

Article

Stress–Strain Relationship of Rubberized Geopolymer Concrete with Slag and Fly Ash

Sunday U. Azunna ^{1,*} , Farah N. A. A. Aziz ^{1,*} , Raizal S. M. Rashid ²  and Ernaleza B. Mahsum ¹¹ Housing Research Centre, Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia (UPM), Serdang 43400, Selangor, Malaysia² Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia (UPM), Serdang 43400, Selangor, Malaysia

* Correspondence: gs67063@student.upm.edu.my (S.U.A.); farah@upm.edu.my (F.N.A.A.A.)

Abstract

Rubberized concrete is a more environmentally friendly material than natural concrete as it helps to reduce rubber disposal issues and has superior impact resistance. Geopolymer concrete, on the other hand, is an economical concrete with higher mechanical properties than nominal concrete that uses fly ash and slag, among other industrial solid wastes, to lower carbon footprints. Rubberized geopolymer concrete (RuGPC) combines the advantages of both concrete types, and a thorough grasp of its dynamic compressive characteristics is necessary for its use in components linked to impact resistance. Despite the advantages of RuGPC, predicting its mechanical characteristics is sometimes difficult because of variations in binder type and combination. This research investigated the combined effect of ground granulated blast furnace slag (GGBFS) and fly ash (FA) on the workability, compressive strength, and stress–strain characteristics of RuGPC with rubber at 0%, 10%, and 20% fine aggregate replacement. Thereafter, energy absorption and ductile characteristics were evaluated through the concrete toughness and ductility index. Numerical models were proposed for the cube compressive strength, modulus of elasticity, and peak strain of RuGPC at different percentages of crumb rubber. It was found that RuGPC made with GGBFS/FA had similar stress–strain characteristics to FA- and MK-based RuGPC. At 20% of crumb rubber aggregate replacement, the workability, compressive strength, modulus of elasticity, and peak stress of RuGPC reduced by 8.33%, 34.67%, 43.42%, and 44.97%, while Poisson's ratio, peak, and ultimate strain increased by 30.34%, 8.56%, and 55.84%, respectively. The concrete toughness and ductility index increased by 22.4% and 156.67%. The proposed model's calculated results, with R^2 values of 0.9508, 0.9935, and 0.9762, show high consistency with the experimental data. RuGPC demonstrates high energy absorption capacity, making it a suitable construction material for structures requiring high-impact resistance.

Keywords: crumb rubber; rubberized geopolymer concrete; stress–strain relationship; modulus of elasticity; energy absorption capacity



Received: 16 May 2025
Revised: 11 June 2025
Accepted: 17 June 2025
Published: 25 June 2025

Citation: Azunna, S.U.; Aziz, F.N.A.A.; Rashid, R.S.M.; Mahsum, E.B. Stress–Strain Relationship of Rubberized Geopolymer Concrete with Slag and Fly Ash. *Constr. Mater.* **2025**, *5*, 42. <https://doi.org/10.3390/constrmater5030042>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The worldwide production of car tires is continually increasing due to growing demand. But it also leads to the common problem of old tires being disposed of in landfills [1]. By 2030, there could be a potential rise in the yearly accumulation of abandoned tires from the current estimate of 1000 million [2]. Tires submerged in the wet soils of landfills

expose the surrounding ecosystem to dangers from heavy metals and other toxins, causing poisons to leak into groundwater, worsening this issue even more [3]. Given the increasing threat to the environment, the use of rubberized concrete for the construction of structural elements is becoming a key area of interest [4,5]. This entails incorporating crumb rubber (CR), derived from truck and car waste tires, into mixtures for concrete. Over the past few years, investigating the usage of rubber waste has shown a clear trend, especially after it is subjected to treatment and used in place of nominal aggregates such as river sand [6]. Consequently, employing crumb rubber in producing concrete is a greener way to lessen the influence on the environment by disposing of tires and reducing the loss of natural resources [7].

Many studies have explored the application of CR in concrete extensively, with an emphasis on the mechanical characteristics [8–10]. However, almost all report a reduction in the mechanical properties of concrete with CR additions. The mix is affected by the type, size, treatments, and quantity of the rubber aggregate used in it. For example, Osama et al. [11] reported a 9% to 20% reduction in compressive strength resulting from 20% replacement of fine aggregate with rubber. Oppositely, Khaloo et al. [12], found that rubberized concrete with 25% fine rubber replacement possesses a workability and compressive strength within acceptable limits.

To minimize the reduction in strength of rubberized concrete (RuC), pre-treating rubber aggregates has shown to be a successful strategy, and researchers have investigated several techniques to improve rubberized concrete compressive strength [8,13–15]. According to an experimental investigation, chemically treated waste rubber exhibited better mechanical characteristics and adhesion than untreated rubber aggregates in rubberized concrete [16]. According to Pham et al. [17], one of the main factors influencing the better adherence of rubber aggregates to other concrete constituents was pre-treating rubber with NaOH. Because pre-treatment has a major impact on how well rubber aggregates adhere to the geopolymer matrix, it is therefore a crucial step in the production of concrete [17–20]. Khalid Battal Najim [21] investigated the effects of several rubber aggregate pre-treatment techniques experimentally, such as pre-coating with mortar and cement matrix, washing with water, and treating with NaOH. By employing a NaOH solution, Raghavan [22] was able to create rubber concrete with high strength successfully.

