

Synergistic Effects of Fly Ash Geopolymer and Superplasticizer on PET-Modified Concrete

Emmanuel Mwambu Wafula*, James Wambua^{id}, Fundi Sanewu^{id}

Sustainable Materials Research & Technology Centre (SMARTEC), Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya

Email: *emmwaf@gmail.com

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Abstract

The growing environmental issues of cement production, the exhaustion of natural aggregates, and the dumping of plastic waste have led to the necessity of providing the construction industry with sustainable alternatives. Despite the previous studies that have investigated recycled PET plastic, fly ash geopolymers, and superplasticizers when examined individually, very few studies have been conducted where these are studied in combination and in their synergistic effects in concrete systems. This paper thus examined the synergistic nature of fly ash geopolymer and superplasticizer on concrete that had 5% PET plastic as a partial substitution of fine aggregate. The fresh, mechanical, and durability properties of concrete were investigated using experimental studies. Tests of workability were conducted using slump tests, whilst compressive strength test, split tensile strength test, and flexural strength test were conducted at 7, 14, and 28 days of curing. The performance on durability was evaluated by carrying out acid resistance tests using solutions of hydrochloric acid and sulphuric acid. The findings indicated that the incorporation of PET decreased workability and mechanical strength relative to traditional concrete. Nevertheless, the performance of PET-modified concrete was greatly enhanced by the incorporation of superplasticizer and fly ash geopolymer. These optimum workability and strength performance were realized under 3% - 4% of superplasticizer and 3% - 4% of fly ash content. The compressive, tensile, and flexural strength was enhanced by the combined effect of fly ash and superplasticizer, which improves the dispersion of particles, densification of the matrix, and the reaction of pozzolana. There was also an improvement in the durability performance, since there was lower porosity and greater resistance to acid attack. The paper concludes that the negative impact of PET plastic in the concrete can be effectively utilised through the synergistic incorporation of fly ash geopolymer and superplasticizer in the concrete. The results justify the use of recycled PET and fly ash within the construction of environmentally friendly

concrete. Long-term durability, microstructural behavior, and large-scale field applications should be investigated in future studies to enable policy formulation and industrial use of sustainable construction materials.

Keywords

Geopolymer, Superplasticizer, Fly-Ash

1. Introduction

The construction industry is increasingly under pressure to adopt sustainable practices due to the environmental impacts associated with conventional materials such as Portland cement and natural aggregates [1] [2]. The production of cement alone contributes significantly to global carbon dioxide emissions, while the excessive extraction of natural sand and aggregates leads to resource depletion and environmental degradation. Consequently, there has been a growing interest in the development and application of alternative eco-friendly construction materials that can reduce environmental impact while maintaining or enhancing performance [3].

Among these alternatives, geopolymers have emerged as a promising substitute for traditional cementitious binders, as argued by [4]-[6]. Geopolymers are inorganic aluminosilicate materials formed through the reaction of silica- and alumina-rich precursors, such as fly ash, with alkaline activators [7]. These materials are recognized for their low carbon footprint, high mechanical strength, low permeability, and excellent resistance to chemical and thermal degradation [8].

In particular, fly ash-based geopolymers offer the dual benefit of recycling industrial by-products and reducing greenhouse gas emissions associated with cement production, making them highly attractive for sustainable construction applications. Fly ash is a by-product of coal combustion in thermal power stations and is widely used in the construction industry due to its beneficial properties [9]. It is made up of fine particulates, mainly silica and alumina, and its chemical composition depends on the origin of the coal and the combustion techniques used. Classified as a pozzolanic material, fly ash undergoes a chemical reaction with calcium hydroxide in the presence of water, forming compounds that significantly enhance concrete's mechanical properties and durability. Adding fly ash to concrete mixtures improves workability and reduces water requirements and segregation, thereby optimizing the structural integrity of the mix [10]. Using fly ash as a partial replacement for Portland cement in concrete formulations offers considerable advantages by conserving natural resources and reducing greenhouse gas emissions associated with cement production [11]. Fly ash provides a cost-effective alternative to cement, lowering the overall material expenses without compromising the performance of the concrete [12]. Despite these benefits, applying fly ash in construction requires careful consideration of potential challenges, in-

cluding variability in its properties, the risk of alkali-silica reaction, and the need for stringent quality control measures to ensure the reliability and sustainability of fly ash-enhanced construction materials.

