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Effect of Graphene Oxide on the Performance of Fly Ash Concrete Exposed to Ambient Temperature

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Abstract

The rising global temperatures due to climate change are accelerating concrete deterioration by shortening its service life, which subsequently increases maintenance costs. Therefore, the objective of this investigation is to analyze the graphene oxide (GO) effect on the mechanical characteristics and microstructural properties of fly ash (FA) concrete exposed to ambient temperatures. Concrete specimens were created by employing GO from 0.01% to 0.05% by weight of cement and cured using two distinct methods. These include standard curing in immersed water and for 7 days followed by ambient exposure. The mechanical test showed that GO significantly enhanced compressive strength, with 0.04% GO observed to have increased strength by approximately 16% at 28 days. However, exposure to ambient conditions led to decreased compressive and flexural strength and increased mass loss. The microstructural analysis also showed that ambient-exposed concrete exhibited higher porosity and incomplete hydration. The results showed that the addition of GO enhanced durability by refining the microstructure, reducing porosity, and enhancing thermal stability. Thermal analysis also confirmed that GO minimized moisture loss and improved thermal resistance. Furthermore, Fourier Transform Infrared Spectroscopy (FTIR) validated the improvement in bonding for the GO-FA concrete. These results showed that GO could mitigate the adverse effects of environmental exposure, leading to its identification as an advantageous additive to increase the long-term durability and concrete performance in different temperature conditions.

Keywords: Graphene Oxide; Performance; Mechanical Strength; Microstructure; Fly Ash Concrete; Ambient Temperature.

1. Introduction

Concrete is a primary building material because of its robustness, durability, and affordability. However, its performance is significantly influenced by natural conditions, particularly temperature fluctuations. The impacts of climate change have further intensified the challenges because rising global temperatures are accelerating the deterioration of concrete infrastructure, which further leads to increased cracking, reduced service life, and higher maintenance costs [1, 2]. This shows the urgent need for sustainable and resilient concrete materials capable of mitigating temperature-induced damage and improving longevity as global temperatures exceed the critical 1.5°C threshold [3-5].

Supplementary cementitious materials (SCMs) have been widely used to increase concrete performance under extreme conditions. Fly ash (FA), which is generated during coal combustion, is part of the most commonly utilized SCMs due to its pozzolanic properties, which are considered important to enhance thermal stability and reduce heat generation during cement hydration [6-8]. The incorporation of FA in concrete assists in reducing the carbon footprint by partially replacing Portland cement, a principal source of CO_2 emissions in the construction sector [9]. However,

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FA concrete often exhibits slower early-age strength development, which limits its widespread use in rapid construction projects despite the advantages [9-11]. The selection of the appropriate FA replacement levels in concrete mixtures is important for enhancing both mechanical strength and long-term durability while reducing early-age strength loss. An important observation is that a 5% substitution level outcomes in a minimal reduction in early-age compressive strength, rendering it a practical option for applications demanding rapid strength development [12, 13]. Studies have also shown that 10–15% replacement improves long-term durability but has a negative effect on early compressive strength, particularly in lower curing temperatures [14].

Graphene Oxide (GO) is a nanomaterial with a distinctive two-dimensional structure and oxygen functional groups, which has been introduced as a promising additive for improving cementitious composites. Studies indicated that GO could markedly enhance the mechanical characteristics of concrete by increasing strength, refining microstructure, and improving durability to environmental degradation [15, 16]. The primary mechanism behind these improvements is the role of GO as a nucleation site for hydration products, thereby accelerating the hydration of cement and facilitating the development of denser microstructures [17]. GO can also strengthen the bonding between cement particles and hydration products, which leads to enhanced durability and reduced permeability [18]. Previous experimental investigations confirmed the advantages of integrating GO within cementitious composites. A small amount of GO, less than 0.05%, may dramatically improve the structural strength and longevity of concrete. However, increasing the GO content beyond 0.05% is capable of leading to challenges such as reduced workability, increased agglomeration, and potential weakening of the concrete matrix [19]. An example was the report of Wang et al., indicating that the integration of 0.05% GO resulted in a 30% strength improvement and reduced permeability, thereby improving durability [15]. Devi and Khan also observed a substantial rise in the flexural and tensile properties of concrete with GO incorporation, which further enhanced hydration and matrix densification [20]. Moreover, Reddy and Prasad found that the synergistic interaction between GO and FA produced superior mechanical properties compared to conventional concrete [21]. Nguyen *et al.* also showed that an optimal combination of 0.036% GO and 10% FA enhanced the physical and mechanical properties of cement mortar while maintaining essential workability characteristics [22]. Previous investigations have extensively examined the incorporated effects of GO and FA in concrete mixtures; for example, Kumar *et al.* studied concrete containing 5-15% FA and varying GO at 0.05%, 0.065%, and 0.08% dosages. The results showed that 0.05% GO improved mechanical strength, deformation resistance, and drying shrinkage properties [23]. The trends suggest that GO can effectively address the inherent limitations of FA concrete, rendering it a viable solution for sustainable construction practices.

The majority of studies have concentrated on the effects of GO under controlled curing conditions, but there was limited investigation of the performance under ambient temperature exposure despite the promising results identified. High temperatures can accelerate water evaporation, which further leads to increased porosity, reduced strength, and greater mass loss, potentially compromising the structural integrity of concrete over time [24, 25]. Therefore, comprehending the GO-FA concrete performance under different natural conditions is critical for optimizing its practical applications. Studies showed that exposure to ambient temperatures could negatively impact the hydration process and microstructural development of cementitious materials. The trend further emphasized the need for a comprehensive investigation into the role of GO in mitigating these effects [26, 27].

The objective of this investigation is to address the existing gap by analyzing the performance of GO-FA concrete under ambient temperature exposure. The two curing conditions considered were two distinct conditions, including standard curing in water for 28 days as well as for 7 days followed by exposure to ambient temperatures. Moreover, key parameters, including mechanical properties (compressive and flexural strength), mass loss, and microstructural characteristics, were assessed to determine the effectiveness of GO in enhancing FA concrete durability under real-world conditions. The analysis of the interaction between GO and FA in concrete mixtures allows this investigation to offer beneficial knowledge into optimizing material properties, extending infrastructure lifespan, and promoting sustainable construction methodologies.

The organization of this paper includes: The introduction outlines the effect of rising global temperatures on concrete and explores the potential benefits of using GO to improve FA concrete. The Materials and Methods section describes the experimental setup, including the materials used, mix design, mechanical strength tests, microstructural analysis, and thermal characterization. The Results and Discussion section provides findings on workability, compressive and flexural strength, mass loss, and microstructure with an emphasis on the positive effects of GO in enhancing durability under ambient temperature exposure. Finally, the conclusion summarizes key results with a focus on how GO enhances concrete performance and outlines practical recommendations for future studies and applications.

