

Photocatalytic and mechanical performance of Ag/ZnO geopolymer composite coatings

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ABSTRACT

Coatings support sustainability by prolonging the service life of civil infrastructure. Fly ash geopolymer coatings are recognized for their low carbon footprint and industrial by-product utilization, serving as sustainable alternatives to conventional coatings. In this study, fly ash geopolymer coatings incorporating different Ag/ZnO loadings (0, 5, and 10 wt.%) were prepared and spray-applied onto mortar substrates. The geopolymer coatings with different additions of Ag/ZnO were investigated for their adhesion strength, microstructure, and photocatalytic activity. The apparent degradation of methylene blue (MB) was evaluated by immersing the coated specimens in MB solution under direct natural sunlight. The addition of Ag/ZnO enhanced both mechanical and photocatalytic performance. Notably, the 5 wt.% Ag/ZnO coating achieved the highest adhesion strength (0.95 MPa after 28 days of curing) and the greatest apparent MB removal efficiency (75%), whereas overloading at 10 wt.% caused particle agglomeration and performance deterioration. Consequently, 5 wt.% Ag/ZnO is identified as the optimal formulation, offering an ideal balance between mechanical stability and photocatalytic activity for protective and sustainable self-cleaning infrastructure coatings.

Keywords: Geopolymer coatings, Self-cleaning surfaces, Photocatalysis, Sustainable

1. INTRODUCTION

The urgent challenge of developing new materials to mitigate the impacts of global warming and environmental pollution has become increasingly critical. Among the most pressing concerns are the rise in greenhouse gas emissions and the growing burden of water pollution [1, 2]. The construction industry, which heavily relies on ordinary Portland cement (OPC), is a significant contributor to global greenhouse gas emissions due to the large amount of CO₂ released during cement production [3].

At the same time, industrial wastewater has become a major source of aquatic contamination [4]. More than 50,000 tons of dyes are discharged annually into effluents, often accompanied by heavy metals such as copper, chromium, and iron [5]. These pollutants pose serious risks to human health and the environment; for example, chromium from textile wastewater has been linked to skin rashes, respiratory problems, genetic alterations, and lung cancer. Various treatment methods have been developed, including adsorption, ion exchange, oxidation, and electrocoagulation [5]. However, photocatalytic degradation has emerged as a particularly attractive approach, offering efficient breakdown of organic

pollutants under light irradiation without generating harmful secondary products [6].

Geopolymer, a generic term coined by Joseph Davidovits in the 1970s, is an inorganic polymeric material or ceramic-like binder consisting of aluminosilicate chains and networks [7]. These materials are formed through the alkaline activation of precursors such as fly ash, slag, or metakaolin, following a three-step process of dissolution, reorganization, and polycondensation that produces a cross-linked Si–O–Al framework [8]. This unique chemistry imparts high mechanical strength, thermal stability, and resistance to chemical attack, making geopolymers suitable for demanding construction environments. Unlike OPC, which relies on calcium silicate hydration and releases large amounts of CO₂ during clinker production, geopolymers valorize industrial by-products and require lower processing temperatures, thereby offering a significantly reduced carbon footprint [9]. Geopolymers act as a promising class of sustainable binders for infrastructure applications due to their flexibility in raw material selection and mix design, which allows tailoring of properties such as porosity, adhesion, and durability.

Geopolymers have emerged as promising alternatives to ordinary Portland cement (OPC) due to growing environmental concerns, effectively reducing carbon emissions and valorizing industrial by-products such as fly ash. They also can be modified to include photocatalytic particles which allow for pollution degradation and self-cleaning qualities. Previous studies proved that the addition of TiO_2 , ZnO , and WO_3 can enhance geopolymer matrices, resulting in better photocatalytic activity [10, 11]. The potential of these multipurpose materials in sustainable infrastructure and environmental protection has been highlighted by their exploration of applications ranging from self-cleaning building surfaces to wastewater treatment and air purification.

The combined effect of Ag/ZnO loading on both mechanical stability and photocatalytic efficiency has not been fully clarified as compared to other photocatalytic materials. It is noted that agglomeration and microcracking may happen due to excessive particle incorporation, while uniform dispersion and interfacial bonding may be obtained with moderate particle addition. Therefore, it is necessary to determine the most effective composition by carrying out a systematic study of the effect of Ag/ZnO addition on adhesion strength, photocatalytic degradation, chemical bonding (FTIR), and microstructure (SEM).