In addition to alternative binders, the incorporation of recycled materials into concrete has gained considerable attention. Plastic waste, especially polyethylene terephthalate (PET), poses a major environmental challenge due to its non-biodegradable nature and increasing accumulation in landfills and water bodies. Utilizing crushed plastic as a partial replacement for fine aggregates in concrete presents an innovative solution to waste management while conserving natural sand resources. However, the inclusion of plastic in concrete often leads to reduced mechanical strength and increased porosity, necessitating the use of supplementary materials to mitigate these adverse effects.

Superplasticizers, which are high-range water-reducing admixtures, play a crucial role in improving the workability and performance of concrete without increasing the water-cement ratio [13]. By enhancing particle dispersion and reducing water demand, superplasticizers contribute to better compaction, reduced porosity, and improved mechanical properties. When used in combination with geopolymer materials such as fly ash, they have the potential to significantly enhance the overall performance of modified concrete mixtures.

Despite the growing body of research on sustainable construction materials, most studies have focused on the individual application of recycled plastic, fly ash-based geopolymers, or superplasticizers in concrete [5] [14] [15]. While each of these materials has demonstrated significant benefits, their combined and interactive effects within a single concrete system remain insufficiently explored.

This study, therefore, investigated the combined use of fly ash-based geopolymer and superplasticizer in concrete containing 5% crushed PET plastic as a partial replacement of sand. The novelty of this research lies in the evaluation of the synergistic interaction between these components within a single concrete matrix, alongside a holistic assessment of fresh, mechanical, and durability properties.

Unlike previous studies that independently investigated PET waste, fly ash geopolymer, or superplasticizer incorporation, this study systematically evaluated the interactive and synergistic influence of these materials within a unified concrete matrix. The study therefore contributes a multi-parameter optimization framework for sustainable PET-modified concrete, considering fresh, mechanical, and durability performance simultaneously.

2. Materials and Methods

2.1. Experimental Setup and Materials Source

All the experimental work was conducted at the Materials Laboratory of Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. The materials used in this study included Ordinary Portland Cement (OPC), fine aggregates (sand), coarse aggregates (ballast), recycled polyethylene terephthalate (PET) plastic, fly ash-based geopolymer, superplasticizer, and chemical reagents for durabil-

ity testing.

The Ordinary Portland Cement used in the study was CEM I 42.5N conforming to BS EN 197-1 specifications. The fine aggregate consisted of river sand with a fineness modulus of 2.63 and a particle size range of 0.075 - 4.75 mm, while the coarse aggregate comprised crushed granite with a nominal maximum size of 20 mm.

Table 1 indicates that the shredded PET particles had an irregular geometry with particle sizes ranging between 2 mm and 6 mm and a specific gravity of approximately 1.34. The fly ash used in the geopolymer system was classified as Class F fly ash containing predominantly silica (SiO_2) and alumina (Al_2O_3), with combined oxide composition exceeding 70%. The superplasticizer (MasterGlenium 118) was dosed as a percentage of cementitious binder content and had a specific gravity of 1.08 ± 0.02 at 25°C .

Table 1. Physical and chemical properties of constituent materials.

Material	Property	Value
OPC	Cement Grade	CEM I 42.5 N
Sand	Fineness Modulus	2.63
Coarse Aggregate	Maximum Size	20 mm
PET	Particle Size	2 - 6 mm
PET	Specific Gravity	1.34
Fly Ash	Classification	Class F
Superplasticizer	Specific Gravity	1.08

Ordinary Portland Cement conforming to relevant standards was sourced from a local supplier in Juja, Kiambu County. Natural river sand was used as fine aggregate, while ballast served as coarse aggregate; both were obtained from a quarry near Juja town. The aggregates were used in their natural state after ensuring they were free from deleterious materials.

