1 (OPC) and mix 2 (PPC) and in 3 % NaCl aqueous environment over a period of 23 days.

Time (days)	OPC			PPC		
	E_{corr} (mV)	I_{corr} (μA/cm^2)	Corrosion Rate (mpy)	E_{corr} (mV)	I_{corr} (μA/cm^2)	Corrosion Rate (mpy)
3	−600	4.53	4.17	−487	1.24	1.14
10	−530	7.43	6.84	−640	1.06	0.98
15	−522	23.05	21.21	−431	3.47	3.19
23	−520	32.54	29.94	−582	3.36	3.09

Table 6
Corrosion rates of reinforcing steel rods embedded in concrete mix 1 (OPC) and mix 2 (PPC) and in 5 % NaCl aqueous environment over a period of 23 days.

Time (days)	OPC			PPC		
	E_{corr} (mV)	I_{corr} (μA/cm^2)	Corrosion Rate (mpy)	E_{corr} (mV)	I_{corr} (μA/cm^2)	Corrosion Rate (mpy)
3	−580	8.24	7.58	−540	3.33	3.06
10	−550	13.82	12.72	−556	4.42	4.07
15	−506	45.02	41.43	−521	12.39	11.40
23	−640	61.82	56.89	−578	15.75	14.50

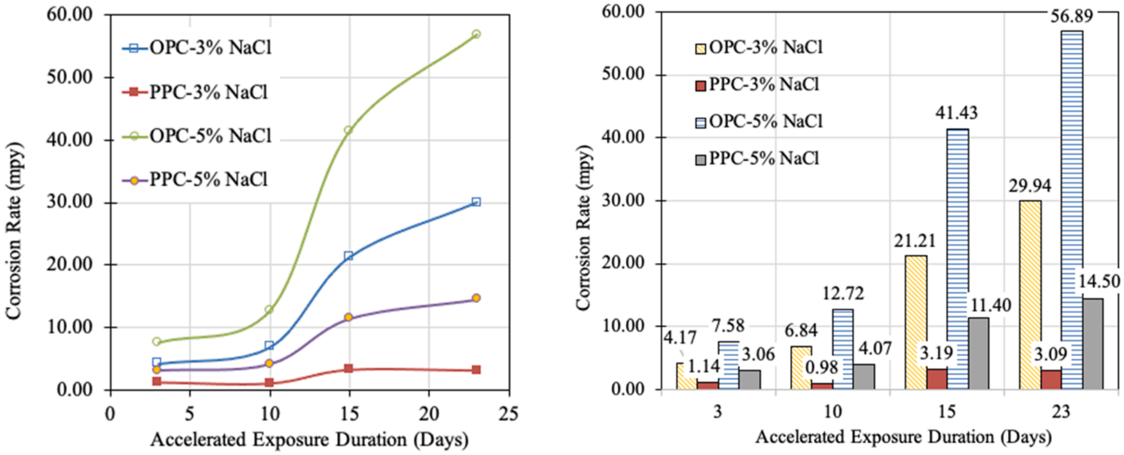

Fig. 5. Changes in corrosion rate of reinforcing steel rods in concrete mix 1 (OPC) and mix 2 (PPC) with time within various chloride environments.

hindering chloride ingress. The finer particle size of calcined clay facilitates better packing, resulting in fewer voids and channels for chloride migration. Additionally, calcined clay reacts with calcium hydroxide to produce secondary calcium silicate hydrate (CSH) and alumina hydrate phases, which act as chloride-binding compounds. These phases chemically immobilize chloride ions, reducing their availability to induce corrosion. Previous studies have established the effectiveness of pozzolanic materials in mitigating chloride ion transport through concrete [19,20].

To validate the observed trends, a one-way ANOVA test was performed to statistically analyze the corrosion rate data for Mix 1 (OPC) and Mix 2 across the exposure durations and chloride concentrations. This is shown in Table 7. The analysis revealed an F-statistic of 4.83 and a p-value of 0.0703. While the p-value is slightly above the traditional significance threshold of 0.05, the results indicate a strong trend towards significance. This suggests that the differences in corrosion rates between the two mixes are meaningful and align with the hypothesis that calcined clay pozzolan enhances the durability and corrosion resistance of concrete in chloride-rich environments. Increasing the sample size or including additional exposure durations may further substantiate these findings.