2. Materials and Methods

The research was conducted in Lhokseumawe, Aceh, Indonesia with the temperature profile for 2023 presented in Figure 1. The temperature variations were observed throughout the year with significant fluctuations during the research period. Moreover, relative humidity ranged from 44% to 99% in Lhokseumawe, and this showed the tropical climate and frequent rainfall in the area. A schematic diagram of the procedure used to analyze the effect of GO on the performance of FA concrete under ambient temperature is presented in Figure 2.

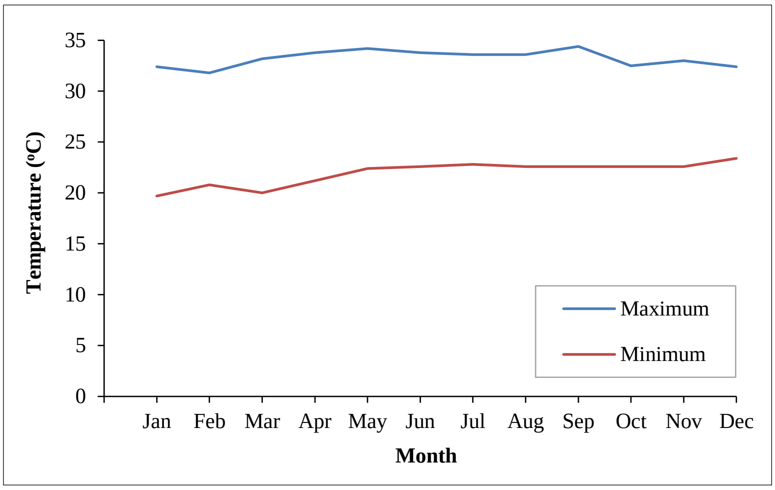


Figure 1. Temperature profile in Lhokseumawe, Aceh Indonesia for 2023

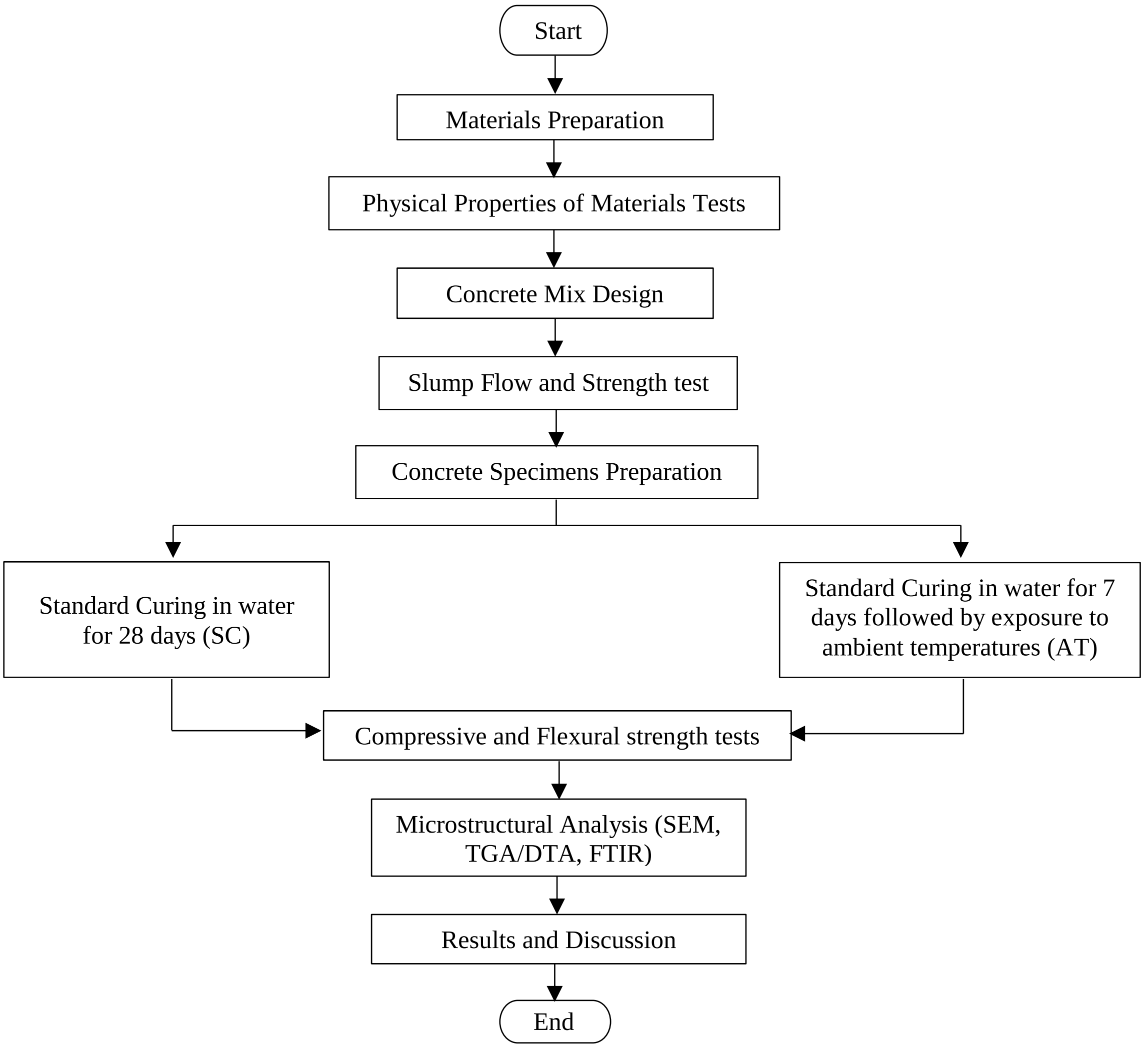


Figure 2. A schematic diagram to assess the effect of GO on the FA concrete performance under ambient temperature conditions

2.1. Materials

The concrete specimens were produced using selected materials, including OPC (Ordinary Portland Cement) Type I, fine and crushed coarse aggregates, tap water, fly ash, and GO. The OPC was sourced from PT Semen Indonesia (SIG) with a 3.11 specific gravity and conformed to the ASTM C150 standards. Moreover, crushed coarse and fine aggregates were obtained from the available quarry materials. The specific gravity, water absorption, and fineness modulus of the fine aggregates were 2.465, 1.68%, and 2.28 while the coarse aggregate exhibited 2.6 2.05%, and 3.26 respectively (Table 1) and the aggregates size distribution is presented in Figure 3. The pre-dispersed GO in water was purchased from IT Nano Medan Indonesia and observed to have a black-brown color, a 99% purity and a 10 mg/mL concentration. The precise properties of the GO are shown in Table 2. Furthermore, the FA provided by the Nagan Raya power plant in Aceh Indonesia, is categorized as Class F (ASTM C618-00, 2001), according to oxide compounds identified through the XRF test, as shown in Table 3. The materials used for specimen preparation are also presented in Figure 4.

