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Experimental Investigation of Mechanical, Durability, and Impact Properties of Crumb Rubber Modified Fly Ash Geopolymer Concrete

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Abstract

The high carbon dioxide emissions associated with Ordinary Portland Cement (OPC) production have intensified the need for sustainable alternatives in the construction industry. This study investigates the mechanical, durability, and impact performance of crumb rubber-modified fly ash-based geopolymer concrete (RGPC) as an eco-friendly material for structural applications. Crumb rubber was incorporated as a partial replacement for the coarse aggregate at proportions of 0%, 5%, 10%, 15%, 20%, 25%, and 50% by weight of the coarse aggregate. Concrete specimens were prepared and cured under ambient conditions, and tested at 3, 7, 14, 28, and 56 days. The experimental tests included slump, compressive strength, impact resistance (drop-weight test), and durability under sulphuric acid exposure. The results indicate that workability increased with increasing crumb rubber content, with slump values rising from 15 mm for the control mix to 55 mm at 50% replacement. Compressive strength improved with curing age for all mixes; however, optimum performance was observed at 5 - 10% crumb rubber content. At 56 days, the 10% replacement achieved a compressive strength of 31.67 N/mm^2, comparable to the control (31.50 N/mm^2), while higher replacement levels ($\geqslant$20%) resulted in significant strength reductions of up to 39%. Impact resistance increased with curing age but decreased with increasing rubber content, although the 5% replacement exhibited relatively improved energy absorption at intermediate ages. Durability results showed that low crumb rubber content (5–10%) enhanced resistance to sulfuric acid attack, reducing strength loss compared to the control, whereas higher contents led to increased porosity and deterioration. In conclusion, the incorporation of crumb rubber in fly ash-based geopolymer concrete improves workability and can enhance durability and impact performance at low replacement levels. An optimum crumb rubber content of 5–10% is recommended to be used in the production of concrete.

Keywords: Compressive Strength; Crumb Rubber; Durability; Fly Ash; Geopolymer Concrete; Impact Resistance

1. Introduction

Concrete is among the most widely used construction materials globally. However, Portland cement, one of its primary constituents, is not environmentally sustainable, as its production generates significant greenhouse gas emissions and contributes to global warming [1]. The production of Ordinary Portland cement is, in fact, a major contributor to climate change, as it produces one tonne of CO2 for every tonne produced [2]. Replacing traditional Portland cement (OPC) with crumb rubber in fly ash-based geopolymer mortar or concrete can reduce both waste tyre disposal and the demand for natural mineral aggregates, thereby contributing to lower CO_2 emissions. Geopolymer concrete is increasingly recognized as a sustainable substitute for conventional concrete because of its ability to significantly reduce the environmental burden associated with cement production. At the same time, many industrial

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wastes, if not properly managed, create serious ecological problems. Waste rubber is one such material of concern, since its burning produces hazardous emissions that negatively affect human health and the environment [3].

Geopolymer is an alternative binder to Ordinary Portland Cement (OPC) in the construction industry. It is produced by activating silica (Si) and alumina (Al) rich source materials using alkaline solutions. The production of tyres continues to increase annually, and due to their non-biodegradable nature, their disposal poses significant environmental challenges. In the present context, waste materials should be reused or recycled in order to conserve natural resources while simultaneously protecting the environment [4]. Crumb rubber geopolymer concrete or mortar is produced through the activation of Class F fly ash using alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), which leads to the formation of an aluminosilicate gel responsible for strength development [5].