Furthermore, researchers are still very interested in learning more about the modulus of elasticity (MoE) of rubberized concrete. The MoE of rubberized concrete is found to decrease with an increase in the percentage replacement of rubber aggregates [23–25]. Zheng et al. [26] previously reported that replacing 15% to 45% of the naturally occurring coarse aggregate with crumb and crushed rubber aggregates resulted in a drop in MoE of 5.7% to 28.6% and 16.5% to 25%, respectively. According to Li et al. [25], a 10% rubber crumb concentration was associated with a 41.9% drop in the value of MoE. Another investigation by Xie et al. [24], which used recycled aggregates as coarse aggregates, found that replacing 16% of the fine aggregates with rubber resulted in a 56.3% decrease in MoE. Considering the range of research findings, it is difficult to accurately establish a link between MoE and the amount of rubber in concrete.

A lot is yet to be understood about the elasticity modulus of RuGPC, which is dependent on the stress–strain relationship. According to Luhar et al. [27], when the amount of rubber in RuGPC increased, the elasticity modulus fell. This report also agrees with that of Dong et al. [18]. To date, the stress–strain behavior of RuGPC has not been satisfactorily confirmed by the existing experimental results. According to the findings, RuC, GPC, and RuGPC display stress–strain characteristics different from that of normal concrete [28–30]. The stress–strain relationship of GPC, made with a combination of fly ash and GGBFS at 570 to 620 kg/m³, with an alumina activator solution with a fineness modulus ranging from 0.75

to 1.5 and heat-cured for 48 h at 50 °C, was investigated by Thomas and Peethamparan [31]. The outcomes revealed that GPC failed in a more brittle manner than nominal concretes did. Prior to reaching peak stress, the GPC concrete exhibited stress–strain characteristics that were comparable to that of nominal concrete, but there was a noticeable quick drop in stress (reduced toughness) amid the weakening that follows peak stress. This was especially noticeable in the case of GGBFS GPC, which showed a brittle fracture right after peak stress. When compared to nominal concrete, the GPC with fly ash binder studied by Thomas and Peethamparan [31] showed a somewhat lower strain at ultimate stress. Hassan et al. [29] studied the effect of pre-treatment on the stress–strain performance and elastic modulus of RuGPC with a GGBFS binder and CR replacement at 5%, 15%, and 25%. The increase in the percentage replacement of rubber aggregates led to a reduction in the modulus of elasticity of RuGPC, recording 20% and 36% drops for the treated and untreated RuGPC specimens, respectively.

Aluminosilicate precursors of geopolymer concrete are eco-friendly substitutes for Portland cement, as they emit less than 70% of the greenhouse gases [32,33]. While geopolymer concrete is a practical material for construction, more studies have been conducted on rubberized concrete (RuC) than on rubberized geopolymer concrete (RuGPC). Just like nominal concrete, geopolymer concrete's (GPC) compressive strength is a crucial design factor. Research indicates that the compressive strength of GPC improves as the concentration of NaOH increases with respect to molarity [34,35]. RuGPC's compressive strength can rise by 49% when the concentration of NaOH is increased from 10 M to 14 M, according to a recent investigation by Giri et al. [35]; according to Luhar et al. [27], replacing 10% of the fine aggregate with NaOH-treated crumb rubber only results in an 11.66% decrease in compressive strength. In another investigation, Moghaddam et al. [36] partially substituted Portland cement and sand with fly ash and crumb rubber (CR). The research found that replacing 20% and 10% of Portland cement and fine aggregate with fly ash and rubber aggregate increased compressive strength by 8%. This indicates that fly ash and crumb rubber have a better adhesive bond than ordinary Portland cement and rubber. Thus, RuGPC will most likely display better strength properties than RuC, and the properties can be improved with NaOH molarity in RuGPC.

The literature review indicates that when the amount of rubber in concrete increases, its compressive strength usually decreases. Nevertheless, the degree of strength loss can be considerably decreased by pre-treating crumb rubber aggregates. To describe the characteristics of any kind of concrete, compressive strength, elasticity modulus, and stress–strain relationship are key parameters. Because the mechanical performance of RuGPC differs depending on the type of binders employed for the test, it is important to evaluate the stress–strain characteristics of RuGPC after every trial mix. A lot of studies in the past have investigated the overall performance of the stress–strain curve RuGPC made with fly ash, GGBFS, or a combination of both at different ratios, but none have evaluated the stress–strain behavior of RuGPC made with a combination of GGBFS and FA as binders in a ratio of 3:2. This research will investigate the fresh and mechanical properties of RuGPC with a 3:2 ratio combination of GGBFS and FA, together with the stress–strain characteristics, modulus of elasticity, Poisson's ratio, and energy absorption capacity.

2. Experimental Program

This includes an overview of the material characteristics, design approach, concrete formulation, and laboratory tests conducted in the research.

2.1. Materials

The materials utilized for this study include ground granulated blast furnace slag and fly ash (binders), sodium silicate and sodium hydroxide (alkaline activator solution), superplasticizer, fine and coarse aggregates, and crumb rubber aggregate as the primary components.

2.1.1. Binders

Class F fly ash and GGBFS were adopted for this research from Dataran Juta Sdn. Bhd. Kota Damansara, Selangor, Malaysia, as can be seen in Figures 1 and 2, and their physical and chemical properties and percentage composition are displayed in Table 1.



Figure 1. Class F fly ash.



Figure 2. Ground granulated blast furnace slag.

Table 1. Chemical composition and properties of fly ash.