Waste PET plastic bottles were collected from landfill sites within Nairobi City County. The plastics were manually sorted to remove contaminants, washed thoroughly, and air-dried. The cleaned plastics were then mechanically shredded into small, irregular particles suitable for partial replacement of fine aggregates. The preparation stages included collection, sorting, cleaning, and shredding, as illustrated in **Figure 1**.

Fly ash, used as the precursor material for geopolymer formation, was obtained from a local supplier. In the study, the fly ash was added as a supplementary binder in the geopolymer formation. Sodium hydroxide (NaOH) was used as an alkaline activator in the geopolymer system. A commercially available high-range water-reducing admixture (MasterGlenium 118) was used as the superplasticizer to improve workability and reduce water demand. In this study, the fly ash geopolymer was not used as a full replacement of Ordinary Portland Cement (OPC), but rather

as a supplementary cementitious binder added alongside cement to enhance matrix densification and pozzolanic reactivity. The geopolymer system was synthesized using Class F fly ash activated with sodium hydroxide (NaOH) solution. A NaOH molarity of 10 M was adopted based on previous studies demonstrating optimum geopolymerization and mechanical performance in fly ash systems. The alkaline activator-to-fly ash ratio was maintained at 0.40 throughout the experimental program to ensure consistency in geopolymer formation and workability.

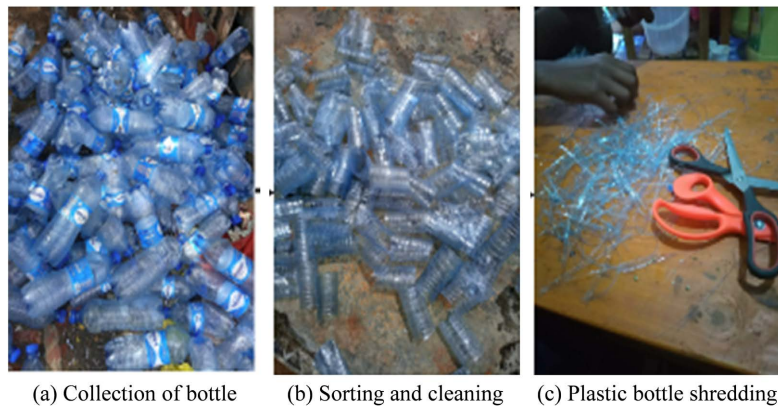


Figure 1. PET plastic waste preparation process.

The selected geopolymer dosage range of 1% - 4% was based on the percentage mass of cementitious binder content. The dosage interval was adopted from preliminary trial mixes and previous literature indicating that low-volume geopolymer incorporation can significantly improve matrix packing, particle dispersion, and durability performance without adversely affecting setting behavior or workability. For durability assessment, sulphuric acid (H_2SO_4) and hydrochloric acid (HCl) solutions were prepared and used to evaluate the resistance of concrete specimens to aggressive chemical environments.

2.2. Mix Design and Batching

The study used concrete class C25. The sand was progressively replaced with crushed plastics as the superplasticizers were also added. **Table 2** and **Table 3** provide a summary of the replacement percentages used in the study.

Concrete of characteristic strength class C25 was selected as the control mix. The mix design was based on standard procedures for normal-weight concrete, ensuring adequate workability and strength performance. In the modified mixes, sand was partially replaced with 5% crushed PET plastic (by volume). To evaluate the influence of chemical and mineral admixtures, superplasticizer and fly ash-based geopolymer were incorporated at varying percentages as summarized in **Table 1**. The superplasticizer and geopolymer were introduced both individually and in combination (at their optimal percentages) at different percentage dosages to investigate their independent and synergistic effects on concrete properties. The mixing was carried out using a mechanical mixer to ensure homogeneity. The

experimental program consisted of three main categories:

i) Control mix (C25): conventional concrete without PET, geopolymer, or superplasticizer.

ii) PET-modified concrete: concrete with 5% PET replacing sand, without additional admixtures.

iii) Hybrid mixes: concrete containing 5% PET combined with varying dosages of superplasticizer and/or fly ash-based geopolymer.

