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The Potential of Fly Ash Based Geopolymer Coatings for Steel Corrosion Protection

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Abstract. Nowadays, researchers are trying to understand whether geopolymers have the potential to be used as a coating material, particularly for protecting metal from corrosion attack. This study aimed to evaluate the effectiveness of fly ash-based geopolymer coatings in protecting steel by immersing the coated samples in a 3.5 wt% NaCl solution for immersion periods of 1, 7, 14, and 28 days. The uncoated steel showed the NaCl color changed to yellowish and became darker with increasing immersion time, indicating severe corrosion on the uncoated steel after 28 days. Surprisingly, with 3mm geopolymer thickness coated on the steel, NaCl solution remain unchanged until 28 days immersion period. The corrosion rate exhibits a very gradual increase, with only 0.112 mm/year recorded after 28 days of immersion. No defects such as blistering, peeling, or cracking were observed on the coated steel. These results indicate that geopolymer holds considerable promise as a coating material, warranting further investigation for its potential applications in this area.

1. Introduction

In civil engineering, protection of the structure becomes primary concern. The application of protective coatings is beneficial due to their resistance to acids, alkalis, and salts. It also can protect the structure from the severe civils environments such as humidity and moisture, high and low temperature and freeze-thaw cycles. Most frequently coating which has been used to protect the structure is an organic coating such as acrylic, polyurethane, epoxy, alkyd coatings [1]. While organic coatings offer significant advantages in protecting civil engineering structures, they also come with certain disadvantages such as become rigid and crack under thermal or mechanical stress if not formulated for flexibility [2], toxicity concerns due to release of volatile organic compound [3] and shorter lifespan [4]. Cement based coating materials are the most common inorganic coating materials used in structure protection. Although these coatings can give high durability, yet, less focus have been paid on their protection mechanism and performance. The focus has been given in understanding the function of cement-based coatings as a surface treatment which discussing on the overlay, pore blocking and hydrophobic impregnation. Overlay coatings will serves as a barrier to inhibit substance exchange between steel surface with environment [5]. Hydrophobic impregnation coatings functioning by adjusting surface state so that it will becomes hydrophobic [6]. Pore blocking machine was applied normally to the highway bridges to barricade capillary pore in the substrate, thereby enhancing its permeability [7].

Recently, a new category of inorganic coatings, primarily composed of geopolymers, has been explored and utilized for protecting concrete and steel surfaces [8]. Geopolymers are a kind of inorganic polymers typically synthesized via alkaline activation of aluminosilicate precursor. Geopolymers are inorganic polymers formed through the alkaline activation of aluminosilicate precursors. Their unique spatial network structures, resulting from the geopolymerization process, make them well-suited for coating and surface protection applications. These materials are often characterized by their exceptional mechanical strength, chemical stability, water resistance, and thermal durability [9]. Study by Zhang et al. [10] on the sodium aluminosilicate hydrate (NASH) gel in marine environment found the chemically binding water to the Si-Al skeleton weaking tensile strength of the coating. Meanwhile, the feasibility of geopolymer as a fire-retardant coating material was studied by Temuujin et al. [11], who found that geopolymer successfully protected the panel and able to withstood fire heat up to a 1300°C. observing the vast potential of geopolymer for application as a coating material, had conceived the idea for the present work to be carried out. This research aims to evaluate the performance of fly ash-based geopolymer in protecting steel from corrosion and to determine the minimum corrosion rate achievable with geopolymer coating.

2. Material and Methods

Coal fly ash was sourced from a local power plant in Malaysia. To ensure consistency in particle size distribution and eliminate larger particles, the fly ash was sieved through a 45 µm mesh using a vibratory sieve shaker (AS200 Basic, RETSCH, Germany). The geopolymer was synthesized using a sodium hydroxide (NaCl, ≥99.5%, Merck, Darmstadt, Germany) alkaline solution, with sodium-to-alumina and water-to-solid ratios set at 1.0 and 0.33, respectively. For the corrosion test, a carbon steel plate with dimensions of 3 × 50 × 127 mm was prepared. Before the coating process, the plate underwent surface finishing using abrasive paper of a specific grade. Grinding was done using waterproof silicon carbide paper (CarbiMet, Buehler, USA) of various grit sizes (P240 to P1200).