Table 1. Physical characteristics of the aggregates

Characteristics of aggregate	Crushed coarse aggregate	Fine aggregate
Specific gravity	2.6	2.465
Water absorption (%)	2.05	1.68
Unit weight (kg/m^3)	1632.5	1563.08
Water content (%)	0.84	2.15
Fineness modulus	3.26	2.28

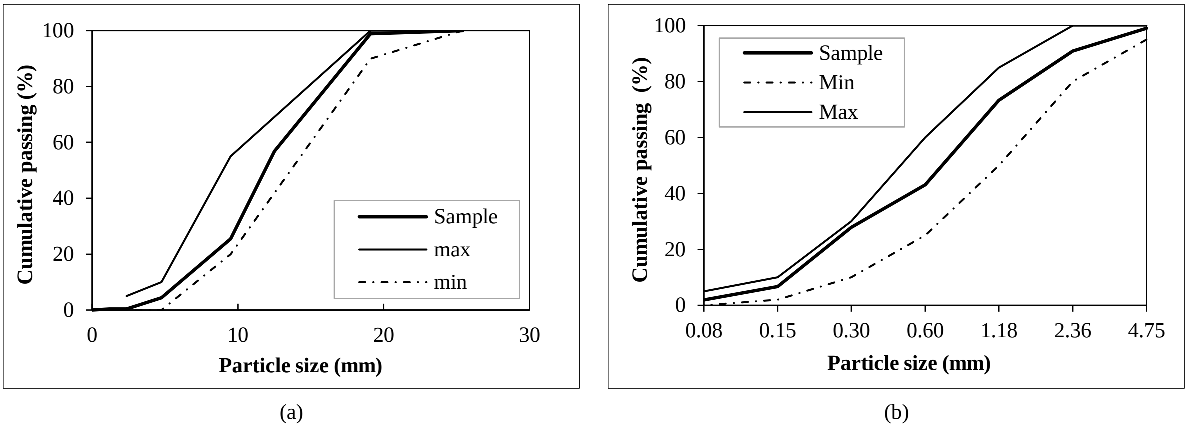


Figure 3. Distribution of particle sizes of the aggregates (a) coarse aggregate (b) fine aggregate

Table 2. The characteristics of GO utilized in this research

Characteristics	Value
Purity	99 %
Form	Dark brown dispersion
Molecular formula	$C_{140}H_{42}O_{20}$
Molecular weight	2043.8
Layer	6 – 7 layers (XRD)
Carbon	81 wt%
Oxygen	19 wt%
Sulfur	0.1%
Raman (I_D/I_G ratio)	0.95
UV-Vis spectrophotometer (peak)	230 nm

Figure 4. Materials used for specimen preparation

Table 3. Chemical compounds in FA from the Nagan Raya power plant, Aceh Indonesia

Chemical Compounds	Weight Percentage (wt. %)
CaO	6.67
SiO_2	46.4
Al_2O_3	28.0
Fe_2O_3	7.17
MgO	3.12
Na_2O	1.93
K_2O	1.85
TiO_2	0.743
P_2O_5	0.455
SO_3	2.90
Cl	0.415
MnO	0.0979
NiO	0.0138
CuO	0.0134
ZnO	0.0129
Rb_2O	0.0110
SrO	0.135
Y_2O_3	0.0066

2.2. Mix Design

The concrete mix proportions were based on Indonesian Standard SNI 03 2834 2012 and the target compressive strength was set at 40 MPa with a design slump flow ranging from 50 to 75 mm. Moreover, the effect of GO on concrete properties was evaluated using five distinct GO contents at 0.01%, 0.02%, 0.03%, 0.04% and 0.05% by weight of cement. FA also replaced 5% of the cement content in all specimens and the concrete was mixed at a 0.46 water-cement ratio. The detailed information of mix proportions to prepare the specimens is presented in Table 4. The “FAC” refers to fly ash concrete while “GO” represents the graphene oxide in the mix. The mixing procedures for the concrete are described as follows:

- Put coarse and fine aggregates in a rotary mixer and blend thoroughly for 5 minutes.
- Add cement to the mixture and continue mixing for 5 minutes.
- Gradually add 80% of the mixing water and GO followed by mixing for 15 minutes.
- Add the remaining water and mix for another 10 minutes.
- Conduct a slump flow test to estimate the concrete mix workability.

Cast the mixture into specimen molds. Store the specimens at room temperature for one day, demold, and cure in water for 28 days.

Table 4. Mix proportion for the preparation of concrete specimens (in m^3)

Specimen	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Water (kg)	FA (kg)	GO (kg)
Control mix	542.5	1087.6	520.3	215.3	-	-
FAC	515.375	1087.6	520.3	215.3	27.125	-
GO-FAC01	515.375	1087.6	520.3	215.3	27.125	0.052
GO-FAC02	515.375	1087.6	520.3	215.3	27.125	0.104
GO-FAC03	515.375	1087.6	520.3	215.3	27.125	0.156
GO-FAC04	515.375	1087.6	520.3	215.3	27.125	0.208
GO-FAC05	515.375	1087.6	520.3	215.3	27.125	0.26

2.3. Mechanical Strength Test

The slump flow was initially performed using slump cone tests to assess the concrete mix workability. This was succeeded by the evaluation of the concrete mechanical properties using compressive and flexural tensile strength tests.

The process required processing cylindrical tubes of 15×30 cm and beams of 15×15×60 cm specimens for compressive and flexural tensile strength tests, based on ASTM standards. Moreover, each concrete mix was tested using three specimens at 28 days as shown in Figure 5.

(a) (b)

Figure 5. Test for mechanical properties (a) compressive strength (b) flexural strength

2.4. Microstructural Characterization

The microscopic characterization of concrete specimens was evaluated employing a Scanning Electron Microscope (SEM). This approach allows detailed analysis of the microstructure of concrete, including the particle dimensions, morphology, and surface characteristics. The analysis was conducted with samples prepared from 1×1×1 cm^3 fragments and subsequently coated with gold applying a JFC 1600 device to enhance the conductivity. Moreover, several complementary methods, including DTA (Differential Thermal Analysis), TGA (Thermogravimetric Analysis), and FTIR (Fourier Transform Infrared Spectroscopy) were also applied to further investigate the chemical composition and thermal behavior of the concrete.