The Ag/ZnO-modified geopolymer coatings at three loadings (0 wt.%, 5 wt.%, and 10 wt.%) were analyzed to fill the gap. Adhesion strength, photocatalytic degradation of methylene blue under sunlight, microstructural integrity and functional group interactions were tested on the coating samples. The multifunctional geopolymer coatings support global efforts which lower carbon emissions and enhance water quality, in addition to addressing environmental issues. This study provides a dual perspective on how Ag/ZnO-modified geopolymers can simultaneously deliver environmental protection and structural stability, expanding their utility in sustainable construction compared to prior studies that focused on either mechanical reinforcement or photocatalytic activity alone.

2. METHODOLOGY

2.1. Raw Materials

Class F fly ash (FA) was used as the aluminosilicate precursor to synthesize the geopolymer coating. It was sourced from Macro Dimension Concrete Sdn. Bhd. The chemical composition of FA was determined using X-ray Fluorescence (XRF) as shown in Table 1, where SiO_2 , Al_2O_3 , Fe_2O_3 , and CaO are the major components of FA. Figure 1(a) shows fly ash particles with predominantly spherical morphology and relatively smooth surfaces. Ag/ZnO particles exhibiting quasi-spherical to irregular morphology, as shown in Figure 1(b), were used as photocatalyst. Figure 2 shows the particle size distribution of FA where $D_{10}=2.24 \mu\text{m}$, $D_{50}=15.50 \mu\text{m}$ and $D_{90}= 55.20 \mu\text{m}$.

Sodium hydroxide (NaOH) and liquid sodium silicate (Na_2SiO_3) were used as alkaline activators in this study.

The NaOH was 97% pure caustic soda pellets produced by HmbG® Chemicals, while the liquid Na_2SiO_3 was supplied by South Pacific Chemicals Industries Sdn. Bhd., Malaysia, which exhibited a specific gravity of 1.4 g/cm^3 and a viscosity of $0.4 \text{ Pa}\cdot\text{s}$ at 20°C , with a composition of 60.5 wt% H_2O , 30.1 wt% SiO_2 , and 9.4 wt% Na_2O , corresponding to a $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio of 3.2.

Table 1. Chemical composition of FA.

Compound	Weight Percentage (%)
SiO_2	61.61
Al_2O_3	13.91
Fe_2O_3	9.68
CaO	4.42
K_2O	1.79
TiO_2	1.11
Others	7.48

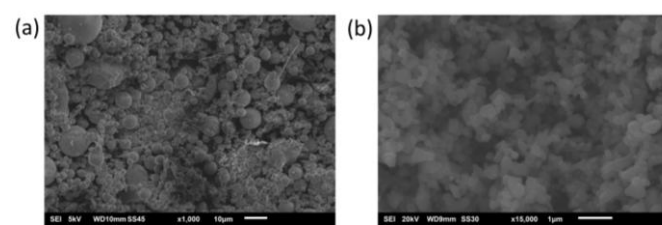


Figure 1. SEM micrographs of (a) FA and (b) Ag/ZnO particles.

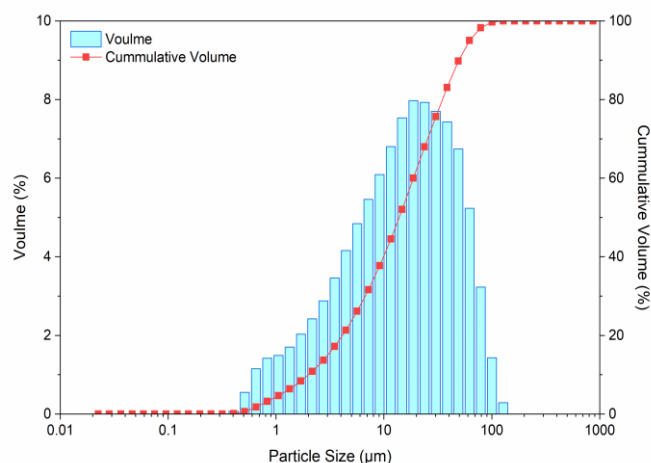


Figure 2. Particle size distribution of FA.