To remove impurities, the plate was degreased with distilled water and acetone (analytical grade, Merck, Darmstadt, Germany). The pretreated steel plate was coated with geopolymer paste using dip coating method, whereby the plate was dipped in the paste for 10 seconds. It was then taken out and suspended for 30 seconds to remove excess geopolymer. The coating process is illustrated in the schematic image Figure 1. A digital Vernier caliper (model 530-122, Mitutoyo Corp., Kanagawa, Japan) was used for cured sample's thickness measurement. Only samples with a thickness of 3mm ± 0.3mm were accepted for further corrosion testing.

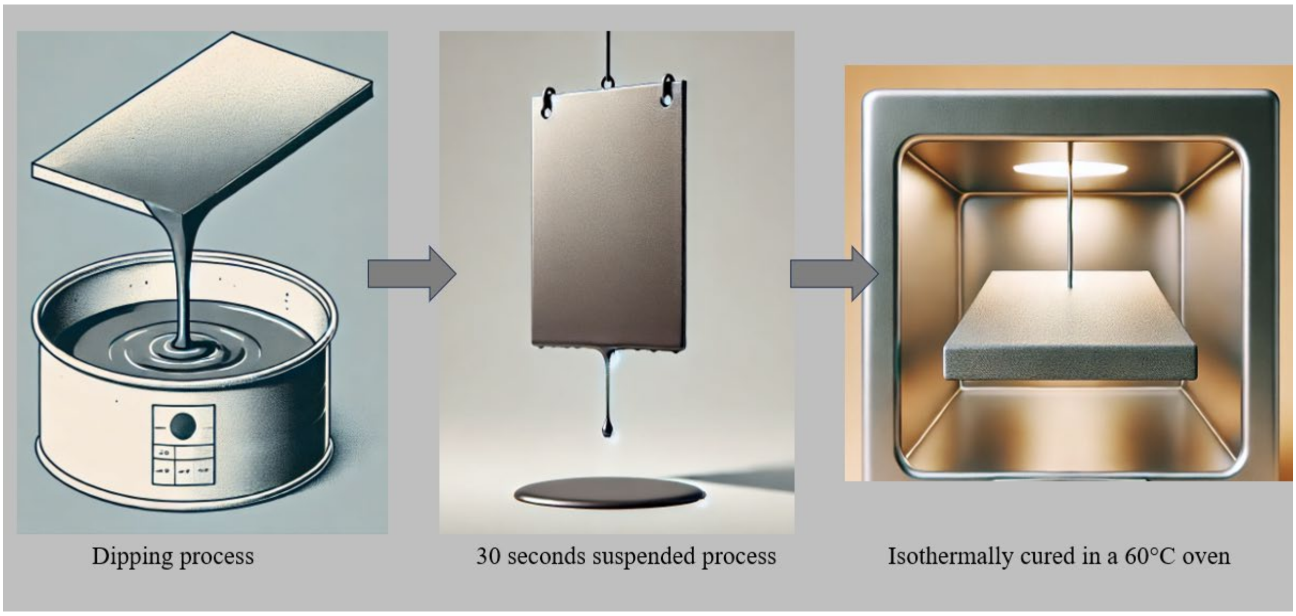

Fig.1. Dip method to coat the steel plate with geopolymer coating

The pretreated steel substrate was then coated with 3mm thickness geopolymer paste using a dip-coating method for 10 seconds. Subsequently, it was isothermally cured in an oven at 60°C for three days. The coated steel was immersed in 3.5wt% NaCl solution for 1, 7, 14 and 28 days. The solution's color change was monitored, and the corrosion rate was measured using the weight loss method. Equation 1 shows the formula used to calculate the corrosion rate using weight loss method [12].

$$Corrosion\ Rate\ (CR) = \frac{K.\Delta W}{A.T.D} \qquad (Equation\ 1)$$

where, ΔW is weight loss of the material (g), A is surface area of the material exposed to the corrosive environment (cm^2), T is time of exposure (hours), D is density of the material (g/cm^3) and K is conversion factor (typically 8.76×10^4 for corrosion rate in mm/year when using g, cm^2, hours, and g/cm^3)