Fly ash is a lightweight powder rich in silica and alumina generated as a by-product when coal is burned [6]. A report by [7] indicated that in Nigeria, 2 million metric tons of fly ash is produced annually, which could be recyclable toward green construction. By recycling these tires to crumb rubber, it provides two solutions as it generates a lightweight aggregate material that is reported to enhance concrete ductility and impact resistance [8]. Research has demonstrated that the addition of crumb rubber enhances the ability for impact absorption as well as results in lighter geopolymer concrete [9]. Although several studies have investigated the incorporation of crumb rubber in geopolymer concrete, the majority have focused primarily on compressive strength and workability, with limited consideration of durability and impact performance [1, 5]. Furthermore, most existing studies have been conducted under controlled laboratory conditions or elevated-temperature curing regimes, which may not adequately represent field conditions in tropical regions such as Nigeria [3]. While previous researchers have reported the influence of crumb rubber on the mechanical properties of geopolymer concrete [10], there remains insufficient information on the combined effects of crumb rubber on compressive strength, impact resistance, and durability under sulphuric acid exposure. In addition, studies evaluating crumb rubber-modified geopolymer concrete produced from materials readily available in Nigeria are scarce. Consequently, the optimum crumb rubber content required to achieve a balance between mechanical performance, durability, and impact resistance under ambient curing conditions remains unclear. The novelty of this research lies in the integrated assessment of strength development, impact energy absorption, sulphuric acid resistance, and weight-loss characteristics to establish an optimum crumb rubber replacement level suitable for sustainable construction applications in Nigeria.

A report by [11] on evaluation of geopolymer concrete based on Fly ash containing steel fibers and rubber crumbs using cement as a partial substitute for Fly ash, indicated that the addition of fibres resulted in a significant improvement in mechanical properties. Incorporating 0.5% fibres increased the compressive strength by approximately 9%, while 1% fibre content led to a higher increase of about 26%. Similarly, tensile strength showed substantial enhancement with fibre inclusion. On average, the addition of 0.5% fibres improved tensile strength by about 25%, whereas 1% fibres resulted in an increase of up to 34%. A study by [4] indicated that the compressive strength decreases as the content of crumb rubber increases. The highest compressive strength of 39.6 MPa was recorded at 5% rubber crumb replacement after 28 days of exposure to seawater. In addition, the density of the geopolymer samples increased for all mixes following immersion in seawater. A study carried out on the effect of crumb rubber on compressive strength of fly ash based geopolymer concrete by [10] indicated that there is a reduction in all compressive strength for crumb rubber mixture, but still higher than normal rubberized concrete. Rubberized geopolymer concrete is a suitable solution in some non-structural applications. A research by [3] identifies an optimal CR fraction of 6% as volume replacement of fine aggregate. At an Alkaline Liquid Ratio of 2.5 and a curing temperature of 100°C, it achieves a 28-day compressive strength of 33 MPa and 35.2 MPa, respectively, for 14M and 16M NaOH solutions. The obtained results by [12] were calculated and analyzed, revealing a reduction in strength parameters with increasing crumb rubber content.

Within the range of 5% to 25% replacement, the mix containing 15% crumb rubber was identified as the optimum geopolymer composition when compared with conventional Portland cement concrete. Effects of tyre derived aggregate (TDA) as partial replacement of coarse aggregate in concrete were investigated by [13] and found that the compressive strength of TDA-concrete decreased progressively with an increase in the percentage proportion of TDA content. A study conducted by [14] indicated that increasing the granular activator content beyond 12% by weight of fly ash slightly reduces both the

strength and workability of one-part geopolymer cement pastes. The optimum mix was identified at 12% by weight of fly ash, corresponding to 6% Na_2O, after 28 days of curing. According to [15], experimental investigations showed that the mechanical properties of the OPAAM decreased as the proportion of recycled plastic aggregate (RPA) in the mixture increased. At 28 days, both the control mix and the mixture containing 10% plastic aggregate recorded the highest compressive strength of approximately 46 MPa, compared with the other mixtures. Rubberized Geopolymer Concrete (RGPC) is a potential sustainable material for the Nigerian construction sector, but the deployment of the two-phase concrete technology is curbed by the urgent need to evaluate its structural performance under impact loads and its chemical response to aggressive environments. Despite existing studies on rubberized concrete, there remains a lack of comprehensive evaluation of its performance, particularly under impact loading and aggressive environments within the Nigerian context.
Therefore, this study investigates the mechanical, durability, and impact properties of crumb rubber-modified fly ash-based geopolymer concrete under ambient curing conditions.

2. Materials and Methods

Materials used in this study are Fine Aggregate, Coarse Aggregate, Fly Ash, Crumb Rubber, Sodium Hydroxide (NaOH), Sodium Silicate (Na_2SiO_3) and Water.