3. Results and Discussion

3.1. Workability of Concrete

Figure 6 indicates the concrete workability of specimens using slump flow tests. The results indicated that the substitution of the mix with FA led to a 5.4% reduction in workability compared to the control specimens. This effect became even more pronounced with the inclusion of GO which caused a significant reduction in workability. In particular, the workability dropped by 23% when the GO content reached 0.05%. This substantial decrease is ascribed to the exceptionally high surface area of GO, which increases the overall surface area within the mix. The condition led to the absorption of more water and allowed less free water available for flow which subsequently reduced the slump value. The findings indicated that GO markedly altered the rheology of the mixture, rendering the concrete stiffer and more rigid [28].

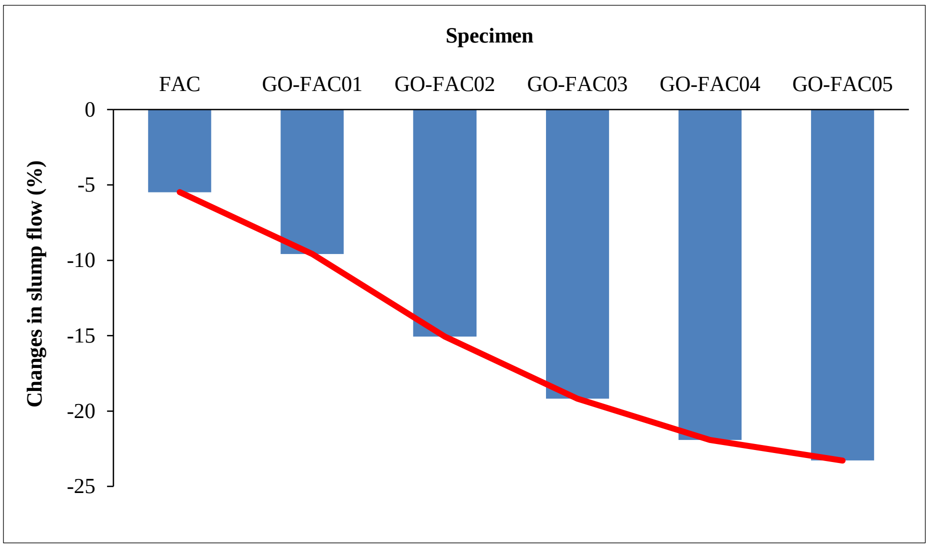


Figure 6. Changes in slump flow of concrete compared to control mixes

Several studies have reported similar effects of FA and GO on concrete workability. For example, Li et al. observed that FA reduced workability because of the spherical shape of its particles, and the process improved density [29]. Similarly, Liu et al. found that nanomaterials such as GO further reduced slump flow by forming hydrogen bonds with water molecules to reduce water available for lubrication within the mix [30]. These results are in line with the trend in the current study and reinforce the understanding that incorporating FA and GO altered the rheological properties of concrete. The reduction in workability poses a challenge but can be effectively addressed through optimized mix design strategies.

3.2. Concrete Compressive Strength

The concrete compressive strength was assessed under two distinct conditions, including standard curing (SC) in water for 28 and 7 days followed by exposure to ambient temperatures (AT). Figure 7 showed the compressive strength values of the concrete specimens at 28 days under standard curing conditions. The effects demonstrated that incorporating FA into the mixture initially reduced the compressive strength because of the slower pozzolanic activity of FA compared to the ordinary Portland cement hydration. However, the inclusion of GO effectively mitigated the reduction in strength associated with FA concrete by enhancing its mechanical properties. Adding 0.04% GO led to a significant 16% compressive strength improvement corresponded to the control concrete. This improvement shows the GO ability to refine the microstructure and enhance the overall performance of FA concrete.

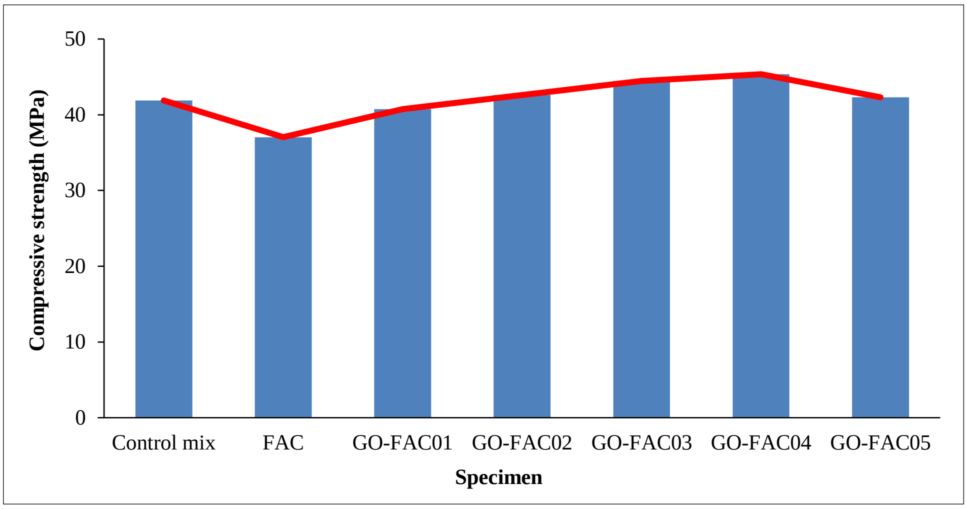


Figure 7. Specimen compressive strength at 28 days under standard curing condition

The exposure effect to ambient temperatures on the compressive strength is presented in Figure 8. The results indicated that exposure to ambient conditions reduced compressive strength by approximately 10% for the control mixes, 7.8% for FA concrete, and only 4% for GO-FA concrete. This was primarily due to the evaporation of free water which was considered very important for the hydration process. The raise in the exposure duration led to the more water evaporation from the concrete structure. The process caused higher porosity and, consequently, a reduction in mechanical properties [31]. Prolonged exposure to ambient temperatures could also accelerate hydration to cause rapid moisture loss with further effect on the concrete mechanical properties [32].