2.2. Fabrication of Geopolymer Coatings

A 12 M NaOH solution was prepared by dissolving NaOH pellets in distilled water and allowing the solution to cool and equilibrate for 24 h at room temperature prior to use. The NaOH solution was first mixed together with the liquid Na_2SiO_3 at a 2.5 weight ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$. Then sieved FA was mixed homogeneously with a solid-to-liquid ratio of 2.0. Lastly, different Ag/ZnO loadings (0, 5, and 10 wt.%) were incorporated as photocatalytic additives. The mixture was then applied onto the mortar substrate through a spraying method with a spray gun. The coated samples were then subjected to testing and analysis after 7 and 28 days.

2.3. Testing and Analysis

2.3.1. Mechanical Testing

The adhesion strength of the coated samples was determined in accordance with ASTM D4541 using the pull-off method with an Elcometer 106 adhesion tester. The dollies were first glued on the coated samples using Araldite glue and left to cure for 24 h at room temperature. Then the dollies were pulled out using the Elcometer 106 and the results were recorded. For every formulation, three duplicate measurements were made, and the average value was reported in MPa.

2.3.2. Photocatalytic Performance and Apparent MB Removal

The photocatalytic analysis of the coated samples was studied through the degradation efficiency of the methylene blue (MB) dye. The concentration of the MB used in this study is 5 mg/L. The coated samples with an area of 9 cm² were immersed in the MB solution (225 ml) with sample-to-solution ratio of 0.04 cm²/ml. The samples were then placed under the direct outdoor sunlight (average intensity of ~800–1000 W/m²) for one hour without stirring. Because the specimens did not undergo dark adsorption-desorption equilibration prior to photocatalytic testing, the contribution of dye adsorption by the geopolymer matrix cannot be completely ruled out. The samples were collected every 20 minutes and then tested using the Ultraviolet-Visible spectrophotometer to obtain the absorbance value at 664 nm and calculate the degradation efficiency by using the formula:

$$\text{Degradation efficiency (\%)} = \frac{A_0 - A_t}{A_0} \times 100\% \quad (1)$$

where A_0 is the initial absorbance of MB solution, and A_t is the final absorbance of the MB solution at measurement time.

2.3.3. Characterization Analysis

The microstructural analysis of the coated samples was conducted by using Scanning Electron Microscopy (SEM) analysis. The FA, Ag/ZnO and interface of the coated samples were examined. The samples were coated with a thin layer of platinum before testing.

As for chemical characterization, PerkinElmer Spectrum 65 Fourier-transform infrared spectroscopy (FTIR) was used. The FA geopolymer coating was ground into powder form prior to use. The powdered samples' absorbance spectra were acquired in the 4000–400 cm⁻¹ range at a resolution of 4 cm⁻¹.

3. RESULTS AND DISCUSSION

3.1. Adhesion Strength Analysis

Figure 3 demonstrates the adhesion strength of coated samples after 7 and 28 days. The adhesion performance of the FA geopolymer coating varied significantly with Ag/ZnO loading. The FA geopolymer coating incorporating 5 wt.% Ag/ZnO achieved the highest performance (0.91 to 0.95 MPa) among all formulations, particularly after 28 days of curing. Although the maximum adhesion strength (~0.95 MPa) is lower than commercial white cement coatings (>3MPa) [12], similar ranges have been reported for geopolymer coatings. Metakaolin geopolymer coating incorporated with ZnO typically show adhesion values between 0.55–0.90 MPa [13]. The adhesion development was primarily governed by the geopolymerization process of FA in the absence of Ag/ZnO. The pure geopolymer with the absence of Ag/ZnO provided baseline adhesion which limits reinforcement and fewer active sites for bonding, resulting in moderate strength at both 7 and 28 days.

The coating achieved the best overall performance at 5 wt.% loading, particularly after 28 days. This may have contributed to microstructural densification by filling unoccupied sites in the geopolymer matrix resulting in optimal dispersion of Ag/ZnO particles and enhanced interfacial adhesion. A denser and more homogeneous network was obtained by the moderate incorporation of Ag/ZnO without significantly interfering with gel formation. This is consistent with results in [14], where cohesiveness and long-term stability were enhanced by modest oxide inclusion.

At 10 wt.% loading, the coating showed the highest adhesion at 7 days but dropped to the lowest after 28 days. The relatively high early strength may be due to the surface densification and enhanced particle-matrix interactions promoted by the higher Ag/ZnO content. However, over time, excessive Ag/ZnO loading may interfere with the polycondensation process and reduce the continuity of the geopolymer network, as described in prior ZnO studies [3]. The geopolymerization process was affected by excessive Ag/ZnO loading, resulting in a less uniform matrix which increases the formation of voids and microcracks. The adhesion strength decreased due to particle agglomeration, which weakened the structure [15].