2.1 Fly Ash

Fly ash, an alumino-silicate source, was sourced from Lagos industrial waste in Nigeria

2.2 Coarse Aggregate

Crushed granite with a maximum nominal particle size of 20 mm was sourced from a quarry opposite the Nigeria College of Aviation Technology (NCAT), Zaria.

2.3 Fine Aggregate

The Fine aggregate, as one of the aggregates used in the study, was sourced from Shika Dam, Zaria.

2.4 Alkali Activator

The Stevemore Chemical Suppliers Emanto, located along Samaru Road, Zaria, was the source of Alkali Activator (sodium hydroxide and sodium silicate).

2.5 Crumb Rubber

The crumb rubber was sourced from Waste Tire within Zaria.

2.6 Water

The water used in this research was obtained from the Department of Civil Engineering, Ahmadu Bello University, Zaria.

2.7 Methods

2.7.1 Geopolymer Concrete Preparation

The preparation of Rubberized Geopolymer Concrete (RGPC) specimens was conducted using a systematic laboratory procedure to ensure consistency and accuracy of results. The alkali activator solution was prepared 24 hours before mixing to allow complete dissolution of its constituents and to promote effective geopolymerization.

The dry materials, including fly ash, fine and coarse aggregates, and crumb rubber (used as a lightweight aggregate), were batched by weight according to the trial mix proportions and thoroughly mixed to achieve a uniform distribution. The pre-prepared alkali activator solution and the required amount of water were then added to the dry mixture in accordance with the mix design, followed by continuous mixing until a homogeneous and workable paste was obtained.

The fresh geopolymer concrete was cast into moulds of the required dimensions for subsequent mechanical and durability testing. After initial setting, the specimens were demoulded and cured at ambient laboratory temperature to simulate practical field conditions. The hardened samples were subsequently tested for compressive strength, durability, and impact resistance in accordance with the relevant standard procedures.

2.7.2 Workability (Slump)

The slump test performed on fresh concrete was carried out in accordance with BS 1881:102 (1983) [16].

2.7.3 Compressive Strength

The compressive strength of rubberized fly ash based geopolymer concrete at different replacement levels was determined in accordance with [17]. Cube specimens measuring 100 mm × 100 mm × 100 mm were prepared, with three specimens produced for each mix proportion. The samples were cured under ambient conditions for 3, 7, 14, 28, and 56 days, after which testing was carried out using an Avery Denison Universal Testing Machine.

2.7.4 Durability

The durability of rubberized fly ash-based geopolymer concrete at varying replacement levels was assessed using 100 mm × 100 mm × 100 mm cube specimens, with three specimens prepared for each mix proportion in accordance with [18]. The test was conducted to evaluate the specimens' resistance to chemical attack. The cured specimens were fully immersed in a 10% H_2SO_4 solution for 7 days under ambient laboratory conditions. The specimens remained completely submerged throughout the exposure period. After exposure, they were removed, washed with clean water, surface-dried, and tested for weight loss and residual compressive strength to assess their resistance to acid attack.

2.7.5 Impact Resistance

Impact resistance was determined using the drop weight test. Cylindrical specimens measuring 152 mm × 63.5 mm were prepared at different crumb rubber replacement levels in accordance with [19] to evaluate the energy absorption capacity of the rubberized geopolymer concrete.

2.7.6. Mix Proportion

Table 1 presents the mix proportions adopted for the production of Rubberized Geopolymer Concrete (RGPC) containing varying levels of crumb rubber replacement. The mix proportions were developed using the Absolute Volume Method, and crumb rubber was used to replace coarse aggregate at replacement levels of 0%, 5%, 10%, 15%, 20%, 25%, and 50%. To adequately evaluate the influence of crumb rubber on the properties of the geopolymer concrete, the alkaline liquid-to-fly ash (AL/FA) ratio, sodium silicate-to-sodium hydroxide (Na_2SiO_3/NaOH) ratio, NaOH molarity, fly ash content, water content, and fine aggregate content were maintained constant for all mixtures.