Oxide/Property	FA (%)	GGBFS (%)
CaO	6.57	41.7
SiO ₂	62.4	33.45
Fe ₂ O ₃	9.17	0.31
Al ₂ O ₃	15.3	13.46
K ₂ O	1.49	0.29
MgO	0.77	5.99
SO ₃	0.65	2.74
P ₂ O ₅	1.23	-
TiO ₂	1.32	0.84
MnO	0.77	-
Na ₂ O	0.39	0.16
Mn ₂ O ₃	-	0.40

Table 1. *Cont.*

Oxide/Property	FA (%)	GGBFS (%)
Loss on Ignition %	1.25	-
Blaine Fineness (m ² /kg)	290	-
Specific Gravity	2.4	2.8
Fineness (m ² /kg)	425	395

2.1.2. Aggregates

Crushed granite measuring not more than 20 mm was employed as coarse aggregate, while sand within the size range of 4.75 mm and 150 µm was obtained from the Department of Civil Engineering, UPM material lab (Universiti Putra Malaysia (UPM), Serdang, Malaysia). Aggregates went through a washing process to eliminate any substance that could alter the properties of the concrete. After that, the moisture content of the wet coarse aggregate was eliminated by drying it for a full day at 105 °C in an oven (ASTM C136-2006 [37]), after which they were well graded in compliance with ASTM C33-2003 [38]. As can be seen in Figures 3 and 4, the passing percentage of the concrete aggregates falls between the midrange of the grading limits that will be employed in the concrete mix design. Fine and coarse aggregates have specific gravities of 2.60 and 2.673, and fine moduli of 7.35 and 2.39, respectively.

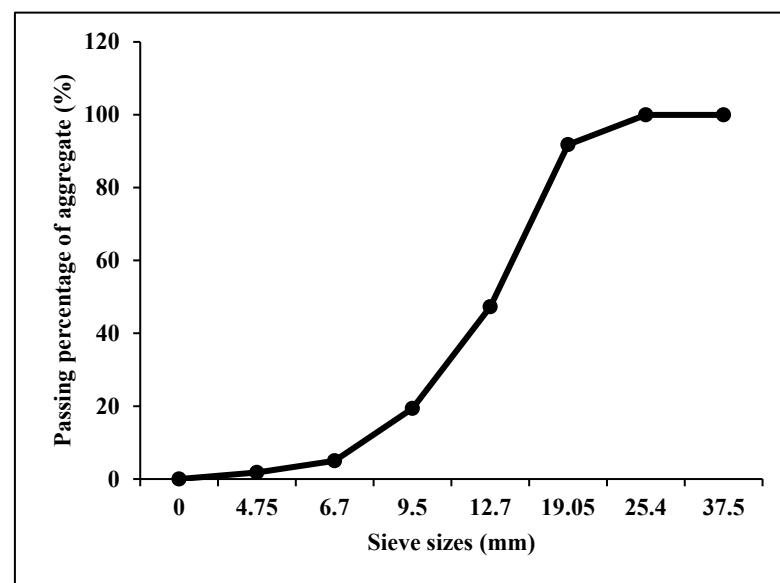


Figure 3. Coarse aggregate particle size distribution.

2.1.3. Alkaline Activator Solution (AAS)

In this investigation, NaOH solution and Na₂SiO₃ were used for the AAS. The current study involved the preparation of NaOH solution through the dissolution of pellets in water. The solution was made a day before use to prevent the emission of excess heat resulting from exothermic reactions during casting. During casting, a mixture of NaOH solution and Na₂SiO₃ was poured into the mix. The Na₂SiO₃, commonly referred to as water glass, is typically offered in gel form. The concentration of NaOH in the solution was 16 M, and the ratio of Na₂SiO₃ to NaOH was 1.5. Because the concentration of NaOH plays a crucial role in the synthesis of geopolymers, it is important to use a high molarity so that even after the addition of extra water, its concentration will still be high enough to synthesize the geopolymer. In addition, the solubility of binders rises as the hydroxide concentration increases. Hence, utilizing a more concentrated solution of NaOH results

in increased compressive strength of RuGPC. Table 2 presents the chemical and physical properties of Na_2SO_3 and NaOH .

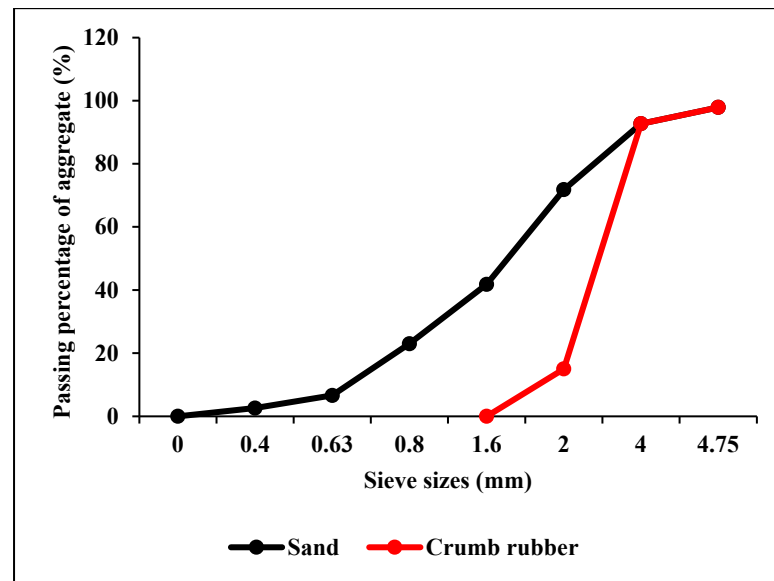


Figure 4. Grading curve for fine aggregate.