3. Results and Discussion

Table 1 presents the corrosion rates recorded after immersion periods of 1, 7, 14, and 28 days. The bare sample, serving as the benchmark, was used as a reference to assess the performance of the coated sample. As shown in the table, the bare sample experienced severe corrosion over time, with the corrosion rate increasing from 0.23 mm/year after 1 day to 0.28 mm/year after 28 days. Notably, coating the steel surface with geopolymer significantly reduced the corrosion rate, achieving a minimum of 0.112 mm/year after 28 days of immersion. Geopolymer coating can protect steel from environmental degradation primarily through its dense, chemically stable, and impermeable structure. The coating acts as a physical barrier, preventing the penetration of corrosive agents such as chloride ions, oxygen, and moisture, which are key contributors to steel corrosion [13]. Additionally, geopolymers exhibit excellent chemical resistance and possess a high pH environment that can help maintain the passivation layer on the steel surface, further reducing the risk of corrosion [14]. These properties make geopolymer coatings a promising alternative for enhancing the durability of steel structures, especially in harsh environments.

According to the current literature, there are no available studies on unfilled geopolymer coatings for corrosion rate inhibition that can be used for direct comparison with the present study. Most existing research focuses on the performance of geopolymer coatings incorporating fillers and additives. Some findings on filler/additive-based coatings were referenced to observe differences in corrosion rates. It is undeniable that the addition of fillers and additives significantly enhances the performance of geopolymer coatings. Yang et al. [15] incorporated graphene oxide as a filler in geopolymer coatings, and the E_{corr} results demonstrated that the modified graphene oxide coating provided the highest level of corrosion inhibition. Similarly, Tomar et al. [16] utilized gamma alumina/zinc phosphate as an additive in a fly ash-red mud geopolymer coating to enhance its protective capabilities. Their study achieved a minimum corrosion rate of 0.01 mm/year with an inhibition efficiency of 96.69%.

Table 1. Corrosion rate of uncoated and coated steel for 1, 7, 14, and 28 days of immersion time

	Bare (uncoated) steel		Coated steel		
Immersion time	Weight loss(mg)	Corrosion rate(mm/yr)	Immersion day	Weight loss	Corrosion rate(mm/yr)
1	33.21	0.23	1	12.79	0.089
7	251.62	0.25	7	97.63	0.097
14	543.49	0.27	14	207.33	0.103
28	1127.26	0.28	28	450.90	0.112

Figure 2 shows the solution becomes increasingly darker and yellowish over the immersion period, indicating the accumulation of rust precipitates on the steel surface due to corrosion. The darkest coloration is observed after 28 days of immersion. Without a protective coating, the steel surface is exposed to aggressive chloride ions, which readily attack the surface. Through the redox process, rust formation becomes evident on the steel [17]. As the redox reaction progresses over time, prolonged immersion allows more corrosive species to penetrate the underlying steel surface, exacerbating the severity of corrosion [18].

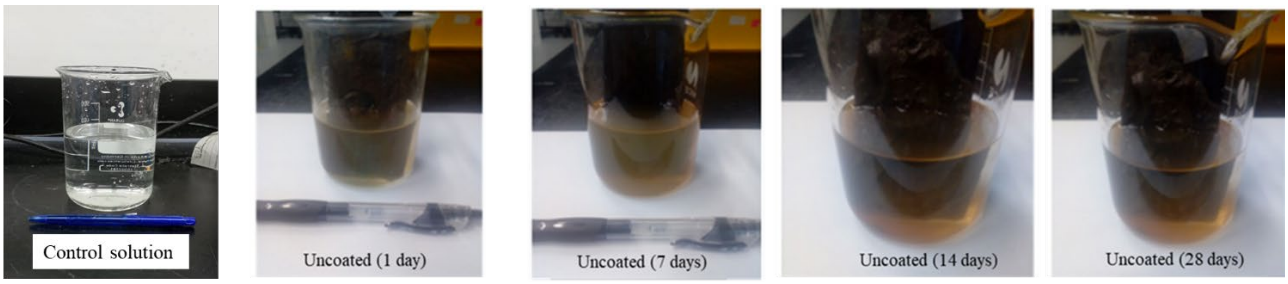

Fig. 2. Uncoated steel in 3.5wt% NaCl solution for 1, 7, 14, and 28 days of immersion time with control solution