Table 1: Mix Proportions of RGPC Mixtures

Percentage (%)	**0**	**5**	**10**	**15**	**20**	**25**	**50**
AL/FA Ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Na_2SiO_3/NaOH Ratio	2.25	2.25	2.25	2.25	2.25	2.25	2.25
NaOH Molarity (M)	12	12	12	12	12	12	12
Fly Ash (kg/m^3)	342.80	342.80	342.80	342.80	342.80	342.80	342.80
Na_2SiO_3 (kg/m^3)	108.60	108.60	108.60	108.60	108.60	108.60	108.60
NaOH (kg/m^3)	48.57	48.57	48.57	48.57	48.57	48.57	48.57
Water (kg/m^3)	54.29	54.29	54.29	54.29	54.29	54.29	54.29
Fine Aggregate (kg/m^3)	761.90	761.90	761.90	761.90	761.90	761.90	761.90
Coarse Aggregate (kg/m^3)	1324.80	1258.60	1192.30	1126.10	1059.80	993.50	662.40

Percentage (%)	**0**	**5**	**10**	**15**	**20**	**25**	**50**
Crumb Rubber (kg/m³)	0.00	66.24	132.48	198.72	264.96	331.20	662.40

3. Results and Discussions

3.1 Chemical Composition (XRF) of Fly Ash

Table 2 shows that the fly ash is predominantly composed of SiO_2 (68.12%), with smaller amounts of Al_2O_3 (3.539%) and Fe_2O_3 (3.529%). The combined content of these three major oxides is 75.188%, which exceeds the 70% minimum requirement of ASTM C618 for Class F fly ash. This indicates strong pozzolanic characteristics and suitability for use as a supplementary cementitious material in concrete and geopolymer production. The negligible amounts of CaO, MgO, Na_2O, K_2O, and SO_3 classify the material as a low-calcium (Class F) fly ash, which is known for enhanced long-term strength development and improved resistance to sulfate attack and alkali-silica reactions.

Table 2: Chemical Composition (XRF) of Fly Ash

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Total (S+A+F)
Percentage (%)	68.120	3.539	3.529	-	-	-	-	-	75.188

3.2 Workability (Slump)

As shown in Figure 1, the workability of rubberized geopolymer concrete increased with increasing crumb rubber content, in agreement with the findings of [20]. The control mix with 0% crumb rubber exhibited a slump of 15 mm, indicating a very low or stiff consistency. However, at 50% replacement, the slump value increased to 55 mm, reflecting high workability. This enhancement can be attributed to the hydrophobic nature of rubber particles, which limits their absorption of the alkaline activator, thereby increasing the availability of free liquid in the mix and improving particle lubrication, as noted by [21].

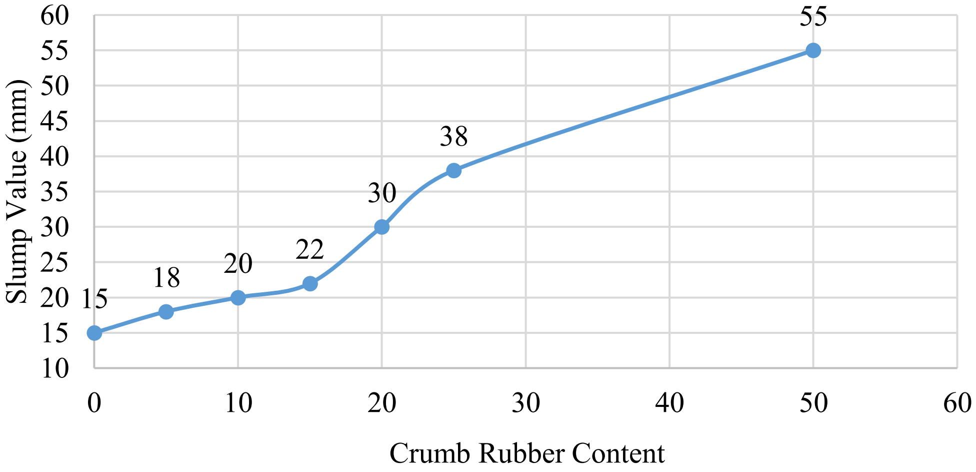

Figure 1: Slump against Crumb Rubber Replacement (%)