Table 2. Batching of concrete was used in the study.

Mix Code	Cement (kg/m ³)	Sand (%)	PET (%)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)	Superplasticizer (%)	Fly Ash (Geopolymer, %)
C25 (Control)	380	100	0	1100	190	0	0
C25-P5	380	95	5	1100	190	0	0
SP1	380	95	5	1100	190	1	0
SP2	380	95	5	1100	190	2	0
SP3	380	95	5	1100	190	3	0
SP4	380	95	5	1100	190	4	0
FA1	380	95	5	1100	190	0	1
FA2	380	95	5	1100	190	0	2
FA3	380	95	5	1100	190	0	3
FA4	380	95	5	1100	190	0	4
SP4FA3	380	95	5	1100	190	3	3

Table 3. Geopolymer activator characteristics.

Parameter	Value
Fly Ash Type	Class F
NaOH Molarity	10 M
Activator-to-Fly Ash Ratio	0.40
Geopolymer Dosage Basis	% of Binder Mass
Activator Curing Condition	Ambient Curing

2.3. Specimen Preparation and Curing

Fresh concrete was cast into appropriate moulds to produce cubes (150 × 150 × 150 mm), cylinders, and prismatic beams. Concrete was placed in moulds in layers and compacted using standard procedures to eliminate air voids. After casting, specimens were covered to prevent moisture loss and demoulded after 24 hours (Figure 2). They were then cured in water at ambient laboratory temperature until the time for testing (7, 14, and 28 days). The experimental program evaluated fresh, mechanical, and durability properties of the concrete.



Figure 2. Sample preparation.

For each concrete mix and curing age, three specimens were prepared and tested, and the reported values represent the arithmetic average of the three measurements. Cube specimens of dimensions $150 \times 150 \times 150$ mm were used for compressive strength testing, cylindrical specimens measuring 150 mm diameter \times 300 mm height were used for split tensile strength testing, while prismatic beam specimens measuring $100 \times 100 \times 500$ mm were prepared for flexural strength testing.

2.4. Testing Procedures

Workability Test

The workability of fresh concrete was tested using the slump test in accordance with BS EN 12350-2:2019. The test measured the consistency and ease of placement of concrete. **Figure 3** shows the test setup.

Compressive Strength Test

The compressive strength tests were conducted in accordance with BS EN 12390-3:2019. Cube specimens were tested at curing ages of 7, 14, and 28 days using a compression testing machine. Each specimen was centrally positioned in the testing machine, and load was applied at a controlled rate of $0.6 \text{ MPa/s} \pm 0.2 \text{ MPa/s}$ until failure, as shown in **Figure 4**. The maximum load at failure was recorded, and the compressive strength was calculated using Equation (1).

$$f_c = \frac{P}{A} \quad (1)$$

where f_c is the compressive strength (MPa), P is the maximum load at failure (N), and A is the cross-sectional area of the specimen (mm^2).



Figure 3. Concrete workability test setup.



Figure 4. Experimental setup of compressive strength test.

Split Tensile Strength Test

The tensile strength of concrete was determined using the split-cylinder test in accordance with BS EN 12390-6: 2009. Cylindrical specimens were loaded diametrically in a compression testing machine until failure, as shown in **Figure 5**. The tensile strength was calculated based on the applied load and specimen dimensions.

Flexural strength testing was conducted in accordance with BS EN 12390-5:2019 using a third-point loading configuration. The beam specimens were simply supported and subjected to monotonic loading until failure. The maximum failure load was recorded and used to compute flexural strength.

Acid Resistance Test

Durability of the concrete was evaluated through acid attack tests based on BS 1881-124:1988. After a curing period of 28 days, specimens were immersed in pre-

pared sulphuric acid (H_2SO_4) and hydrochloric acid (HCl) solutions for a 24-hour exposure period. The extent of deterioration was assessed by measuring changes in weight after exposure, allowing evaluation of the resistance of the concrete mixes to aggressive chemical environments.