Table 2. Characteristics of AAS.

Chemical Composition			
Na_2SO_3		NaOH	
Constituent	(%)	Constituent	(%)
Na_2O	15.90	Carbonate	2×10^0
SiO_2	31.40	CL	1×10^{-2}
H_2O	52.70	SO_2	5×10^{-2}
*	*	Pb	1×10^{-3}
*	*	Fe	1×10^{-3}
*	*	K	1×10^{-1}
*	*	Zn	2×10^{-2}
Physical Property			
Appearance	Liquid (Gel)	Appearance	Pellets
Color	Light yellow liquid (gel)	Color	White
Boiling point	102 °C for 40% aqueous solution	Boiling Point	102 °C for 40% aqueous solution
Molecular Weight	122.06324 g/mol	Molecular Weight	39.997 g/mol
Specific Gravity	1.7	Specific Gravity	1.5

2.1.4. Crumb Rubber Fine Aggregate

Rubber aggregates with a size range of 1 mm to 4 mm with a specific gravity of 0.52 were obtained from Yong Fong Rubber Ind S/B, Kampong Telok Gong, Selangor, Malaysia, and were used as a partial replacement for fine aggregate. Before starting the pre-treatment process, the rubber aggregates were thoroughly cleaned with water to remove any impurities or dust from the surface, as stipulated by Shahzad and Zhao [19]. After that, they were submerged in the NaOH solution for a whole day in a container, as shown in Figure 5a. The quantity of the NaOH solution was equal to five times the weight of the rubber aggregates. Five kilograms of crumb rubber aggregates were pre-treated using a 25 L NaOH solution. To prevent the fluid from becoming contaminated and forming sodium carbonate, the container was covered as shown in Figure 5b. After the necessary

amount of time had elapsed, the crumb rubber aggregate was extracted from the solution of NaOH. Following that, rubber aggregates were immersed in clean water for another five minutes and washed to attain a pH of 7 and finally allowed to dry under the sun as shown in Figure 5c. The final water cleaning is necessary to remove any remaining NaOH solution to prevent any negative impacts on the durability of the concrete. Approximately 25 to 30 min were needed to thoroughly extract the NaOH solution from the crumb rubber aggregates. Figure 5d shows the treated rubber aggregate ready for mixing.

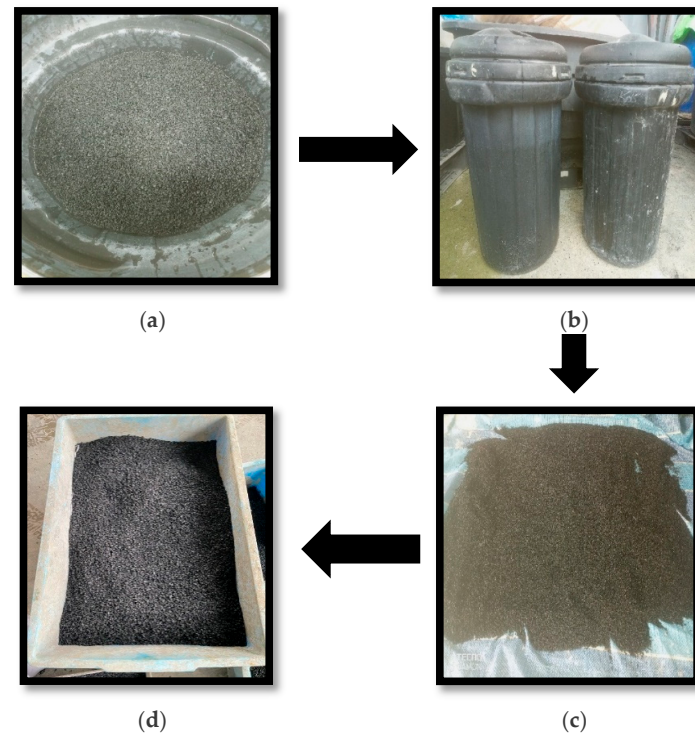


Figure 5. Crumb rubber pre-treatment procedure. (a) Rubber submerged in NaOH solution; (b) container is covered to prevent contamination (24 h); (c) sun-drying the rubber after washing twice; (d) rubber aggregates ready for concrete mixing.

2.1.5. Superplasticizer

High-performance superplasticizing admixture Fosroc Conplast SP430 from Fosroc Chemtech Construction Chemicals, Klang, Selangor, Malaysia, was used for the research in accordance with ASTM C494 [39]. The superplasticizer helps to retard the setting of RuGPC, increase flow rheology, boost workability and strength, and minimize the need for extra water. The characteristics of Conplast SP430 are presented in Table 3.

Table 3. Characteristics of Conplast SP430.

Property	Concentration
Color	Brown liquid
pH	5.6
CL content	No CL
Density	1.8 g/cm ³
Specific Gravity	1.2 @ 22 °C + 2.2 °C
Alkali Content	Typically less than 53 g. Na ₂ O equivalent/liter of admixture

2.2. Concrete Preparation

Table 4 shows the mix fraction for a design strength of 40 MPa prepared with the mix design procedure initiated by Pavithra et al. [40], according to BS EN 206 [41] reference

tables, which approximate an ACI mix technique for a mix design. The alkaline liquid-to-binder ratio, admixture dosage, and extra water were 0.4, 3%, and 22%, respectively.

Table 4. Mix design for predicted strength.