The effectiveness of the geopolymer in protecting the steel surface from corrosion is evident in Figure 3. From day 1 to 28 days of immersion, the solution remains clear without any yellowish tint, indicating minimal and controllable rust formation on the steel surface. This is attributed to the geopolymer coating forming a dense and impermeable layer over the steel, preventing the penetration of corrosive agents such as oxygen, water, and chloride ions, which drive the corrosion process. Additionally, geopolymers are inherently chemically stable and resistant to harsh environments, maintaining their integrity as a protective barrier [1]. As shown in Table 1, the lowest corrosion rate at 28 days for the coated steel demonstrates that the geopolymer coating adheres strongly to the steel surface, providing a consistent and long-lasting protective layer. However, further investigation is needed to improve geopolymer fabrication, as the microstructure of the coatings is expected to have very low porosity. Despite this, corrosion still occurs over time, albeit at a significantly reduced rate.

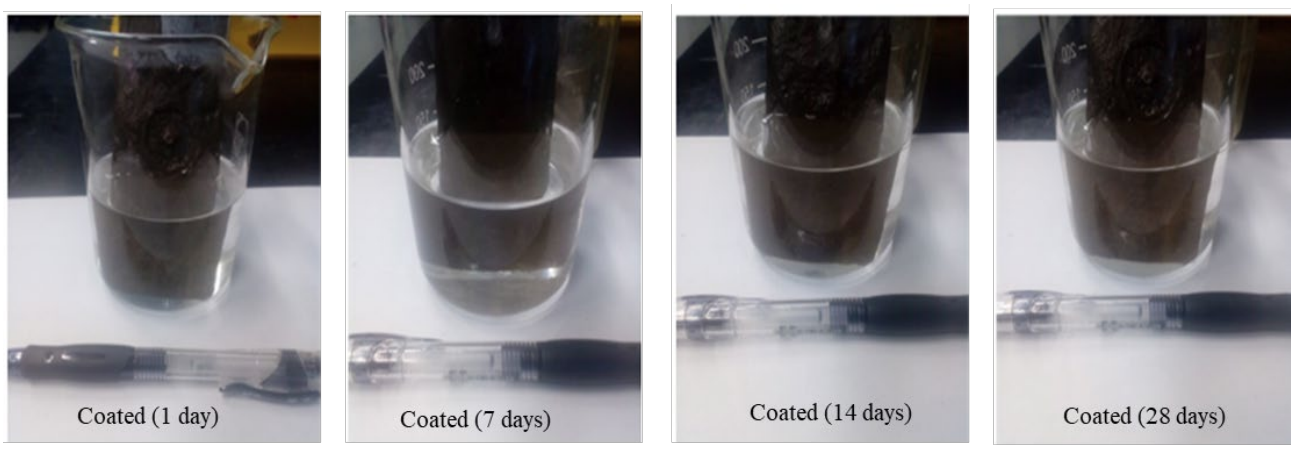

Fig. 3. Fly ash based geopolymer coated steel in 3.5wt% NaCl solution for 1, 7, 14, and 28 days of immersion time

After 28 days of immersion, the geopolymer coatings were evaluated for potential defects on the coated steel. As shown in Table 2, no defects such as bubbles, blisters or cracks were observed on the coated sample.

Table 2. Potential defects on coated steel

Steel	Bubbling	Blistering	Cracking
coated (1 day)	No	No	No
coated (7 days)	No	No	No
coated (14 days)	No	No	No
coated (28 days)	No	No	No

Further evaluation using SEM (as shown in Figure 4) was performed on the coated sample to assess the presence of cracks within the coating. The results indicated that no cracks were observed from the first day until 28 days of immersion time. This can be attributed to the tightly packed geopolymer structure, which effectively minimized void formation that could potentially act as crack initiators. Additionally, the image confirms that a 3mm coating thickness is sufficient to provide effective protection for the steel, preventing corrosion by eliminating liquid entrapment beneath the layer during and after application.