Figure 5. Experimental setup of tensile strength test.

3. Results and Discussion

Workability (Slump Test)

The slump test results revealed a clear influence of both superplasticizer (SP) and fly ash (FA) on the workability of PET-modified concrete, as presented in **Figure 6**. The control mix exhibited moderate workability, while the inclusion of 5% PET resulted in a reduction in slump. This reduction can be attributed to the irregular shape, low surface adhesion, and hydrophobic nature of PET particles, which increases internal friction and reduces cohesion within the mix.

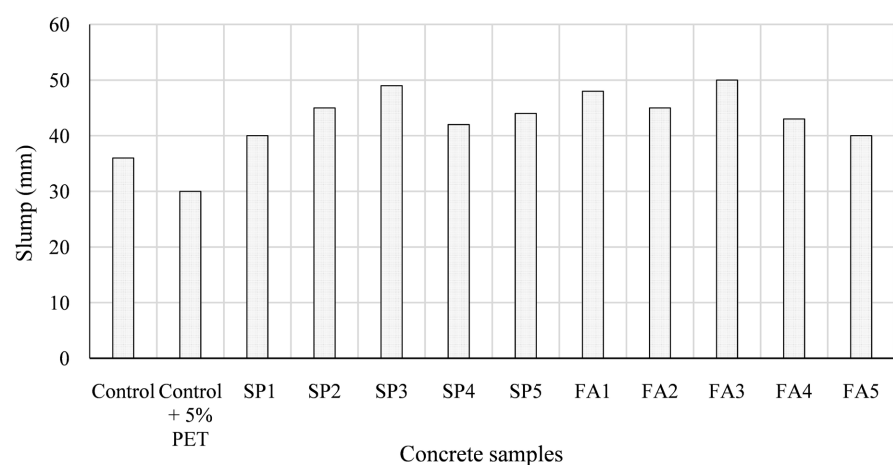


Figure 6. Workability test results.

The addition of superplasticizer significantly improved workability across all mixes. Slump values increased progressively with SP dosage, with the optimum

workability achieved at 3% SP. This behavior is consistent with the dispersing action of superplasticizers, which reduce particle agglomeration and improve flowability without increasing water content [16].

Similarly, the incorporation of fly ash enhanced workability due to its finer particle size and spherical morphology, which improves particle packing and reduces inter-particle friction. The optimum workability was observed at 3% FA, beyond which no significant improvement was recorded.

Overall, the results indicate that PET reduces workability; both SP and FA compensate for this effect. The combined use of SP and FA demonstrates a synergistic improvement in flowability, enabling PET-modified concrete to achieve acceptable workability without increasing water content.

Compressive Strength

The compressive strength results presented in **Figure 7** demonstrated that the inclusion of 5% PET alone led to a reduction in strength compared to the control mix. This is primarily due to the weak interfacial bond between plastic particles and the cement matrix. However, the addition of superplasticizer significantly enhanced compressive strength, with the highest values recorded at 4% SP after 28 days of curing. This improvement can be attributed to the reduced water-cement ratio without compromising workability and improved cement particle dispersion and hydration.

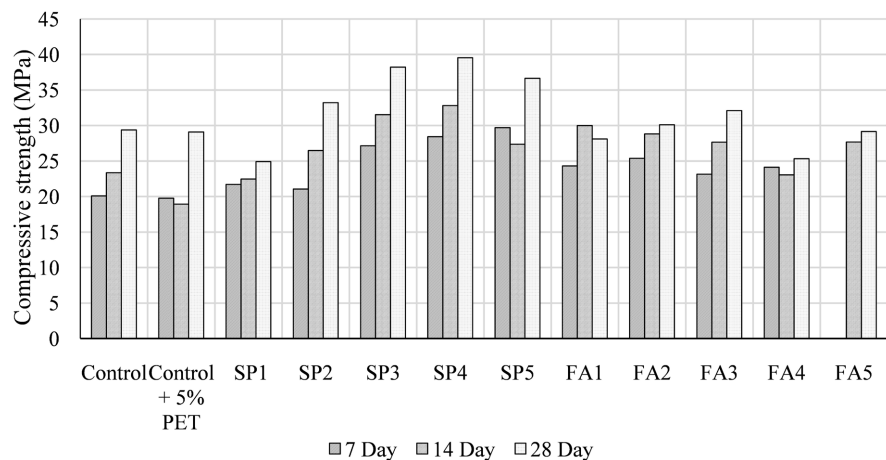


Figure 7. Compressive strength test results.