Strength (MPa)	AAS/B _c	Binder Content (Kg/m ³)		AAS (Kg/m ³)		CA (Kg/m ³)	FA (Kg/m ³)	Water/GPS	SP (Kg/m ³)	Extra Water (Kg/m ³)
		FA	GGBFS	NaOH	Na ₂ SiO ₃					
40	0.20	200	300	80	120	1114.86	470.58	0.2	15	110

The mixing order depicted in Figure 6 was followed in the development of each geopolymer concrete mix. After mixing all the constituents of geopolymer concrete in the mixer, the concrete was cast into different molds. Slump tests were conducted for every mix, and the required number of standard-size cubes (100 mm × 100 mm × 100 mm), and cylinder (100 mm dia. × 200 mm) specimens were cast. After casting the specimens in the laboratory, they were left in the mold for 1 day before demolding and allowed to cure at ambient temperature for 28 days. The mix design calls for three concrete batches, replacing nominal fine aggregate with crumb rubber aggregate at 0%, 10%, and 20%, respectively, as shown in Table 5. Cubes were subjected to compression tests at 3, 7, and 28 days, while cylinder specimens were subjected to modulus of elasticity tests at 28 days.

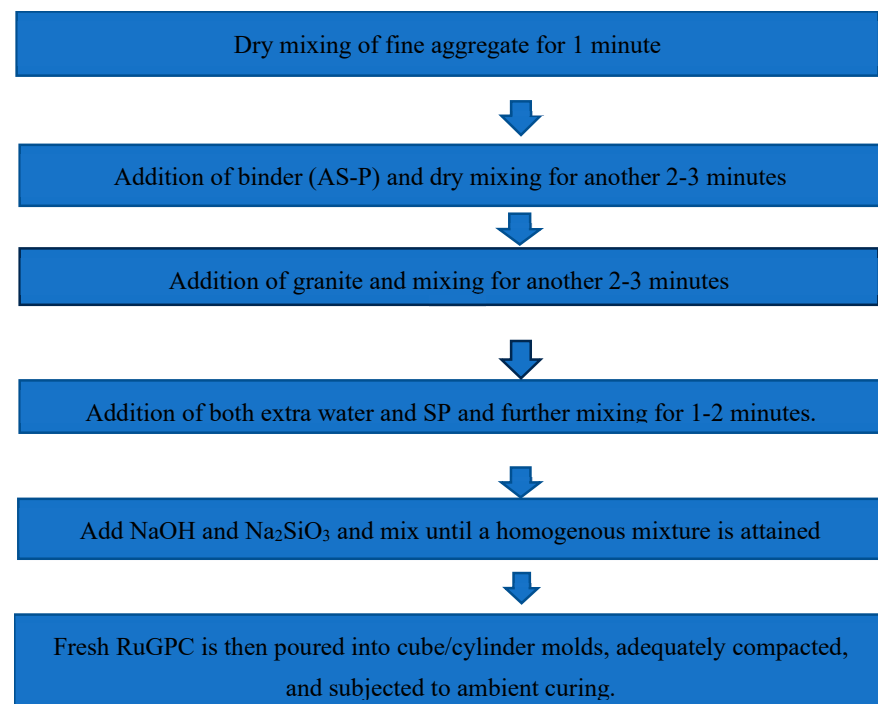


Figure 6. Steps involved in the manufacture of RuGPC.

Table 5. Mix proportions of Grade 40 Concrete for various CR replacements.

% Rep. F. A	Conc. Vol. (m ³)	Binder Content (kg)		Alkaline Solution (kg)		C.A (kg)	F.A (kg)		SP (kg)	Extra Water (kg)
		Fly Ash	GGBFS	NaOH	Na ₂ SO ₃		F. A	CR		
0%	0.0132	2.641	3.961	1.056	1.585	14.721	6.214	-	0.20	1.452
10%	0.0132	2.641	3.961	1.056	1.585	14.721	5.592	0.621	0.20	1.452
20%	0.0132	2.641	3.961	1.056	1.585	14.721	4.971	1.242	0.20	1.452

2.3. Slump Test

The slump test followed the steps as specified by BS EN 12350-2:2009 [42]. This test helps to describe how workable concrete is and the ease with which it can be handled during casting. The test determines how consistent a batch of concrete is and how consistent freshly mixed concrete is. In construction sites, the slump test is used to guarantee consistency across various concrete batches.

2.4. Compressive Strength Test

The compressive strength test was conducted using a fully automatic Universal Testing Machine (UTS) in accordance with BS EN 12390-4:2000 [43]. Figure 7 shows the UTS machine used for the concrete cube compression test. A compressive load was applied on the opposite surface of the concrete cube with a loading rate of 6kN/s until failure. The peak compressive load applied to the concrete cube and the peak stress were recorded. The average results of three cube samples are considered to be the final compressive strength of the concrete mix.



Figure 7. Universal Testing Machine.

2.5. Modulus of Elasticity Test

The modulus of elasticity for RuGPC specimens was determined in accordance with BS EN 1992-1-1: 2004 [44] as shown in Figure 8, with standard cylinders with a height of 200 mm and a diameter of 100 mm. Before subjecting the cylinder to the compression test, the bottom end was properly ground while the top end was capped with sulfuric material. The resulting bottom end and cap were smoothened, levelled, and perpendicular to the axis of the cylinder so that the load was uniformly distributed over the entire cylinder sample. The vertical and horizontal strains were recorded by two 30 mm strain gauges placed at the center of the cylinder, respectively, at every 10 kN load interval.