In conclusion, strong early adhesion was obtained by the 10 wt.% sample due to rapid reaction kinetics, but its strength decreases over time due to agglomeration and incomplete network formation. By contrast, the 5 wt.% sample develops a more balanced microstructure that

remains stable throughout curing.

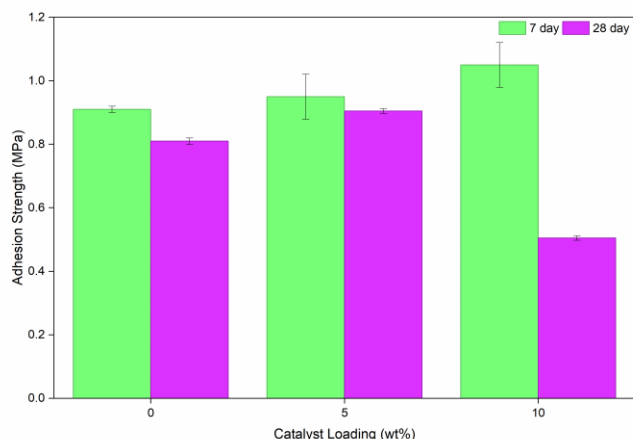


Figure 3. Adhesion strength of FA geopolymer coatings with varying Ag/ZnO loadings

3.2. Photocatalytic Performance and Apparent MB Removal

Figure 4 shows the apparent photocatalytic properties of FA geopolymer coating with various Ag/ZnO loadings evaluated through MB removal under sunlight. The apparent photocatalytic activity was evaluated by monitoring the decrease in MB absorbance at 664 nm under sunlight irradiation, where the best performance of removal of MB (5wt% loading) was shown in Figure 5. As the irradiation time increased from 20 to 60 min, the absorbance of MB at 664 nm progressively decreased. This trend indicates increased dye degradation under sunlight, however, part of the reduction may be due to MB adsorption onto the geopolymer surface. Since adsorption controls were not included, photocatalytic degradation cannot be considered the sole mechanism responsible for the observed MB removal. Therefore, it is appropriate to interpret the data as combined adsorption–photocatalytic effects.

The apparent removal efficiency of methylene blue (MB) increased with catalyst loading up to 5 wt% Ag/ZnO, then declined at 10 wt%. The FA geopolymer coating incorporating 5 wt.% achieved the highest apparent photocatalytic degradation efficiency across all reaction durations (20, 40, and 60 min) as shown in Figure 4. This may be due to the greater availability of photocatalytically active sites, which promote dye adsorption and degradation. It is noted that moderate catalyst dosages enhance reactive oxygen species (ROS) generation and improve photocatalytic efficiency which was reported by Bragta *et al.* [16] and similar observation was obtained in this study.

However, when the catalyst loading was increased to 10 wt.%, the apparent degradation efficiency decreased slightly. This result is likely due to particle agglomeration, which limits the activation of buried catalyst sites. Comparable results were reported by Belahlou *et al.* [17], where the excessive catalyst concentrations lead to nanocomposite accumulation, and reduced photocatalytic performance.

The degradation data were fitted to a pseudo-first-order kinetic model, as shown in Figure 5 to further support the results. The nearly linear relationship between $\ln(A_0/A_t)$ and irradiation time suggests that the removal of methylene blue (MB) follows pseudo-first-order kinetics. The slope of each fitted line represents the apparent rate constant (k), with the 5 wt.% Ag/ZnO coating achieving the highest value (0.041 min^{-1}), compared to 0.031 min^{-1} for the 0 wt.% sample. This shows that both photolysis under sunlight and adsorption within the geopolymer matrix play a role in MB removal.

The enhanced performance obtained with 5 wt.% Ag/ZnO may be attributed to a more effective distribution of photocatalytically active sites within the geopolymer matrix, which promotes greater interaction between the catalyst and dye molecules. In contrast, the lower k value observed at 10 wt.% Ag/ZnO may be due to particle agglomeration, which reduces the effective surface area exposed to sunlight and lowers photocatalytic activity. The satisfactory R^2 values (> 0.94) indicate that the pseudo-first-order model provides a reasonable description of the degradation process.