Similarly, fly ash incorporation enhanced compressive strength, with an optimum observed at 3% FA. The strength gain is linked to the pozzolanic reaction, where fly ash reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), leading to a denser and stronger microstructure. Additionally, the fine particles of fly ash fill voids within the matrix, further reducing porosity.

The combined SP4FA3 hybrid mix exhibited higher compressive strength compared to the individual SP-only and FA-only mixes, confirming the existence of synergistic interaction between fly ash geopolymers and superplasticizer. At 28 days, the hybrid mix achieved approximately 8% - 12% higher compressive strength

than the best-performing single-additive mix. This improvement demonstrates that the simultaneous enhancement of particle dispersion, matrix densification, and pozzolanic activity produced superior mechanical performance compared to isolated additive action.

Split Tensile Test

The tensile strength results in **Figure 8** followed trends similar to those observed in compressive strength, but with distinct optimal values. Concrete containing 5% PET alone exhibited reduced tensile strength due to poor bonding and stress concentration around plastic particles.

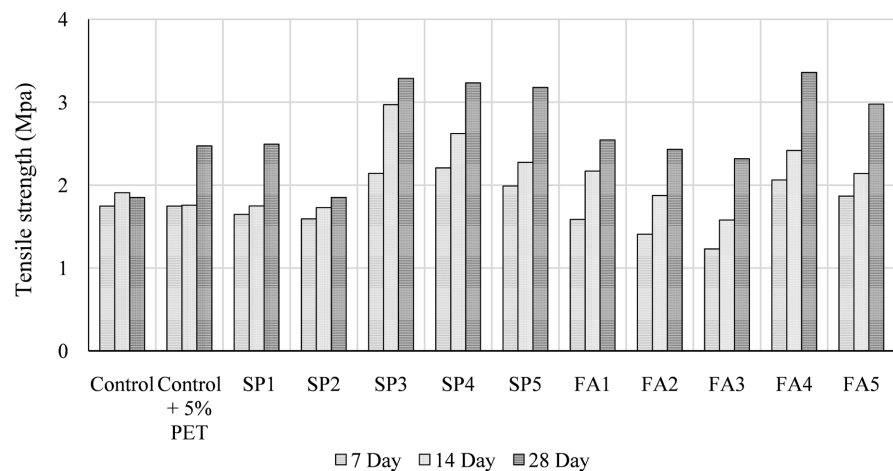


Figure 8. Tensile strength test.

The addition of superplasticizer improved tensile strength, with the optimum observed at 3% SP after 28 days. This improvement is attributed to enhanced compaction and reduced microvoids, which are critical factors in resisting tensile stresses.

Fly ash incorporation resulted in a slightly higher optimal value at 4% FA, indicating its stronger influence on tensile performance. The pozzolanic reaction and improved particle packing contribute to a more cohesive and crack-resistant matrix, thereby enhancing tensile capacity.

The notable difference in optimal percentages between SP and FA highlights their distinct mechanisms of action, where SP acts physically by improving workability and reducing voids while FA acts chemically by enhancing matrix densification and bonding. The hybrid SP4FA3 mix also produced superior tensile performance relative to individual additive systems, indicating that the combined admixture action improved crack resistance and interfacial transition zone integrity more effectively than single-modifier incorporation.

Flexural Strength

The flexural strength test measures the ability of a concrete specimen to resist bending or flexural stresses, which is crucial for understanding how concrete will perform in structures subjected to bending forces like beams, slabs, and pavements. Higher flexural strength indicates better resistance to cracking under load,

crucial for the longevity and maintenance of concrete structures.