The data also demonstrate that higher chloride concentrations accelerate corrosion. Steel rebars in 5 % NaCl solutions exhibited higher I_{corr} values and faster corrosion rates compared to those in 3 % NaCl. This can be attributed to the greater availability of free chloride ions in higher concentrations, which increase ion diffusion rates and lower the pH of the concrete environment [21]. The reduction in pH destabilizes the passive oxide layer on the steel surface, further accelerating corrosion. Although this trend was observed in both mixes, the chloride-binding ability of Mix 2 mitigated these effects more effectively than Mix 1, highlighting the material’s superior performance.

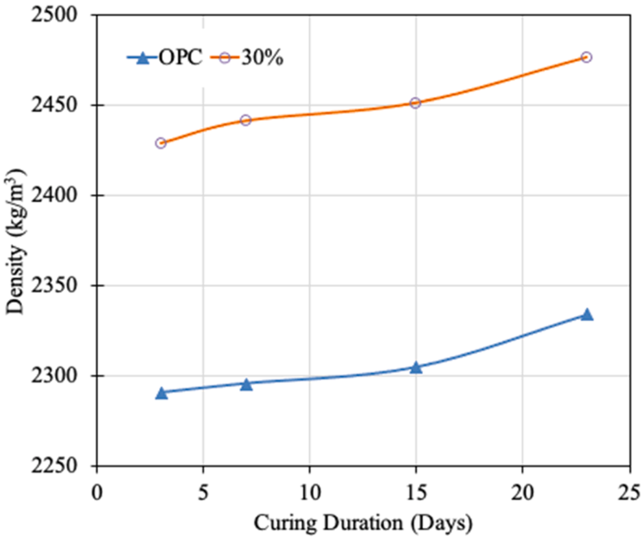

Fig. 6. A comparison of the densities of concrete mix 1 (OPC) and mix 2 (PPC) with curing time.

Table 7
One-Way ANOVA Results.

	Metric	Value
	F-statistic	4.83
	p-value	0.0703
Time (days)	Mix 1 (OPC)	Mix 2 (PPC)
3	4.17	1.14
10	6.84	0.98
15	21.21	3.19
23	29.94	3.09

Morphology and composition of steel rebars

Fig. 7 presents surface images and SEM micrographs of steel rebars embedded in both concrete mixes and exposed to 5 % NaCl solutions for varying durations. These images provide direct visual evidence of corrosion activity on the steel surfaces.

The SEM images reveal distinct differences between the two mixes. For Mix 1, corrosion activity is evident as numerous dark spots and pits, indicating severe degradation. The density and size of these pits increased significantly with exposure time, reflecting the progressive nature of chloride-induced corrosion. Conversely, mix 2 exhibited significantly fewer and smaller pits, even after 23 days of exposure. This reduction in corrosion activity aligns with the observed corrosion rate trends and underscores the protective effect of PPC concrete.

To enhance clarity, the SEM images in Fig. 7 have been annotated to highlight key features, such as the distribution and size of corrosion pits. These annotations facilitate a deeper understanding of the visual data and how it supports the study's conclusions. For instance, in Mix 2, the smaller and less dense pits suggest that the refined microstructure and chloride-binding phases effectively reduced chloride ion mobility and delayed active corrosion.

To quantify the differences observed in the SEM images, image analysis was performed to calculate the pit density (number of pits per unit area) and average pit size. The results showed that Mix 2 reduced pit density by approximately 55 % and average pit size by 48 % compared to Mix 1 after 23 days of exposure. These quantitative metrics were statistically analyzed using a *t*-test, and the p-values were below 0.05, confirming that the observed differences are statistically significant.

The improved performance of Mix 2 can be attributed to the combination of physical and chemical mechanisms. The densification of the concrete matrix reduces porosity and permeability, while the chemical binding of chloride ions by alumina and CSH phases further inhibits their transport [21–23]. These interconnected mechanisms form a robust barrier against chloride ingress, protecting the steel reinforcement.