3.3 Compressive Strength

Figure 2 illustrates the variation in compressive strength of geopolymer concrete with different crumb rubber (CR) replacement levels and curing ages. In general, compressive strength increased with curing age for all mixes, reflecting continued geopolymerization and progressive densification of the matrix. The control mix (0% CR) showed a steady strength gain from 16.83 N/mm² at 3 days to 31.50 N/mm² at 56 days, representing an increase of about 87.2%. At 5% CR content, the compressive strength exceeded that of the control at early ages, with increases of approximately 7.0%, 2.2%, and 9.2% at 3, 7, and 14 days, respectively. However, at later ages, reductions of about 14% and 12.2% were observed at 28 and 56 days, indicating that while low CR content enhances early strength development, it may slightly reduce long-term strength. For the 10% CR mix, the compressive strength was marginally lower than the control at 3 days by 3.6%, but showed slight improvements at later ages, with increases of 2.9% at 7 days, 4.8% at 14 days, and 0.5% at 56 days. At 28 days, the strength was nearly identical to the control. This suggests that 10% CR provides performance comparable to the control mix. At 15% CR content, a reduction of about 7.3% was observed at 3 days, followed by notable increases at 7 and 14 days of 12.1% and 16.7%, respectively. However, strength declined again at 28 and 56 days by 5.3% and 6.9%. At higher replacement levels of 20%, 25%, and 50%, compressive strength consistently decreased at all curing ages. For example, at 20% CR, reductions of 15.4% at 3 days and 13.2% at 56 days were recorded. At 25% CR, reductions ranged from 19.8% to 28.6%, while the 50% CR mix showed the most significant losses, with decreases of 42.4% at 3 days and 39% at 56 days. The reduction in compressive strength observed at higher crumb rubber replacement levels can be attributed to the increased porosity introduced into the geopolymer matrix and the relatively weak interfacial bond between the rubber particles and the surrounding binder. As the rubber content increases, more voids and micro cracks are created within the matrix, resulting in a less dense internal structure and reduced load-transfer efficiency. Finally, the results indicate that compressive strength increases with curing age regardless of mix composition but is significantly influenced by crumb rubber content. An optimum replacement level of 5% to 10% is recommended, beyond which the structural performance of the geopolymer concrete is adversely affected.