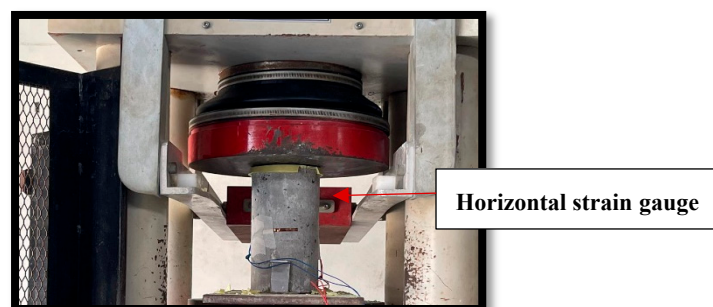


Figure 8. Experimental setup for modulus of elasticity test.

3. Experimental Results and Discussions

3.1. Initial Setting Time of RuGPC

The increase in rubber content leads to an increase in the setting time of geopolymer concrete. Figure 9 shows the relationship between the initial setting time of RuGPC and rubber content from the mix design tests. The initial setting times of 0%, 10%, and 20% RuGPC were 19 min, 22 min, and 25 min. This is because the entrapped air in the concrete caused by the rubber aggregates increases pores in the interior of the concrete; these pores partially retain water and delay hydration processes, thereby increasing the setting time. This agrees with the reports from other research [45,46]. This is because of the hydrophobic nature of rubber, which prevents the adhesion of rubber aggregates with the geopolymer matrix and other concrete constituents, thus weakening the interfacial transition zone (ITZ) between the rubber aggregates and the geopolymer matrix [29,47–49]. The ITZ of RuGPC can be strengthened by treating the rubber aggregate surface with NaOH to make it hydrophilic. As the rubber content increases, the porosity of the microstructure of the concrete increases, thus inhibiting more moisture and requiring a longer period to hydrate. This implies that the percentage of crumb rubber introduced into geopolymer concrete is dependent on the desired design strength, as even an above 20% proportion will provide adequate time for casting and compaction. If the interfacial transition zone between the geopolymer matrix and rubber aggregates is improved by rubber treatment or a highly alkaline geopolymer matrix, RuGPC can be applied in areas where high strength is required.

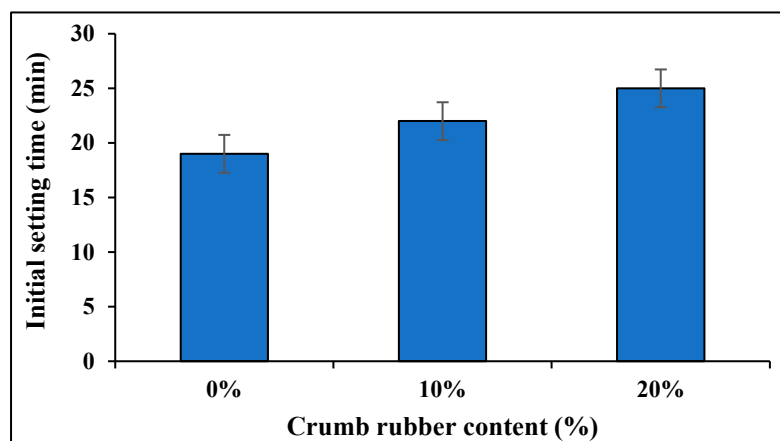


Figure 9. Relationship between initial setting time and crumb rubber content.

In the investigation by Zhang et al. [6], GPC made with GGBFS and FA as binders displayed an initial setting time of 28 min and a final setting time of 41 min. The initial setting time recorded in the Zhang et al. [6] report is 12% higher than the result in this research. However, neither result fulfilled the standard condition that the initial setting time must exceed 40 min. OPC displayed an initial setting time exceeding 45 min and a final setting time of approximately 281 min [6]. Zhang et al. [6] found that the initial and final setting time of GPC can be increased by 67.86% and 29.27%, respectively, if BaCl_2 is added to the mixture. This is because BaCl_2 will impede geopolymerization by decreasing the alkalinity of the AAS and the utilization of electrolytes [50,51], as well as by coating the surface of the binder particles with a product resulting from its reaction with water glass, which obstructs its interface with the AAS [52]. Thus, it slows the rate of geopolymerization. As the process of geopolymerization progresses, the products that coat the surface of the binder particles will lose their effect, resulting in a vigorous reaction between the AAS and binders. This could be why the initial and final setting times are not far apart.

3.2. Workability

When CR is used in place of sand, concrete slump and flow are decreased. Figure 10 shows the relationship of GPC slump values with rubber content from the laboratory mix tests. RuGPC at 0%, 10%, and 20% CR replacement had initial slump results of 180 mm, 170 mm, and 165 mm, respectively. Compared to the control specimen, the concrete slump was reduced by an average of 5.56% and 8.33% at 10%, and 20%, respectively, of crumb rubber fine aggregate replacement. Even though the percentage reduction in the concrete slump from 0 to 20% is small, substantial CR content in concrete greatly influences its fluidity. This is due to the decreased effectiveness of the AAS-to-AP ratio [53–55]. Despite the decline, the rate of decline is somewhat diminished with an increase in rubber content; 0% to 10% declined by 5.56% and 10% to 20% declined by 2.94%. This suggests some sort of stability in the adverse effect of CR on concrete workability. The fact that CR has a lower density than sand is one of the reasons why the workability of RuGPC reduces with an increase in CR content, resulting from the increased resistance to flow under its weight. Additionally, rubber that has been mechanically processed possesses a greater surface area of contact over nominal fine aggregate, because the mechanical process makes the surface rougher, which later translates to an increased surface area with other concrete constituents, preempting the need for more water to counter the internal friction amongst the concrete constituents. The hydrophobic nature of CR enables air to be easily trapped within the concrete during mixing and this aids in reducing concrete workability because of increased flow resistance [18,56–60]. The mixture of CR and AAS being exposed to air might have led to a quick carbonation process because of its elevated pH due to the pre-treatment of CR with NaOH. Although the resulting sodium carbonate may be utilized to activate GGBFS and FA, it was considerably less efficient than its silicate and hydroxide equivalents. This led to a decrease in the dissolution reaction, which may have consequently lowered the slump. Similar results were published by Dong et al. [18] and Zhang et al. [6], where the concrete slump was reduced by 10 mm at 15% CR replacement.