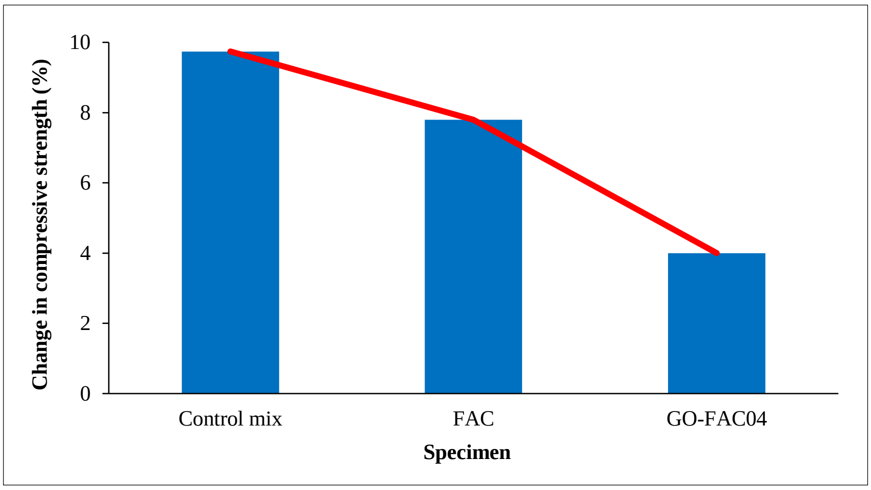


Figure 8. Changes in compressive strength caused by exposure to ambient temperature

The effect of different curing conditions on compressive strength reported in previous studies is summarized in Table 5. It was found that temperature fluctuations and environmental factors were important in determining the reduction in strength. Conventional concrete typically experienced reductions ranging from 10% to 26%, depending on the exposure conditions. More extreme temperatures, particularly those above 100°C, led to even greater reductions, as shown in the study by El-Zohairy et al., where concrete subjected to 260°C lost up to 40% of strength. Similarly, Shoukry et al. reported a 26% reduction when concrete was subjected to temperatures between -20°C and 50°C with varying moisture levels, reinforcing the idea that both hot and cold extremes contributed to structural degradation. Almusallam) further showed how factors such as humidity and wind velocity influenced strength loss with reductions reaching 25% under high-temperature casting conditions.

Table 5. Effect of different curing conditions on concrete compressive strength

Research	Curing condition	Reduction in compressive strength (%)	References
This research	Curing at 20ºC-35ºC	10% (Control concrete)	
	Humidity: 44%-99%	4% (GO-FA concrete)	
ACI 305R-20	Curing at 10ºC-50ºC	10%–15%	ACI 308R-20 [33]
El-Zohairy et al.	Cured at 0, 21, 40, 121, and 260°C	10%–20% (Heated to 100 °C)	El-Zohairy et al. [34]
		30%–40% (Heated at 260 °C	
Shoukry et al.	Curing -20ºC to 50ºC	26%	Shoukry et al. [35]
	Moisture level 0-100%		
Almusallam	Casting at 30ºC and 45ºC	25%	Almusallam [24]
	Humidity: 25, 50, and 95%		
	Wind velocity: 0, and 15 km/h		
Ortiz et al.	Hot weather: 22.4ºC-34.1ºC	2%-5% (decrease)	Ortiz et al. [36]
	Cold weather: 6.4ºC-22.4ºC	5%-8% (increase)	

A contrasting trend was observed in the current study with GO-FA concrete exhibiting better durability under ambient temperature curing. The findings indicated only a 4% reduction in compressive strength for GO-FA concrete compared to 10% for control concrete under similar conditions of 20°C–35°C temperature and 44%–99% humidity. This showed that the addition of GO to FA concrete enhanced the durability against environmental fluctuation conditions and showed the potential of the material for improving long-term structural performance. The results were in line with the report of ACI 305R-20 that a 10%–15% strength loss was recorded for concrete cured at temperatures between 10 and 50°C, further validating the general impact of temperature on strength degradation. The significant performance of GO-FA concrete showed the potential as an effective strategy for reducing strength loss and improving structural resilience.

The failure modes of the concrete specimens subjected to compression tests at 28 days of curing under both standard and ambient temperature conditions are presented in Figure 9. The concrete cured at ambient temperature exhibited more pronounced and irregular cracking, whereas those under standard curing conditions displayed a more controlled and uniform failure pattern. The integration of GO into FA concrete affected the failure characteristic compared to control specimens by improving the structural integrity and load-bearing capacity. This shows that GO contributes to enhanced microstructural bonding and possibly improves resistance to crack propagation [37]. The hydration process in GO-FA concrete under ambient temperature can be less uniform than in standard curing conditions but offers a noticeable improvement over control specimens. It was also observed that control concrete under ambient temperature curing experienced more significant crushing and splitting failures, indicating a weaker internal cohesion and less resistance to compressive stress. The results indicated the GO positive effect in enhancing the concrete strength, particularly in less controlled curing environments, by assisting in mitigating premature cracking and failure [38].

Figure 9. Concrete specimen failures at 28-day compression testing (a) Control concrete under standard curing (b) Control concrete under ambient temperature (c) GO-FA concrete under standard curing (d) GO-FA concrete under ambient temperature

3.3. Mass Loss

Concrete exposed to ambient temperatures, particularly in environments with low humidity or high temperatures, experiences a progressive loss of free water which is crucial for both hydration and long-term strength development. The water evaporates when the surrounding conditions promote moisture loss and drive a noticeable decline in the mass of concrete over extended periods. This mass loss directly affects the internal structure because the moisture loss contributes to the development of micro voids and increased porosity which further lower the mechanical performance.

The degree of loss was analysed by comparing the initial mass of samples cured under standard conditions with the mass after 28 days of exposure to ambient temperature. As presented in Figure 10, control concrete exhibited a mass loss of approximately 1.7%, FA concrete showed a slightly lower reduction of 1.62%, and GO-FA concrete had the least at 1.53%. This trend showed GO-FA concrete mixtures exhibited improved moisture retention and self-healing properties primarily due to the refined microstructure which effectively slowed down water migration and evaporation. The improved performance in mitigating mass loss can be attributed to the presence of GO which improves particle dispersion, strengthens interfacial bonding within the mix, and further limits moisture loss [39]. Therefore, GO-FA concrete retains water more effectively and maintains mechanical strength over time which leads to more resistance to environmental stressors.

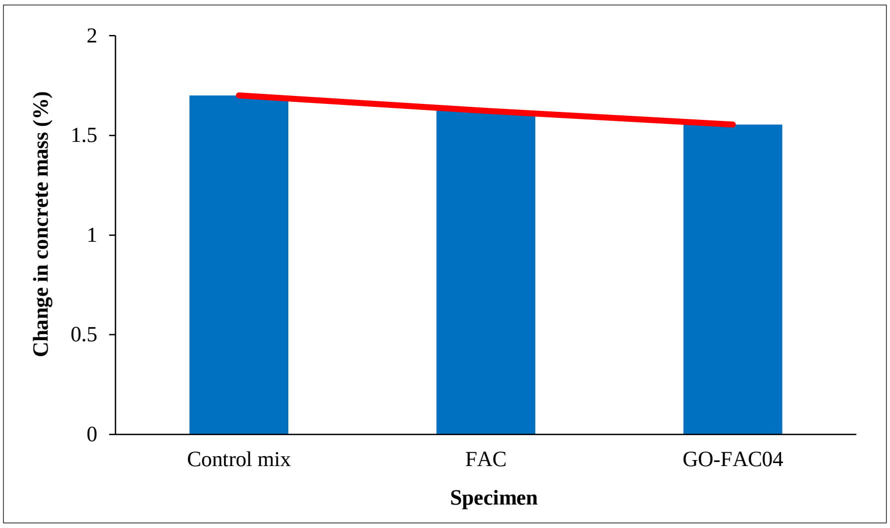


Figure 10. Changes in the mass of concrete caused by exposure to ambient temperature

The correlation of mass loss and compressive strength reduction shows the importance of minimizing environmental exposure for concrete structures. This is because increased porosity due to moisture loss weakens the overall binding force within the concrete which leads to more vulnerability to mechanical stresses and external loads [40]. In practical construction scenarios, strategies such as the inclusion of SCMs in the form of FA and GO can be highly effective in prolonging the lifespan of concrete and enhancing its resilience against ambient environmental conditions [41].