Implications of findings

The findings of this study carry profound implications for the construction industry, particularly for large-scale infrastructure projects in chloride-heavy environments, such as coastal regions, industrial zones, and areas subjected to de-icing salts. These environments present significant challenges due to the aggressive nature of chloride ions, which accelerate the corrosion of steel reinforcements in conventional concrete structures. The incorporation of calcined clay pozzolan (PPC) into concrete offers a sustainable and effective solution to these challenges, with both short-term and long-term benefits for construction and maintenance practices.

In coastal regions, the presence of high concentrations of chlorides from seawater and salty air poses a continuous threat to the longevity of reinforced concrete structures such as bridges, ports, marine structures, and highways. The results of this study indicate that PPC concrete significantly reduces the rate of chloride ingress and mitigates corrosion, making it an ideal material for such applications. The ability of PPC concrete to densify the matrix and bind chloride ions chemically ensures that critical structures maintain their integrity over extended service lives, reducing the frequency and cost of maintenance interventions.

For large-scale infrastructure projects, where material costs and maintenance budgets represent significant proportions of the overall investment, PPC offers considerable cost savings. The reduced corrosion rates observed in PPC concrete directly translate into longer service lives for reinforced structures, minimizing the need for frequent repairs or replacement of corroded elements. This is particularly beneficial for bridges, tunnels, and seawalls, where downtime and maintenance costs can have substantial economic implications. The initial costs of adopting PPC concrete may be slightly higher due to material adjustments and quality control, but these are offset by the significant reduction in lifecycle costs.

The use of PPC concrete aligns with global efforts to reduce the carbon footprint of the construction industry. The partial replacement of OPC with calcined clay pozzolan reduces the demand for OPC, a material whose production is a major contributor to CO_2 emissions. For large-scale projects, where concrete is required in vast quantities, even a partial reduction in OPC use can lead to substantial environmental benefits. Furthermore, the utilization of calcined clay, which is often locally sourced, supports the use of sustainable and regionally available materials, reducing the energy and emissions associated with transportation.

Beyond coastal areas, the benefits of PPC concrete extend to industrial zones, where reinforced structures are exposed to harsh chemical environments. Chlorides and other aggressive agents in industrial wastewater, chemical spills, or exhaust fumes often compromise the integrity of conventional concrete. The findings of this study indicate that PPC's enhanced resistance to chloride penetration and its refined pore structure can mitigate such effects, making it suitable for use in wastewater treatment plants, chemical storage facilities, and factory foundations.

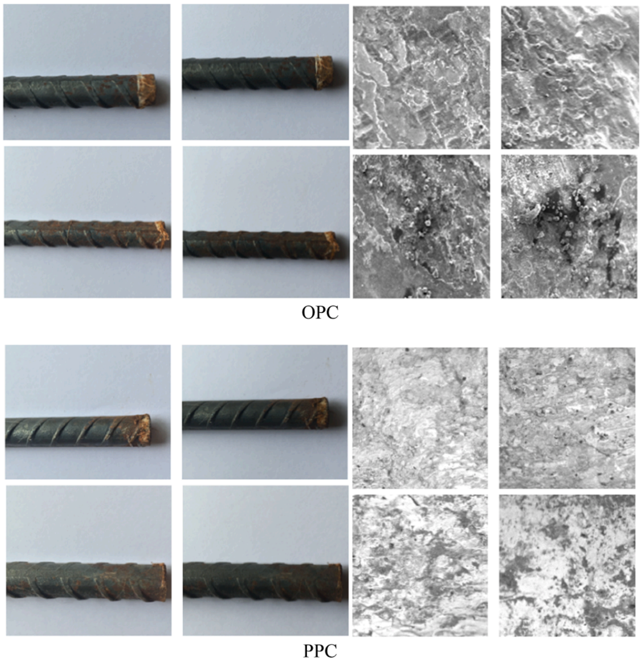

Fig. 7. Surface view and corresponding SEM (500 µm) images of steel embedded in concrete mix 1 (OPC) (Top row) and mix 2 (PPC) (Bottom row) immersed in 5 % NaCl. Top left: three-day exposure. Dark areas show areas of corrosion activity or corrosion pits. Top right: 10 days exposure. Bottom left: 15 days exposure. Bottom right: 23 days exposure.