Overall, the kinetic analysis indicates that 5 wt.% Ag/ZnO loading provides the optimal balance between catalyst dispersion and apparent MB removal performance, yielding the highest degradation efficiency and the most pronounced reduction in the MB absorption peak at 664 nm.

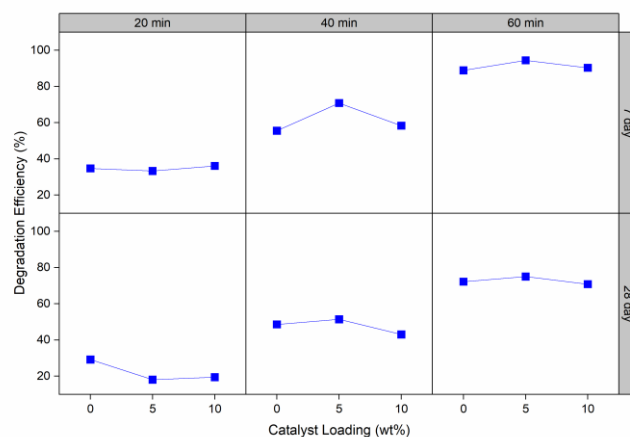


Figure 4. Degradation efficiency of FA geopolymer coatings with varying Ag/ZnO loadings.

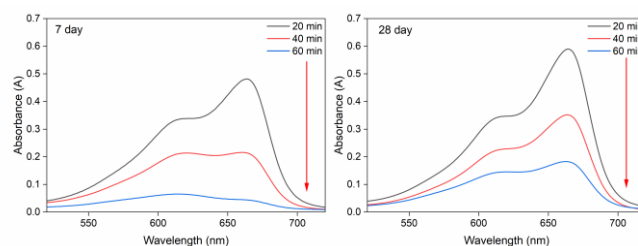


Figure 5. Absorbance of FA geopolymer coating incorporated with 5 wt.% Ag/ZnO.

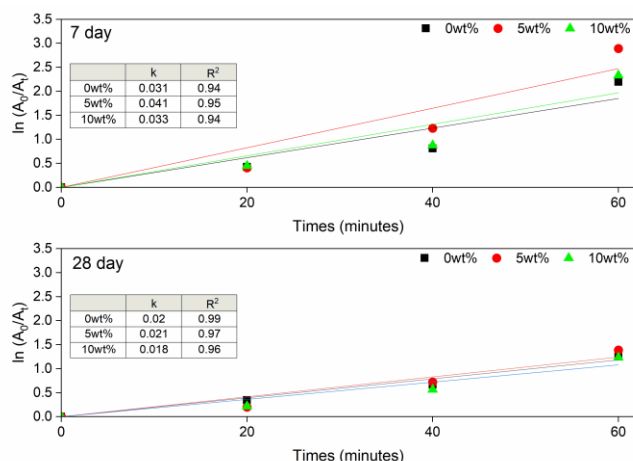


Figure 6. Pseudo-first-order kinetics of MB degradation by different Ag/ZnO loading of FA geopolymers coating.

3.3. Microstructure Analysis

Figure 7 illustrates the SEM micrographs of FA geopolymers coatings containing different Ag/ZnO loadings, where (a) shows the interface between the coating (right side) and substrate (left side) and (b) demonstrates the coating only. At 0 wt.% Ag/ZnO, the coating surface appears relatively porous and uneven, indicating incomplete geopolymersization and weak interfacial bonding between the coating and the substrate. This microstructure supports the lower adhesion strength as shown in Figure 3, matrix densification and bonding sites were limited in the absence of catalyst particles.

In contrast, a dense, uniform, and well-bonded surface was observed for the 5 wt.% Ag/ZnO coating. This suggests improved interfacial contact between the geopolymers matrix and the substrate, resulting in the highest adhesion strength (Figure 3). This compact structure contributed to improved apparent photocatalytic degradation efficiency by promoting effective interaction among sunlight, photocatalyst particles, and dye molecules. The enhancement in apparent MB removal efficiency while maintaining strong mechanical cohesion is attributed to well-distributed Ag/ZnO particles providing active reaction sites.

At 10 wt.% Ag/ZnO, visible cracks and particle agglomeration were observed, which may be attributed to excessive catalyst loading disrupting matrix continuity [18]. This may lead to lower mechanical strength because structural defects weaken adhesion. Moreover, the apparent photocatalytic efficiency decreased because higher catalyst content leads to agglomeration that hinders sunlight absorption and utilization.