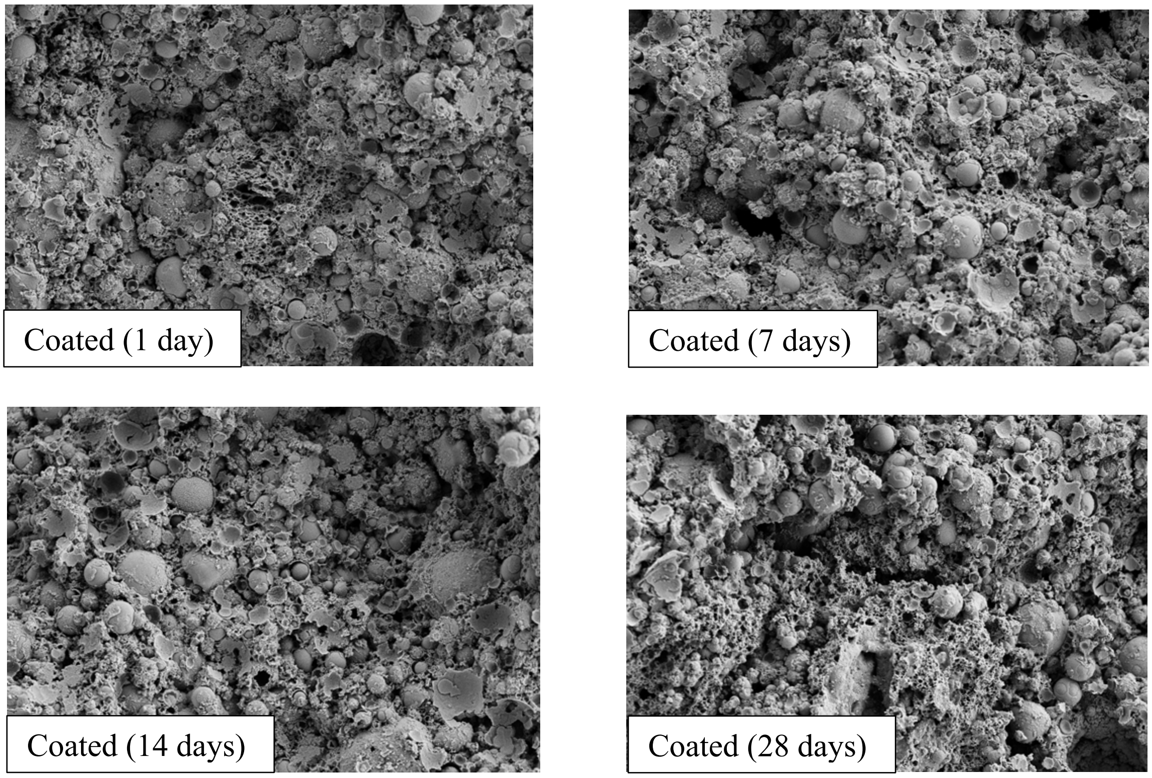

Fig.4. Morphology image of steel coated for 1, 7, 14 and 28 days

Overall, the results demonstrate the potential of fly ash based geopolymer coating for steel corrosion protection. The SEM analysis further confirmed the formation of a dense and homogeneous geopolymer matrix, supporting the corrosion test results. These findings provide a strong basis for the conclusions drawn in the following section.

4. Conclusions

Geopolymer coatings are gaining increasing attention in both academic research and industrial applications due to their unique properties and sustainability advantages. Several factors contribute to their growing interest such as environmental and sustainability benefits, superior corrosion and fire resistance. They have low carbon emissions compared to traditional organic coatings or cement-based coatings. Unlike organic coatings, geopolymer coatings are highly resistant to heat, acids, and harsh environments, making them suitable for extreme conditions such as marine structures, industrial plants, and fireproofing applications.

In this study, a fly ash-based geopolymer was successfully developed and applied as a coating on a steel surface to assess its effectiveness in corrosion inhibition. The results indicate that the geopolymer coating effectively controls corrosion, as shown by the minimal increase in corrosion rate observed from day 1 to day 28. The absence of yellowish discoloration in the test solution confirms the coating's effectiveness in preventing rust formation. Based on the findings of this research, one potential application of the geopolymer coating is its use as an internal protective layer within reinforced concrete structures. Instead of embedding bare steel reinforcement directly into concrete, the application of a geopolymer coating on the steel surface before placement can serve as an additional barrier against corrosion. This approach addresses a critical issue in structural durability, as corrosion of embedded steel can lead to significant deterioration, reducing the lifespan and integrity of concrete structures. By preventing or slowing down the initiation of corrosion, the geopolymer coating can enhance the long-term performance of reinforced concrete, particularly in aggressive environments such as coastal or marine structures.

Declaration of competing interest

The authors do not have any conflict with other entities or researchers.

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Author contributions

All authors contributed equally to this work

Data availability

Data will be made available on request

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