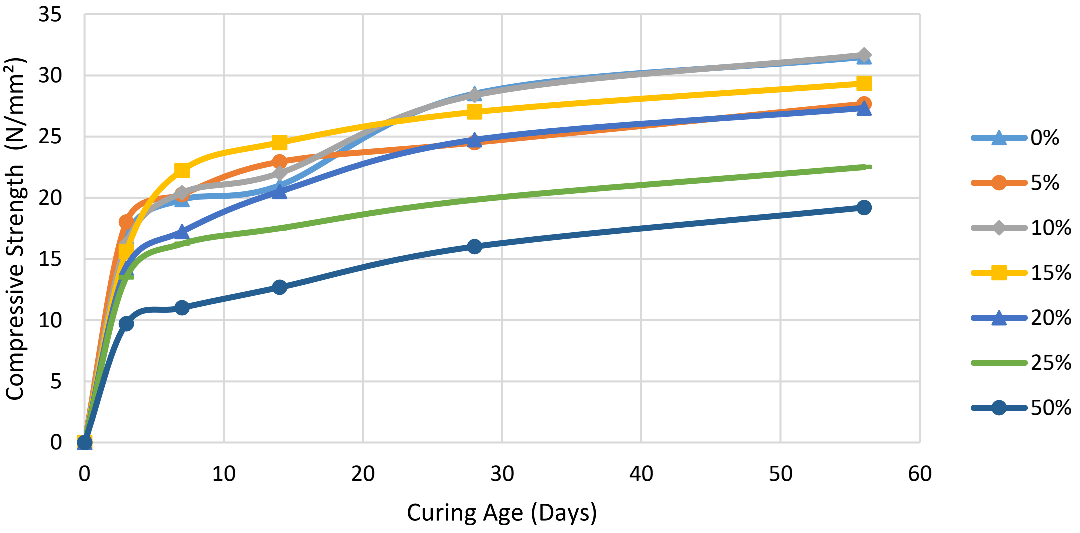

Figure 2: Relationship between Compressive Strength and Percentage Replacement

3.4 Impact Resistance

Figure 3 illustrates the variation of mean impact energy at ultimate failure for different crumb rubber (CR) replacement levels and curing ages. Generally, impact energy increased with curing age for all mixes, reflecting the progressive development of the geopolymer matrix and improved energy absorption capacity over time. The control mix (0% CR) exhibited a steady increase in impact energy from 291.93 J at 3 days to 794.7 J at 56 days, representing an overall increase of approximately 172%. At 5% CR content, the impact energy was slightly lower than the control at 3 days by about 13.8%. However, at 7 and 14 days, the values surpassed the control by approximately 14% and 9.1%, respectively, indicating enhanced performance at intermediate ages. At later ages (28 and 56 days), reductions of 11.4% and 6.7% were observed compared to the control, suggesting that low CR content improves early energy absorption but slightly reduces long term performance. For the 10% CR mix, a consistent reduction in impact energy was recorded at all curing ages, ranging from 22.6% at 3 days to 34.9% at 56 days. At 15% CR content, the impact energy was nearly equal to the control at 3 days, with a marginal decrease of 0.8%, but declined progressively with age, reaching about 44.5% reduction at 56 days. Similar trends were observed for 20% and 25% CR contents, where substantial reductions were recorded across all curing periods. For instance, at 20% replacement, the reduction ranged from 25%

at 3 days to 51.8% at 56 days, while at 25% replacement, it reached up to 56.2% at 56 days. The 50% CR mix exhibited the lowest performance at early ages, with a reduction of 41.4% at 3 days. Although slight improvements were observed with curing time, the impact energy remained significantly lower than that of the control, with a reduction of approximately 47.4% at 56 days. In conclusion, the results indicate that impact energy increases with curing age for all mixes, but decreases with increasing crumb rubber content. The 5% CR mix demonstrated relatively better performance, particularly at intermediate ages, suggesting that it represents an optimum level for maintaining impact resistance.

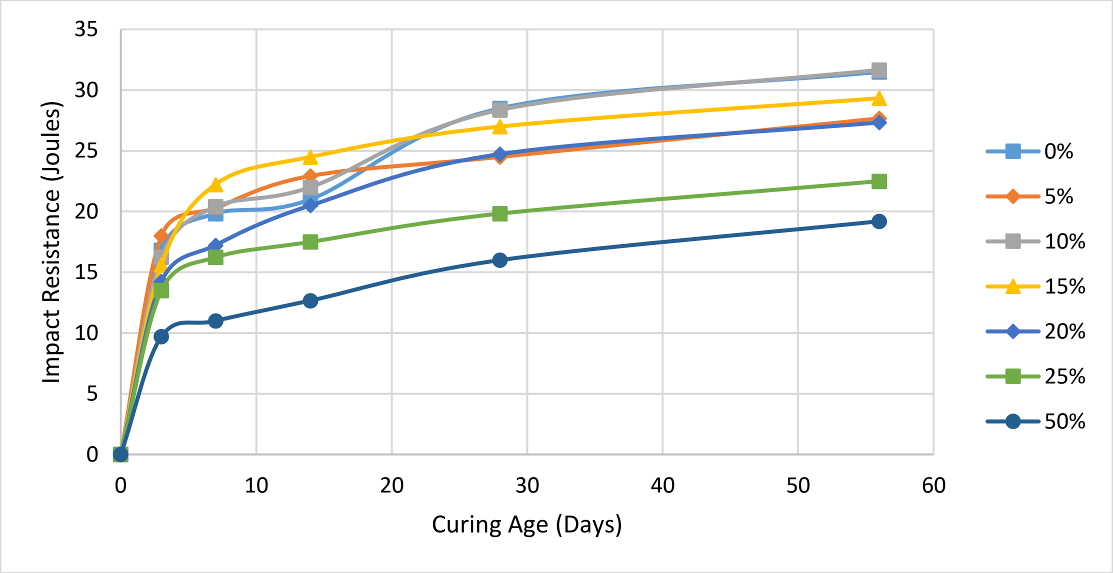

Figure 3: Relationship between Impact Resistance and Percentage of CR Content

3.5 Density of Geopolymer Concrete

Table 3 showed the density of geopolymer concrete produced with crumb rubber. The density of rubberized fly ash based geopolymer concrete decreased with increasing crumb rubber content, primarily due to the lower specific gravity of rubber compared to conventional aggregates. Across all curing ages, density values showed minimal variation, indicating that curing time has little influence on density. Slight increases observed at later ages can be attributed to ongoing geopolymerization and matrix densification, which reduce internal porosity. However, [14] reported that the density of one part geopolymer paste remains nearly constant across different mix proportions. The minor fluctuations recorded in this study may be associated with experimental variability and particle packing effects.