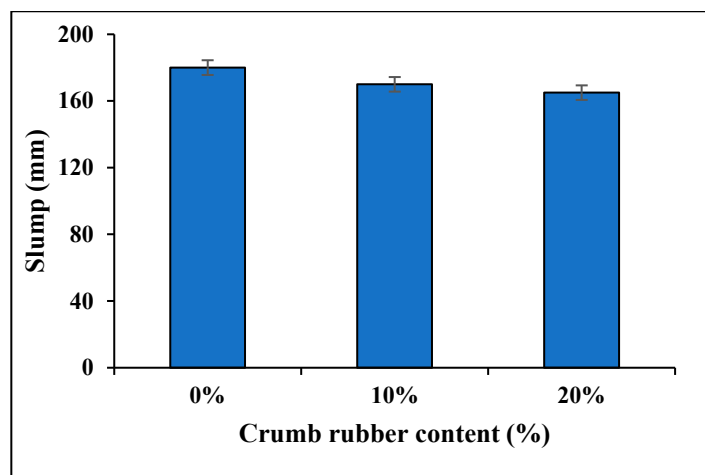


Figure 10. Relationship between slump and crumb rubber content.

Mhaya et al. [61] noticed that using CR as a surrogate of sand at 5%, 10%, 15%, 20%, and 25% reduced the concrete workability by 2.63%, 10.53%, 21.05%, 28.95%, 31.58%, and 38.16%, respectively. Adebayo et al. [62] found that the addition of 15% CR into GPC made with GGBFS and fly ash reduced the workability by 28.6%. Earlier researchers [63,64] attributed this reduction to the numerous morphologies involved in the mechanical process of cutting tires, which give the CR a rough and irregular surface [65,66], and the low water absorption capacity of CR [6]. When CR is used as a partial or full replacement for

sand, it increases the frictional resistance force amongst the concrete constituents. The heightened resistance leads to the retrieval of additional energy within the dynamics of the flow, thus reducing the workability as CR content increases. The authors also supported the fact that the roughness of CR aggregates increased the surface area of contact, which negatively affects workability. The increase in rubber content up to 20% slightly reduces the workability of RuGPC (180 to 165 mm), which is still within the acceptable limit; it is safe to say it can be used for construction purposes without any modification. However, at a higher percentage, the mix design might require minor modifications at some point with respect to the percentage of CR or the addition of admixtures that improve workability to achieve adequate flowability for real-world use.

Comparing the workability of RuGPC with nominal concrete of the same design strength, Manimaran et al. [67] used a mix ratio of 1:1.84:2.65, w/c ratio of 0.4, and cement content of 420 kg/m³, and found of slump of 80 mm. In the investigation by Patil et al. [68] a mix ratio of 1:1.65:2.62 with w/c of 0.39 and cement content of 420 kg/m³ resulted in a concrete slump of 60 mm. In another investigation, Ephraim et al. [69] obtained a slump of 70 mm from a mix ratio of 1:1.2:1.5 and w/c of 0.45. Gornale et al. [70] recorded a smaller slump of 30 mm from a mix ratio of 1:1.35:2.41, which had w/c ratio of 0.4 and cement content of 465 kg/m³. It can be concluded that the slump for nominal concrete of grade 40 is within the range of 30 mm to 80 mm, which is 51.5% less than that of 20% RuGPC. Zhang et al. [6] discovered that GPC displayed higher workability than NC because the particle sizes of the geopolymer binders are finer than those of ordinary Portland cement. The significantly high slump of RuGPC indicates good workability (capacity to flow), which can be advantageous when reinforcement is densely packed or when the concrete needs to seep into narrow spaces without the option to vibrate. Normally, the slump of RuGPC is supposed to be much higher than that of NC in a situation where concrete with high flowability is required. This is because the setting time of RuGPC is much shorter than that of NC, as seen in Section 3.2. For this reason, NC can maintain an average flow for a longer period, while RuGPC cannot. Figure 11 is a pictorial representation of the RuGPC slump at 0% and 20%.



Figure 11. GPC slump at (a) 0% and (b) 20% CR replacement.