In summary, the superior adhesion strength and efficient photocatalytic performance of the 5 wt.% Ag/ZnO coating are supported by the SEM micrographs, which reveal relatively uniform particle dispersion and a compact morphology without visible cracks.

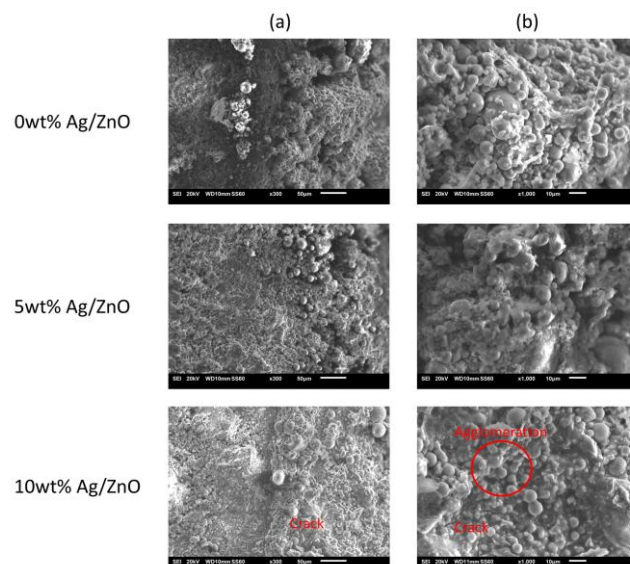


Figure 7. SEM micrographs of (a) interface and (b) FA geopolymers coatings incorporated with varying Ag/ZnO loadings.

3.4. FTIR Analysis

Figure 8 illustrated the FTIR spectra of FA, Ag/ZnO and geopolymers coatings with different Ag/ZnO loadings (0 wt.%, 5 wt.%, 10 wt.%). The O–H stretching vibrations were observed at the broad band around 3400 cm⁻¹, indicating the presence of surface hydroxyl groups and adsorbed water. The H–O–H bending vibrations were observed at the band near 1650 cm⁻¹ which indicates the residual moisture and hydroxyl bonding within the geopolymers matrix [19]. These features may contribute to enhanced photocatalytic activity of the material [11].

CO₃²⁻ vibrations were observed at the peaks around 1400 cm⁻¹, likely arising from atmospheric carbonation of alkali-activated materials. The characteristic of the geopolymers framework was observed at a strong absorption between 1000–1100 cm⁻¹ reflects Si–O–T (T = Si or Al) asymmetric stretching. The residual quartz originating from the fly ash precursor was detected at the band near 797 cm⁻¹ [20]. In addition, the FTIR spectra of Ag/ZnO display a sharp and dominant absorption band at approximately 540 cm⁻¹, corresponding to metal–oxygen (M–O) bonds, where M represents Zn and Ag [21].

The bending vibrations within the aluminosilicate framework are evident for the FA and 0 wt.% Ag/ZnO geopolymers coating [22]. The overlapping contributions of Si–O–Si bonds from the geopolymers framework and Zn–O bonds from the incorporated ZnO particles were reflected by the absorption bands which become sharper and more pronounced in the 5 wt.% and 10 wt.% Ag/ZnO coatings. The effective interaction between the photocatalyst particles and the geopolymers matrix was indicated by the increased intensity in this region which highlights the combined effect of Si–O–Si and Zn–O vibrations following Ag/ZnO addition. The presence of these metal–oxygen

vibrations confirms successful incorporation of Ag/ZnO and likely contributes to the observed photocatalytic activity.

Previous studies have shown that ZnO-based photocatalysts facilitate dye degradation, while Ag species enhance visible-light utilization and suppress electron-hole recombination, thereby improving performance. These mechanisms offer reasonable explanations supported by literature, although optical and charge-carrier characterizations were beyond the scope of this study.

Overall, 5 wt.% Ag/ZnO loading yields the most favorable chemical structure, microstructure, and functional performance which was supported by the FTIR, SEM, and photocatalytic analyses. The simultaneous enhancement of mechanical adhesion and apparent photocatalytic efficiency under sunlight confirms that incorporating 5 wt.% Ag/ZnO into the geopolymer matrix yields an optimal formulation for functional coating applications.