Table 3: Density of Geopolymer Concrete

Crumb Rubber Content (%)	**3 Days (kg/m^3)**	**7 Days (kg/m^3)**	**14 Days (kg/m^3)**	**28 Days (kg/m^3)**	**56 Days (kg/m^3)**
0% CR	2750	2760	2750	2760	2750
5% CR	2620	2630	2640	2730	2730
10% CR	2580	2590	2570	2700	2700
15% CR	2480	2550	2520	2660	2660
20% CR	2530	2540	2540	2550	2550
25% CR	2490	2470	2480	2480	2490
50% CR	2340	2350	2360	2360	2360

3.6 Durability: Resistance to Sulfuric Acid

Figure 4 presents the relationship between residual compressive strength and crumb rubber (CR) content in geopolymer concrete. A slight improvement in residual strength was observed at low replacement levels of 5% and 10% CR, followed by a progressive decrease as the CR content increased. At 5% replacement, the strength increased by approximately 3.94% compared to the control, representing the optimum performance and suggesting enhanced resistance to chemical attack. Similarly, at 10% CR content, the residual strength remained slightly higher than the control, with an increase of about 1.55%, indicating that the 5–10% range provides a buffering effect against acid degradation. However, beyond 10% CR content, a significant reduction in residual strength was observed. At 15%, 20%, and 25% replacement levels, the strength decreased by approximately 7.68%, 24.76%, and 39.15%, respectively. The most severe reduction was recorded at 50% CR content, where the residual strength dropped to 10.43 N/mm², corresponding to a decrease of about 56.23% compared to the control mix.These results indicate that low levels of crumb rubber can enhance or maintain durability under chemical attack, while higher replacement levels adversely affect durability. The deterioration at higher CR contents is likely due to increased porosity and weaker bonding within the matrix, which facilitate acid ingress and accelerate degradation, in agreement with findings reported by [6].