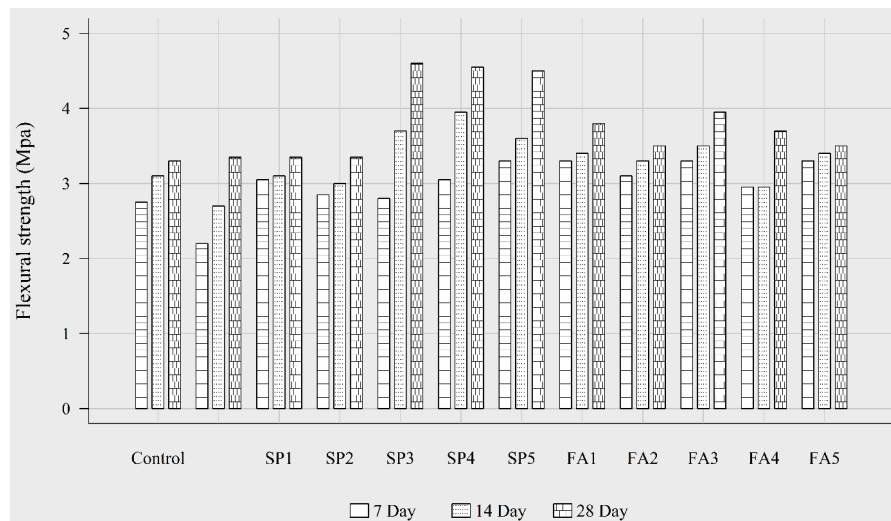


Figure 9. Flexural strength test.

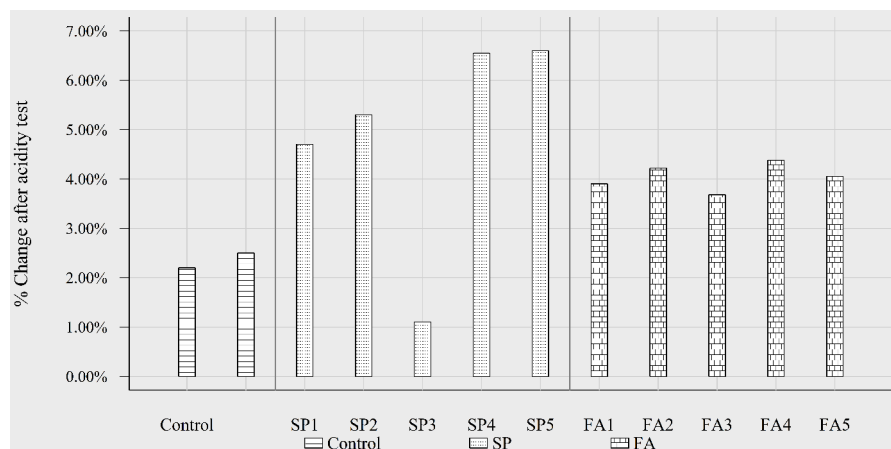


Figure 10. Acidity test results.

The flexural strength performances, as shown in **Figure 9**, reveal how the superplasticizer (SP) and fly ash geopolymer (FA) affect the bending behavior of PET-modified concrete. The introduction of 5 percent PET alone lowered the flexural strength compared to the control mix, owing to the low bonding force among plastic particles and cement matrix, which enhances the initiation of cracks under bending stresses. Nevertheless, flexural performance was greatly enhanced by the addition of superplasticizer, with the best results being reported at 4% SP after 28 days of curing. This advantage is linked with improved workability, improved dispersion of particles, and a reduction in internal voids, leading to a higher-density matrix. The flexural strength of fly ash geopolymer was enhanced by pozzolanic reactions and micro-filler effects, which enhanced the matrix cohesion and crack resistance. These results form the study objective of enhancing the mechanical performance of PET-modified concrete by synergistic use of fly ash geopolymer and superplasticizer.