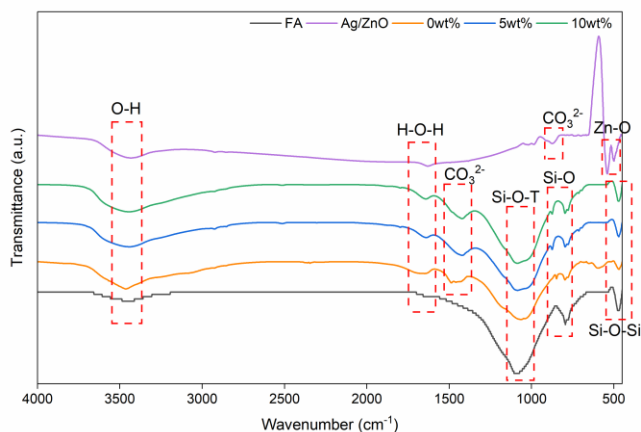


Figure 8. FTIR spectra of FA geopolymer coatings incorporated with varying percentages of Ag/ZnO.

CONCLUSION

This study demonstrates the clear impact of Ag/ZnO particle incorporation on the structural, mechanical, and photocatalytic performance of fly ash geopolymer coatings. The 5 wt.% Ag/ZnO coating achieved the highest adhesion strength a dense and crack-free microstructure, and superior apparent photocatalytic degradation efficiency under sunlight when compared to others. FTIR analysis confirmed successful incorporation of Ag/ZnO through the coexistence of Si-O-Si and Zn-O vibrational bands. This dual chemical integration enhances interfacial cohesion while providing accessible photocatalytic reaction sites. In contrast, the 10 wt.% coating suffered from particle agglomeration and microcracking, whereas the unreinforced 0 wt.% coating exhibited lower adhesion and minimal degradation. Overall, the 5 wt.% Ag/ZnO geopolymer coating represents an optimal formulation that effectively balances mechanical durability with self-cleaning capabilities for sustainable civil infrastructure protection.

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REFERENCES

- [1] S.S. Shetty, D. D. H. S. S. Sonkusare, P.B. Naik, N.S. Kumari, and H. Madhyastha, Environmental pollutants and their effects on human health. *Heliyon*. 9(9), e19496 (2023).
- [2] M. M. Ramirez-Corredores, "Sustainable production of CO₂-derived materials," *npj Materials Sustainability*, vol. 2, no. 1, 2024.
- [3] S. N. Zailan, A. Bouaissi, N. Mahmed, and M. M. A. B. Abdullah, "Influence of ZnO Nanoparticles on Mechanical Properties and Photocatalytic Activity of Self-cleaning ZnO-Based Geopolymer Paste," *Journal of Inorganic and Organometallic Polymers and Materials*, vol. 30, no. 6, pp. 2007-2016, 2019.
- [4] B. J. Singh, A. Chakraborty, and R. Sehgal, "A systematic review of industrial wastewater management: Evaluating challenges and enablers," *J Environ Manage*, vol. 348, p. 119230, Dec 15 2023.
- [5] N. Lertcumfu, P. Jaita, S. Thammamong, S. Lamkhao, S. Tandorn, C. Randorn, T. Tunkasiri, and G. Rujijanagul, Influence of graphene oxide additive on physical, microstructure, adsorption, and photocatalytic properties of calcined kaolinite-based geopolymer ceramic composites. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 602, (2020).
- [6] N. Ramesh, C.W. Lai, M.R.B. Johan, S.M. Mousavi, I.A. Badruddin, A. Kumar, G. Sharma, and F. Gapsari, Progress in photocatalytic degradation of industrial organic dye by utilising the silver doped titanium dioxide nanocomposite. *Heliyon*. 10(24), e40998 (2024).
- [7] S. Duan, J. Liu, S. Zhang, X. Wu, X. Xiang, X. Li, Y. Wu, and Y. Wang, Effect of ZnO on properties of metakaolin-based geopolymer anticorrosive coating. *Journal of Coatings Technology and Research*. 21(6), 2171-2181 (2024).
- [8] N.A. Yaacob, M.M.A.B. Abdullah, L.Y. Ming, S. Ishak, P. Vizureanu, H. Tanyildizi, T. Imjai, M.A. Kamaruddin, and R. Mohamed, Recent advances on photocatalytic geopolymer on the degradation of organic pollutants: A review. *Journal of Hazardous Materials Advances*. 21, (2026).
- [9] S. Zaland, J. Wang, K. Li, S.I. Sadat, and K. Akhunzada, Geopolymers as a sustainable alternative to Portland cement: Synthesis, durability, applications, environmental impacts, and cost analysis. *Renewable and Sustainable Energy Reviews*. 225, (2026).
- [10] L. Jamaludin, R.A. Razak, M.M.A.B. Abdullah, P. Vizureanu, A. Bras, T. Imjai, A.V. Sandu, S.Z. Abd Rahim, and H.C. Yong, The Suitability of Photocatalyst Precursor Materials in Geopolymer Coating Applications: A Review. *Coatings*. 12(9), (2022).
- [11] Y. Ettahiri, B. Akhsassi, M. El Fazdoune, A. Bouddouch, L. Bouna, A. Benlchemi, L. Pérez-