3.4. Concrete Flexural Tensile Strength

Flexural tensile strength denotes to the capacity of a concrete beam to withstand tensile stress due to bending moments without steel reinforcement. This property is important in determining the structural integrity of concrete elements, particularly in scenarios where tensile reinforcement is absent or minimal. The specimens used for the test were prepared using a beam with a cross-section of 15×15cm and a length of 60 cm under simple supports. These dimensions were selected to ensure a standard testing environment that allowed reliable comparisons of results. It is well established that flexural tensile strength correlates with the concrete compressive strength. The trend is associated with the particular that higher compressive strength generally leads to enhanced flexural tensile strength.

Changes in flexural strength due to exposure to ambient temperature are presented in Figure 11 and the pattern closely corresponds to the trends marked in compressive strength. The exposure to ambient temperature reduced flexural strength by approximately 8.8% for control mixes, 6.3% for FA-concrete, and only 4.3% for GO-FA concrete. The smaller reduction recorded for GO-FA concrete showed the capacity of GO to improve resistance to environmental conditions and prevent significant performance degradation. This suggests that the addition of GO in the FA-concrete mix can enhance long-term durability and structural performance. The results showed that all concrete mixes experienced some reduction in flexural tensile strength due to ambient temperature exposure but GO-FA concrete exhibited superior performance. The minimal strength loss in GO-FA concrete shows its potential for use in structures exposed to ambient environmental conditions without significant deterioration [23, 38].

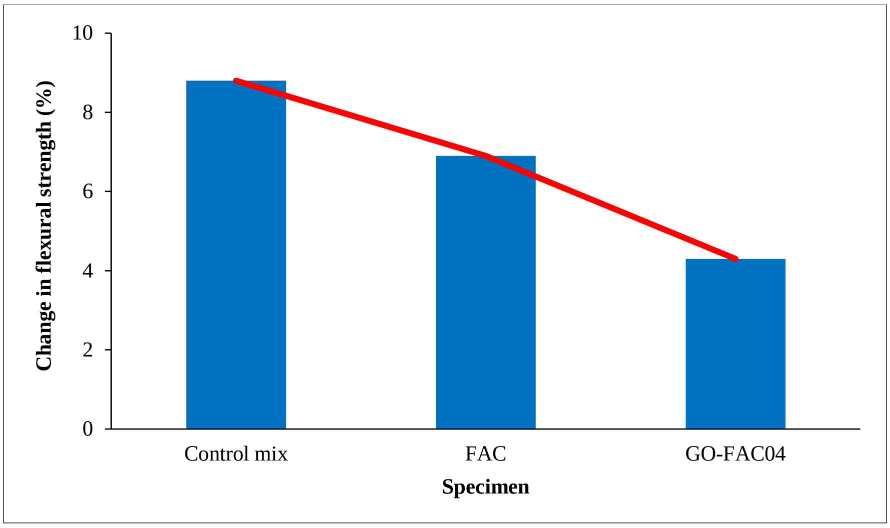
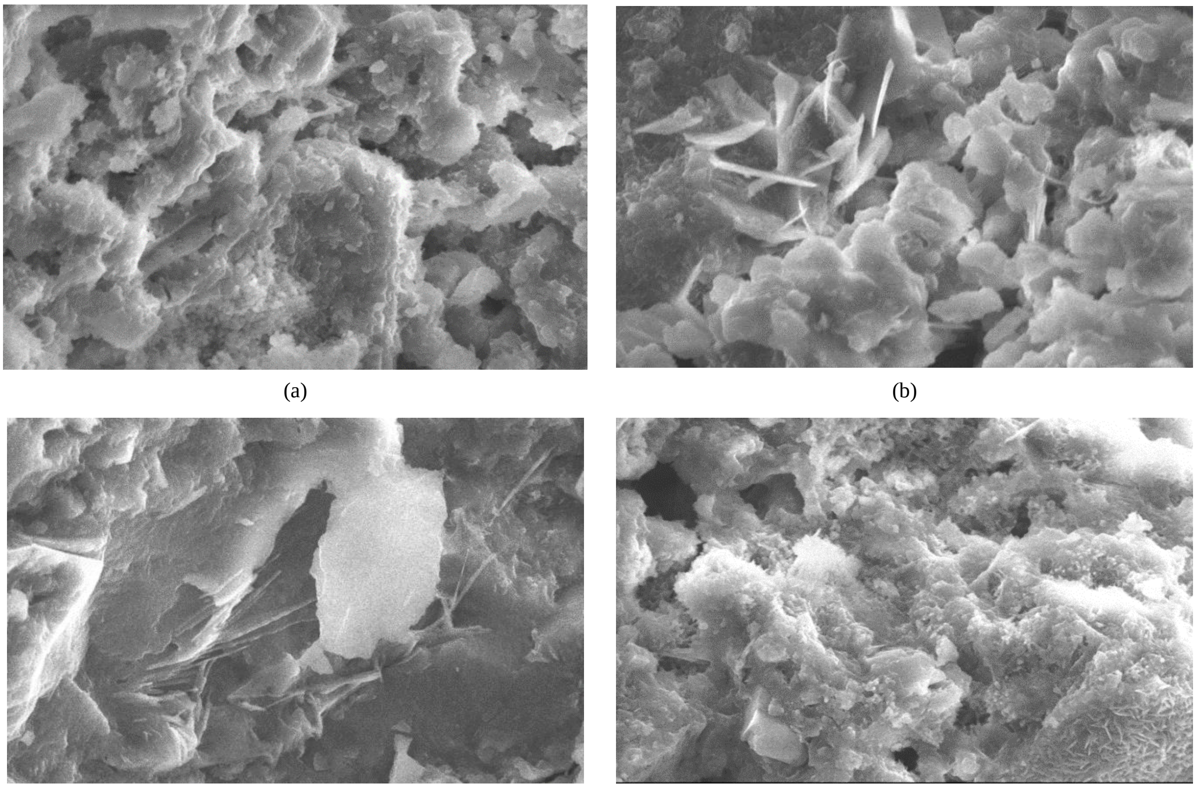