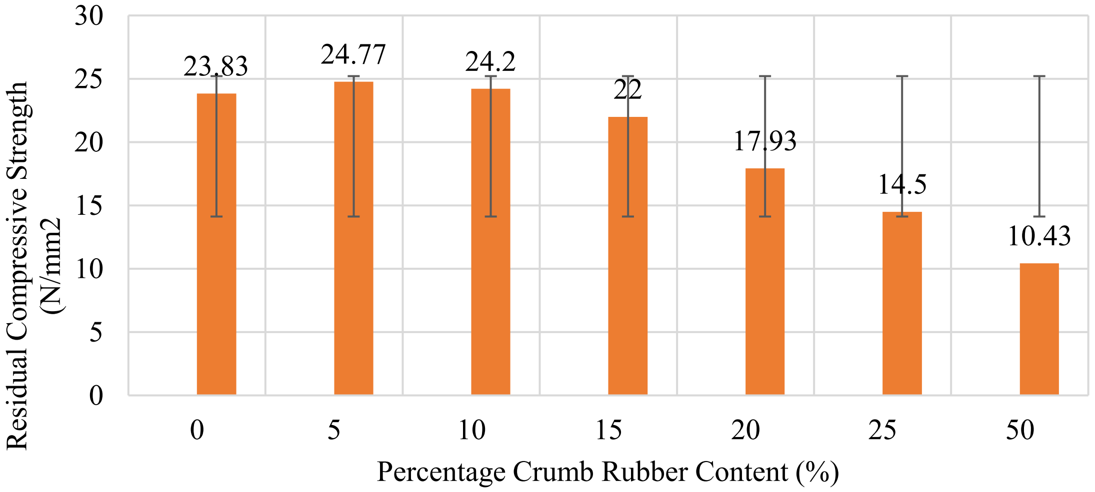

Figure 4: Relationship between Residual Compressive Strength and CR Content

3.7 Percentage Weight Loss

The results of percentage weight loss of geopolymer concrete containing crumb rubber (CR) under acidic exposure are presented in the Figure 5. At lower replacement levels (0–10%), the weight loss gradually decreased from 16.39% at 0% CR to 10.37% at 10% CR, indicating improved resistance to material degradation. This behaviour suggests that a small quantity of crumb rubber enhances the integrity of the concrete matrix. The improvement may be attributed to increased energy absorption capacity and reduced brittleness, which help to limit microcrack formation and slow crack propagation. However, beyond 10% CR content, a reverse trend was observed. At 15% replacement, the weight loss increased to 13.73%, followed by a sharp rise to 27.5% at 20% CR. A similarly high value of 26.88% was recorded at 25% CR, with the maximum weight loss of 34.81% occurring at 50% replacement. This significant increase at higher CR contents indicates a deterioration in durability performance. The increased weight loss at higher crumb rubber contents can be attributed to weaker interfacial bonding between rubber particles and the geopolymer matrix, increased porosity and void formation, and the hydrophobic nature of rubber, which reduces adhesion within the matrix and facilitates easier penetration of aggressive agents.

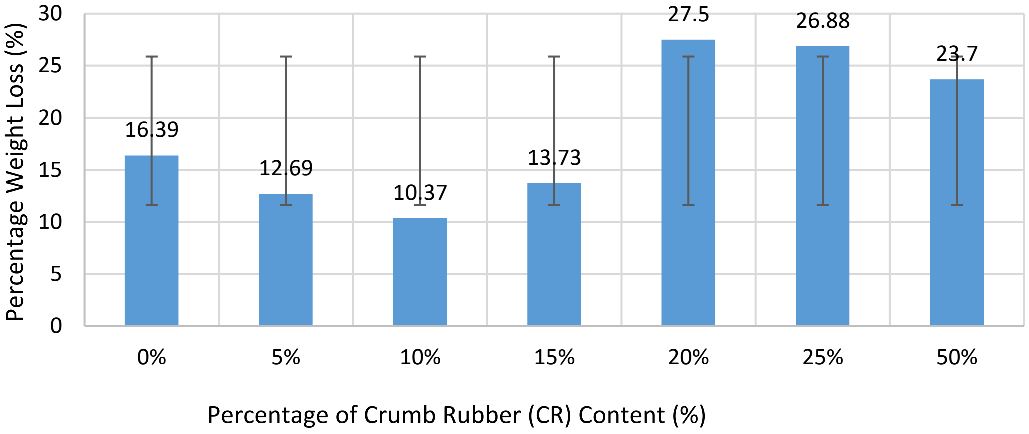

Figure 5: Percentage Weight Loss against CR Content

4. Conclusions

The following conclusions can be made from the results of this study:

i. The incorporation of crumb rubber significantly improved the workability of the geopolymer concrete, with slump values increasing from 15 mm for the control mix to 55 mm at higher replacement levels.

ii. The compressive strength was influenced by both crumb rubber content and curing age, with an optimum value of 31.67 N/mm² achieved at 10 % replacement and 56 days curing, while higher rubber contents led to strength reduction.

iii. The inclusion of crumb rubber enhanced the impact resistance and energy absorption capacity of the geopolymer concrete. The highest impact energy of 735.08 J was recorded at 5% crumb rubber replacement, demonstrating the ability of rubber particles to improve toughness and resistance to sudden loading.

iv. The resistance of rubberized geopolymer concrete to acidic environments decreased with increasing crumb rubber content, indicating that higher levels of crumb rubber adversely affected durability performance under acid exposure.

v. The density of the geopolymer concrete decreased progressively with increasing crumb rubber content due to the lower specific gravity of crumb rubber compared with conventional coarse aggregate. This reduction in density indicates the potential of crumb rubber for producing lightweight geopolymer concrete.

vi. It was concluded that rubberized fly ash-based geopolymer concrete demonstrates strong potential as a sustainable construction material, offering improved energy absorption while utilizing industrial waste.

Competing Interests

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

Data Availability Statement: The supported data associated with this researcher is available upon request from the corresponding author.

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