As climate change increases the frequency and intensity of extreme weather events, including hurricanes and rising sea levels, the demand for resilient infrastructure has grown. PPC concrete offers a robust solution for climate-adaptive construction by providing enhanced durability in environments subject to heavy rainfall, flooding, and high salinity. Its ability to maintain performance in aggressive conditions ensures that critical infrastructure can withstand the impacts of climate change, contributing to the development of sustainable, long-lasting, and resilient communities.

The practicality of implementing PPC concrete in large-scale infrastructure projects is also noteworthy. Calcined clay is widely available in many regions, making it feasible to scale up production and integrate PPC into construction practices without significant logistical challenges. With proper standardization and quality control measures, PPC concrete can be incorporated into existing construction workflows, ensuring that its benefits are realized across a broad range of applications.

The adoption of PPC concrete has strategic implications for the construction industry, particularly in developing economies. In regions where resources are constrained, and durability is critical to the viability of infrastructure investments, PPC offers a cost-effective and environmentally friendly alternative to traditional OPC. By improving the durability of concrete structures, PPC reduces the economic burden associated with corrosion-induced failures, enabling governments and organizations to allocate resources more efficiently to other pressing development needs.

Conclusion

The main objective of this study was to measure the effect of calcine clay pozzolan on the corrosion behavior of concrete steel reinforcement in a chloride environment. this was studies by comparing steel reinforced in a concrete mix containing only ordinary Portland cement as the binder, and another embedded in concrete with 30 % partial replacement of Portland cement with calcined clay pozzolan. These steels were exposed to chloride solutions containing 3 % NaCl and another 5 % NaCl for various durations up to 23 days. These environments are designed to induce accelerated corrosion.

The results of the investigation indicated the corrosion inhibition effects of the added calcine clay pozzolan. The reinforcing steel embedded in the concrete containing calcined clay experienced a 90 % and 74 % respective reduction in the corrosion rate in the 3 % NaCl and 5 % NaCl solution environments compared with the steel embedded in the concrete without calcined clay pozzolan. The corrosion rates of the rebars increased with exposure time. The corrosion inhibition characteristics imparted to concrete containing calcine clay pozzolan are attributed to the following:

- Densification of concrete due to calcine clay addition. Densification by calcined clay is achieved by the introduction of fine clay particles and the provision of additional nucleation sites for hydration phases to grow during concrete curing.
- The chloride binding ability of PPC concrete due to the introduction of aluminosilicate phases promotes the formation of alumina and calcium silicate hydrate (CSH) phases in concrete, which are known to possess the capability to bind chloride ions in concrete.

This result has positive economic implications for the building and construction industry, which is reliant on concrete. It also has sustainability implications for the environment, such as partially replacing Portland cement with calcined clay pozzolans, reducing the cost of the binder, and improving the durability of the resulting concrete. It should be noted that the addition of calcined clay to concrete beyond certain amounts may reduce the compressive strength of concrete. Therefore, it is necessary to optimize the amount of calcined clay to be used with the required compressive strength and desired corrosion rates of the reinforcement.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability

The data and materials supporting the results and analyses presented in this article are available upon reasonable request. Requests for data access should be directed to the corresponding author.

Author contributions

Lucas Nana Wiredu Damoah: Conceptualization, Supervision, Formal Analysis, Writing Original Draft, Writing Review & Editing. **Richard Nii Ayitey Akoto**: Methodology, Formal Analysis, Writing Original Draft, Writing Review & Editing. **Bernard Kwame Mussey**: Investigation, Data Curation, Validation, Writing Review & Editing. **Yaw Delali Bensah**: Investigation, Data Curation, Validation, Writing Review & Editing. All authors contributed to manuscript revision, addressed reviewer comments collectively, and approved the final version, ensuring the integrity and accuracy of the work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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