Figure 11. Changes in flexural strength caused by exposure to ambient temperature

3.5. Microstructure of Concrete

Figure 12 presents images from the SEM analysis conducted to compare the microstructure of concrete under standard curing and ambient temperature exposure. In the control concrete under standard curing, some pores are clearly visible while specimens exposed to ambient temperature develop larger pores primarily due to the increased water evaporation which leads to higher porosity. The results correlated with the trends observed in concrete strength and mass loss. Interestingly, adding a small amount of GO to the FA under standard curing significantly altered the ITZ (interfacial transition zone) existing between the aggregate and cement paste to produce a denser microstructure with smaller pores [42]. Even after exposure to ambient temperature, the microstructure of GO-FA concrete remained relatively unchanged and showed some pores but maintained a smaller size [43]. The results also demonstrated that the addition of GO provided a protective effect against the adverse impacts of environmental exposure, indicating the potential for enhancing the concrete durability and longevity in ambient conditions.



(a) (b)

(c) (d)

Figure 12. Images from SEM analysis (a) control concrete with standard curing (b) control concrete under ambient temperature exposure (c) GO-FA concrete with standard curing (d) GO-FA concrete under ambient temperature exposure

3.6. Thermal Analysis

The thermal behavior of the concrete specimens was evaluated using TGA in the range of 0 to 300°C. TGA analysis provides critical insights into moisture evaporation, the decomposition of cement hydrates, and overall material stability. The results showed that weight loss in the temperature range was primarily attributed to the loss of physically bound water and the decomposition of hydration yields including C-S-H and ettringite [39]. As presented in Figure 13-a, the control concrete exhibited relatively lower total weight loss which showed a more stable microstructure with minimal moisture content under standard conditions. The exposure of the specimen to ambient temperature led to a substantial increase in weight loss for the control specimens. This change can be attributed to the increased porosity and micro-cracking due to moisture evaporation which accelerates the degradation of hydration compounds [44]. The raised porosity weakens the overall integrity of the concrete and increases the susceptibility to further thermal degradation [38]. Meanwhile, the GO-FA concrete had lower weight loss compared to control concrete exposed to ambient temperature. This was observed from the TGA curve for GO-FA concrete which showed a lower mass loss reduction than the control concrete. The results showed the material beneficial role in improving the thermal resistance of the concrete. The lower weight loss in GO-FA concrete also confirmed that the addition of GO improved thermal stability and resistance to dehydration.

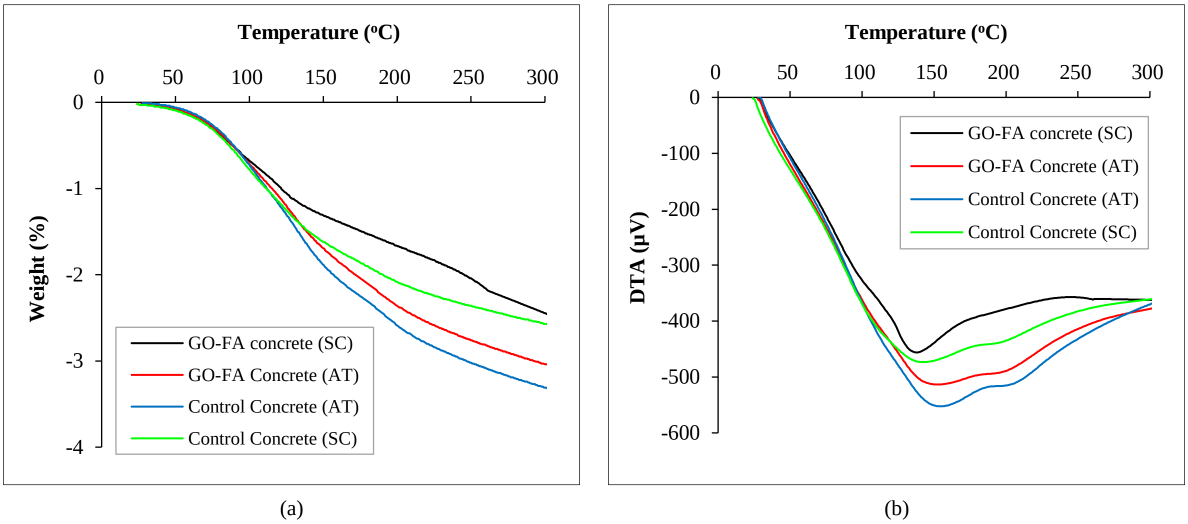


Figure 13. Thermal behaviour of concrete specimens (a) TGA analysis (b) DTA analysis

The DTA analysis further supported the results by providing a detailed thermal signature of each concrete specimen (Figure 13-b). The control concrete exhibited a pronounced endothermic peak, which corresponded to the dehydration of cement hydrates, particularly C-S-H and portlandite ($Ca(OH)_2$). This peak intensified when the concrete was exposed to ambient temperature, indicating accelerated dehydration and potential structural weakening [45]. However, the DTA results for GO-FA concrete showed a significantly lower endothermic peak which was a sign of improved thermal stability for concrete due to the addition of GO. The reduced peak intensity also signaled that the GO effectively retained moisture and delayed the thermal decomposition of hydration products. Nevertheless, GO-FA concrete exhibited a slight increase in the endothermic peak when exposed to ambient conditions compared to the behavior under standard curing conditions [46]. This minor rise suggests prolonged exposure to elevated temperatures can lead to some hydration loss in GO-FA concrete, albeit at a lower rate than control concrete, despite the ability to enhance thermal stability [47]. The results showed the ability of GO-FA concrete to serve as a promising alternative for applications requiring enhanced durability and thermal stability.

3.7. FTIR Analysis

The analysis conducted using FTIR spectroscopy provides in-depth information into the molecular composition and chemical interactions within the concrete specimens under different curing conditions as presented in Figure 14. The peak intensities and the presence of specific functional groups were compared to evaluate the distinct characteristics of concrete subjected to standard curing and ambient temperature exposure. In the control concrete subjected to standard curing, prominent peaks were identified at 1431 cm^{-1} and 3612 cm^{-1} which showed the formation of well-hydrated cementitious phases. The peak at 1431 cm^{-1} corresponds to the bending vibrations of carbonates, typically formed due to carbonation processes in hydrated cement [48, 49]. This phenomenon is often associated with long-term exposure to atmospheric CO_2 which shows to the calcium carbonate formation and contributes to the strengthening of concrete structure. Moreover, the high-intensity stretching peak at 3612 cm^{-1} is associated with hydroxyl (-OH) group vibrations which is essential for facilitating hydration and promoting a dense and durable microstructure.