- Villarejo, and R. de Fátima Peralta Muniz Moreira, From synthesis to applications: A comprehensive review of geopolymer materials for photocatalytic degradation of organic pollutants. *Separation and Purification Technology*. 330, (2024).
- [12] J. Ying, Y. Chai, Y. Ye, Y. Suo, and Z. Zhang, "High-adhesion aluminum-cement composite coating for efficient passive daytime radiative cooling," *Solar Energy Materials and Solar Cells*, vol. 296, 2026.
- [13] P. Viensiri et al., "Formulation of geopolymer coating spray and its antifungal activity," *Journal of King Saud University - Engineering Sciences*, 2024.
- [14] M. L. Z. Zidi, Z. B. Ayadi, L. E. Mir, and X. Nóvoa, "Effect of nano-ZnO on mechanical and thermal properties of geopolymer," *Journal of Asian Ceramic Societies*, vol. 8, no. 1, pp. 1-9, 2019.
- [15] Y. Wang, M. Xu, J. Zhao, and A. Xin, "Nano-ZnO modified geopolymer composite coatings for flame-retarding plywood," *Construction and Building Materials*, vol. 338, 2022.
- [16] D. Bragta, P. Garg, S. Chaudhary, G. Madhok, S. Negi, S. Panwar, A. Singh, and R. Kumar, Eco-friendly biosynthesis of ZnO nanoparticles using fungus *Schizophyllum commune* and their hybrid with chitosan for enhanced UV-A photocatalytic degradation of tetracycline. *Chemosphere*. 387, 144666 (2025).
- [17] K. Belahlou, S. Belaidi, S. Bicha, S. O. Bensaid, S. Sangare, and T. Sehili, "Tuned band gap in green-synthesized ZnO, MgO, and Zn_{1-x}MgxO for photocatalytic degradation of chlorophenylurea herbicide under UV-A and solar light in diverse water matrices," *Separation and Purification Technology*, vol. 376, 2025.
- [18] E. D. Shumuye, C. Liu, S. Mehrpay, B. Dong, G. Fang, and Z. Wang, "Impact of nano zinc oxide and preloading on the distribution of pores and cracks in engineered geopolymer composites," *Composite Structures*, vol. 360, 2025.
- [19] P. Rovnaník, "Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer," *Construction and Building Materials*, vol. 24, no. 7, pp. 1176-1183, 2010.
- [20] Y. Yu-Xin, L. Yun-Ming, H. Cheng-Yong, A. Dasari, L. Chang-Chuan, F. Kai-Loong, L. Wei-Hao, P. Wei-Ken, T. Hoe-Woon, and M.M.A.B. Abdullah, Sustainable fly ash geopolymer coatings: substrate-dependent interfacial mechanisms and functional performance. *Emergent Materials*. 9(5), (2026).
- [21] F.A. Alharthi, A.A. Alghamdi, N. Al-Zaqri, H.S. Alanazi, A.A. Alsyahi, A.E. Marghany, and N. Ahmad, Facile one-pot green synthesis of Ag-ZnO Nanocomposites using potato peel and their Ag concentration dependent photocatalytic properties. *Sci Rep*. 10(1), 20229 (2020).
- [22] T. Hoe-Woon, H. Cheng-Yong, L. Yun-Ming, N. Qi-Hwa, L. Wei-Hao, D. Supramanian, L. Jia-Ni, Y. Yu-Xin, and L. Mei-Ju, Dual-functional geopolymers from industrial and agricultural wastes for copper adsorption and sustainable construction applications. *Journal of Environmental Chemical Engineering*. 13(5), (2025).