Durability Performance

Durability performance is a critical property in determining the long-term serviceability of concrete in aggressive environmental conditions. This paper has tested the durability using the acid resistance test using the solutions of hydrochloric acid (HCl) and sulphuric acid (H₂SO₄). The test measured the percentage of change in the weight of the specimen after exposure, which is used to measure the degree to which the concrete matrix has deteriorated due to exposure to the chemical used. Introduction of PET plastic tends to make the concrete structure more vulnerable to the acid attack since the bonding is weaker and the porosity is higher. Nevertheless, fly ash geopolymer and superplasticizer enhanced the resistance to chemical degradation by increasing the densification of the matrix, decreasing the permeability, and reducing the connectivity of pores. Fly ash was useful in providing pozzolanic reactions, which formed further cementitious compounds, and superplasticizer enhanced compaction and water requirement. The durability results, therefore, illustrate the positive synergistic impact of geopolymer and superplasticizer on the resistance of the PET-modified concrete to the aggressive acidic conditions, in support of the development of sustainable and durable construction materials.

Acid Test

Durability performance was evaluated through acid resistance testing based on BS 1881-124:1988. After 28 days of curing, concrete specimens were immersed in 5% hydrochloric acid (HCl) and 5% sulphuric acid (H₂SO₄) solutions under laboratory ambient conditions for a continuous exposure duration of 24 hours. Three specimens were tested for each mix category, and the reported values represent the average percentage mass loss after exposure relative to the initial specimen mass. The specimens were removed after exposure, surface dried, and reweighed to determine the extent of deterioration caused by acid attack. Lower percentage mass loss indicated improved resistance to aggressive chemical environments and enhanced durability performance (**Figure 10**).

4. Conclusions

Although individual concrete properties exhibited slightly different optimum admixture dosages, the final hybrid mix recommendation was based on overall performance optimization, considering workability, compressive strength, tensile strength, flexural strength, and durability simultaneously rather than a single property criterion. The SP4FA3 hybrid mix was selected because it consistently provided balanced improvements across fresh, mechanical, and durability characteristics. The slight variation in optimum dosage between compressive and tensile performance is attributed to the different mechanisms governing load transfer and crack propagation. Superplasticizer primarily enhanced particle dispersion and compaction, while fly ash geopolymer contributed more significantly to long-term pozzolanic bonding and microstructural densification.

Although recycled PET plastic, fly ash geopolymers, and superplasticizers have all separately exhibited the potential in terms of concrete use, relatively little has been

done to investigate the interaction of these materials in a single concrete system. The study hence measured the synergistic actions of fly ash geopolymer and superplasticizer on PET-modified concrete with a plastic replacement of fine aggregate, 5%.

The results showed that the incorporation of PET alone decreased the workability, compressive strength, split tensile strength, flexural strength, and durability performance because of poor bonding and high porosity in the concrete matrix. Nevertheless, the introduction of superplasticizer had a significant positive influence on the workability and mechanical performance due to the improvement of the particle dispersion and the decrease in the amount of required water. Likewise, fly ash geopolymer enhances strength and durability by facilitating pozzolanic reactions, densification of the matrix, and reduction of pore spaces. Typical best results were observed when using 3 - 4 percent superplasticizer and fly ash content. The synergistic advantages of the combined use of fly ash geopolymer and superplasticizer were clearly demonstrated by the enhancement of fresh and hardened concrete properties, as well as increasing the resistance to acid attack.

The research concludes that fly ash geopolymer and superplasticizer can be effectively used to counter the negative effects of PET incorporation in concrete to achieve sustainable concrete with enhanced mechanical and durability properties. Recycled PET and fly ash are also used to eliminate wastage, conserve natural resources, and minimize environmental effects caused by traditional construction materials.

The study recommends encouraging sustainable concrete technologies that use recycled plastic waste and industrial by-products, using friendly environmental and construction policies. They should also come up with standards and guidelines that would govern the use of geopolymer-based and PET-modified concrete in structures. Future studies are recommended to be on long-term durability under various environmental conditions, microstructural study, optimization of geopolymer activators, and practical application of the technologies on a large scale to facilitate commercialization and field adoption of sustainable concrete technologies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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