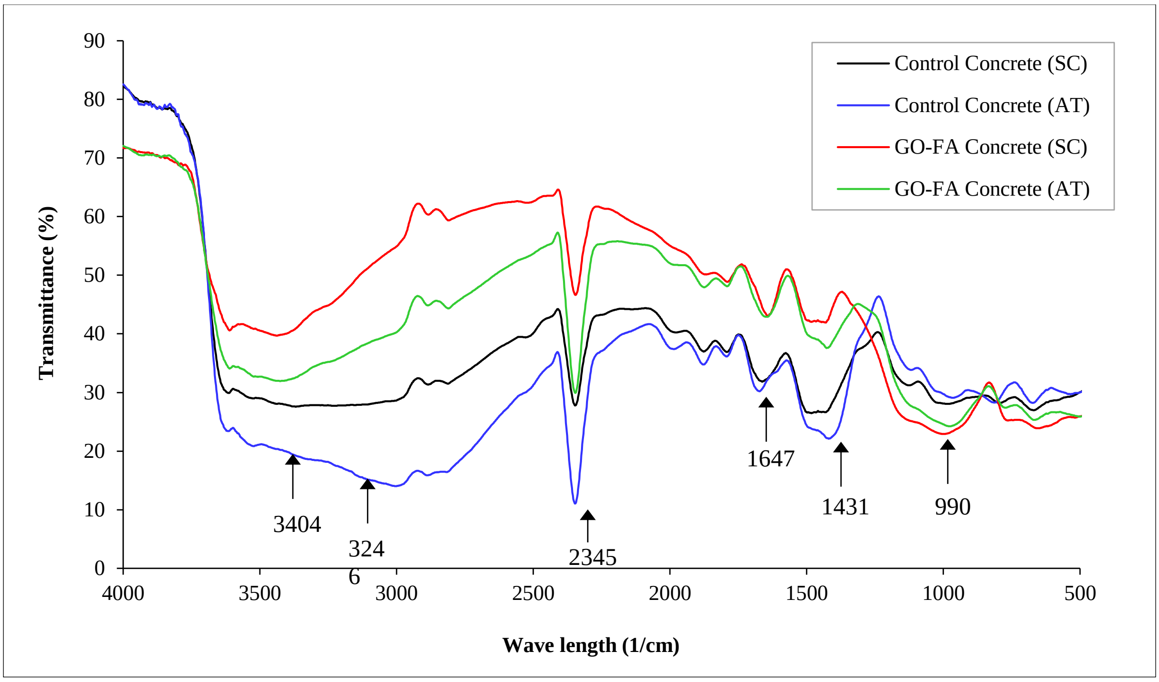


Figure 14. FTIR analysis of concrete specimens analysis

A contrasting observation was made when the control concrete exposed to ambient temperature exhibited lower peak intensities, particularly in the higher wavenumber regions, signifying reduced hydration activity and less effective cement matrix formation. Peaks at 3246 cm^{-1} and 3404 cm^{-1} were absent and this showed diminished hydroxyl (-OH) contributions [50]. The trend is an indication that ambient temperature conditions affect optimal hydration reactions, leading to a less refined microstructure and potentially lower mechanical performance. Moreover, the GO-FA concrete subjected to standard curing exhibited a distinct peak at 3439 cm^{-1} which corresponded to the stretching vibrations of hydroxyl (-OH) groups. This peak suggests improved bonding interactions within the material because of the existence of GO which is known to facilitate the formation of additional nucleation sites for hydration products. GO enhances a more interconnected and compact microstructure, which may result in enhanced mechanical characteristics and increased durability of the concrete.

Another interesting result was the additional peak identified at 3425 cm^{-1} in the GO-FA concrete exposed to ambient temperature which was also associated with hydroxyl (-OH) stretching vibrations. This suggests that despite less favorable curing conditions, moisture retention and hydration processes persisted within the GO-FA concrete [49]. The unique interaction between GO, FA, and the cement matrix possibly contributed to sustained hydration, even though the rate remained lower compared to standard curing conditions. Moreover, the presence of NH groups within the 3400 cm^{-1} range further showed the influence of GO in modifying the hydration mechanisms and potentially improving the durability of the concrete. The highest peak intensities were generally observed in the control concrete under standard curing. The trend reinforced the notion that optimal hydration and robust cement matrix formation occurred under these conditions. However, in both GO-FA concrete samples, significant peaks in the 3400 cm^{-1} range showed the retention of hydroxyl (-OH) and NH groups, which was capable of enhancing concrete properties such as durability, moisture resistance, and mechanical performance [51]. The distinctive peaks in the GO-FA specimens not found in control concrete showed that GO provided beneficial properties to improve concrete performance.

4. Conclusion

In conclusion, the GO effect on the mechanical characteristics and microstructural properties of FA disclosed to ambient temperature was analyzed. The results clearly showed that adding GO decreased workability but significantly enhanced the FA mechanical properties. The incorporation of 0.04% GO specifically led to a substantial 16% increase in compressive strength at 28 days. This improvement was largely attributed to the GO ability in refining the concrete microstructure, leading to a denser and more cohesive matrix that subsequently improved overall performance. Meanwhile, FA concrete exhibited a reduction in both compressive and flexural strength when subjected to ambient temperature conditions. Exposure also led to increased mass loss due to moisture evaporation and increased porosity. Despite these negative effects, GO-FA concrete showed better resistance compared to the control mixes. The incorporation of GO directed to a smaller reduction in strength and a more controlled mass loss. Furthermore, the improved performance of GO-FA concrete was associated with the ability of GO to enhance particle dispersion and strengthen interfacial bonding, which assisted in retaining moisture and maintaining structural integrity.

Further microstructural analysis conducted through SEM confirmed that GO-FA concrete exhibited a denser matrix with smaller pores even after prolonged exposure to ambient temperature conditions. The thermal analysis also supported the results by showing the ability of GO to enhance the stability of hydration products in order to reduce the degradation of cementitious materials. Moreover, FTIR analysis provided evidence that GO influenced hydration mechanisms to ensure better moisture retention and long-term durability. In summary, this research confirmed that GO was an effective admixture in FA concrete due to its ability to significantly improve mechanical strength, durability, and resistance to ambient temperature stressors.

5. Declarations

5.1. Author Contributions

Conceptualization, M.M. and Y.Y.; methodology, M.M., S.J.A., and J.A.; validation, A.B.J.; formal analysis, A.B.J. and M.S.; investigation, M.M. and S.J.A.; resources, J.A.; writing—review and editing, M.M., A.B.J., and M.S.; supervision, S.J.A. and J.A.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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