3.3. Density

The densities decreased as the curing age progressed, with the lowest density observed at 28 days and the highest density reached at 7 days, as demonstrated in Figure 12. The percentage decrease between the densities at 7 and 28 days was 0.84%, 1.26% and 1.32% for 0%, 10% and 20% RuGPC, respectively. This occurs because the RuGPC loses water during the curing process, lowering its density. This water loss is due to inadequate adhesion

of the aggregates and the geopolymer matrix, which creates pores in the microstructure of the concrete where water is stored during mixing. However, water loss did not bring about a reduction in the compressive strength of the concrete because a zeolite-type phase is produced as the primary reaction result of fly ash's alkali activation [71]. The control sample had the lowest percentage reduction because it has a less porous microstructure resulting from the strong adhesive bond in the concrete mixture. This implies that there was less water in the concrete pores and, thus, less water loss between 7 and 28 days as compared to the 10% and 20% RuGPC samples with weaker ITZ that created more pores and more water loss [61,72,73]. The rates of reduction in density between days 7 to 21 were 0.49%, 0.59%, and 0.68%, which later reduced to 0.36%, 0.45%, and 0.46% for 0%, 10%, and 20% RuGPC specimens, respectively, from days 21 to 28, indicating some sort of stability and balance after 28 days.

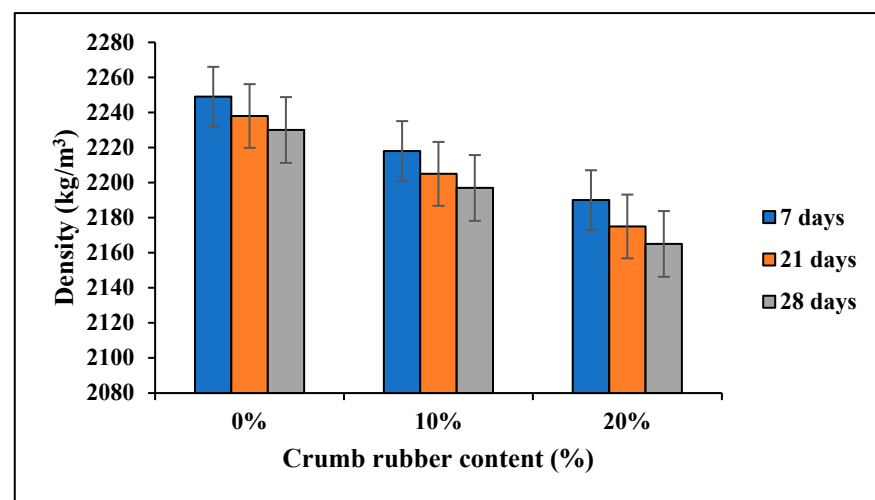


Figure 12. Relationship between density and crumb rubber content.

This reduction in density with curing age is mostly synonymous with ambient curing [74]. When concrete specimens are soaked in water, the concrete density mostly increases with curing age because of improvement in the concrete microstructure [74,75]. Opara et al. [76] found that the density of NC increased by 7.6% between the 7 and 28 days, and Raheem et al. [74] recorded a 2.39% increase in NC density between 7 and 28 days of water curing. Azrem et al. [77] found that the density of RuGPC decreased when the samples were subjected to ambient curing from days 3 to 28. The rate of decrease in RuGPC specimens' density from days 3 to 7 was high, but the percentage reduced from 7 days to 28 days. This was attributed to RuGPC losing water as the curing ages increased, which lowers its density, and the water loss is due to the pores in the RuGPC specimens not being properly sealed [78–80]. This proves that the method of curing should be thoroughly looked into when the unit weight of RuGPC is a key consideration.

Figure 12 gives an overview of the densities of RuGPC at the different CR percentage replacements employed in this study. The incorporation of CR into GPC is shown to reduce its density. The highest and lowest densities of 2230 kg/m³ and 2165 kg/m³ were obtained by GPC at 0% and 20% CR replacements at 28 days. Primarily because rubber aggregates have a specific gravity of 1.12, which is lower than that of natural fine and coarse aggregates. Concrete density is largely affected by the specific gravity of the aggregates that constitute concrete, and this has a key role to play in a structure's dead load. Secondly, the lack of proper adhesion between rubber fine aggregates and the geopolymer gel gives room for the formation of pores within the concrete microstructure and increases the tendency to entrap air bubbles in the concrete [18]. Similar results were reported in another study [29,81,82].

Mhaya et al. [61] revealed that CR addition of 5%, 10%, 15%, 20%, 25%, and 30% reduced the density of RuGPC by 3.7%, 6.5%, 7.2%, 8.1%, 9.3%, and 10.4%, respectively. Adebayo et al. [62] recorded a 2.3% decrease in density at a 10% addition of CR at 28 days. In the investigation by Azrem et al. [77], RuGPC density reduced from 2243 kg/m³ to 1722 kg/m³ at 0% and 20% CR replacement, respectively. All their theories on the reduced density of RuGPC point to a lower density and specific gravity of CR in comparison to sand [47,48,83]. It is crucial to note that CR has a specific gravity of 0.6 to 1.15 [84,85], while sand has a specific gravity of 2.65 [86].

3.4. Cube Compressive Strength

As displayed in Figure 13, the compressive strength of the concrete in all batches improved with the aging of the curing process at 7, 21, and 28 days, regardless of the rubber content, which was comparable to NC [87,88]. This is because as the curing duration increases, polymerization is enhanced with the formation of polymerization chains, which causes the compressive strength to rise [89–91]. This implies that the compressive strength of GPC tends to increase further after 28 days. At 7 days, the RuGPC strength with 0%, 10%, and 20% CR increased by 81.54%, 85.79%, and 82.57%, and at 21 days, the strength reached 90%, 93.7%, and 90%, respectively, of the 28-day compressive strength. The percentage increase in compressive strength at 21 days closely resembles the findings reported by earlier studies on NC [92–94]. However, the percentage increase at 7 days is much higher than those recorded for NC, as most findings reported a percentage increase in the range of 44 to 71% [92–95].

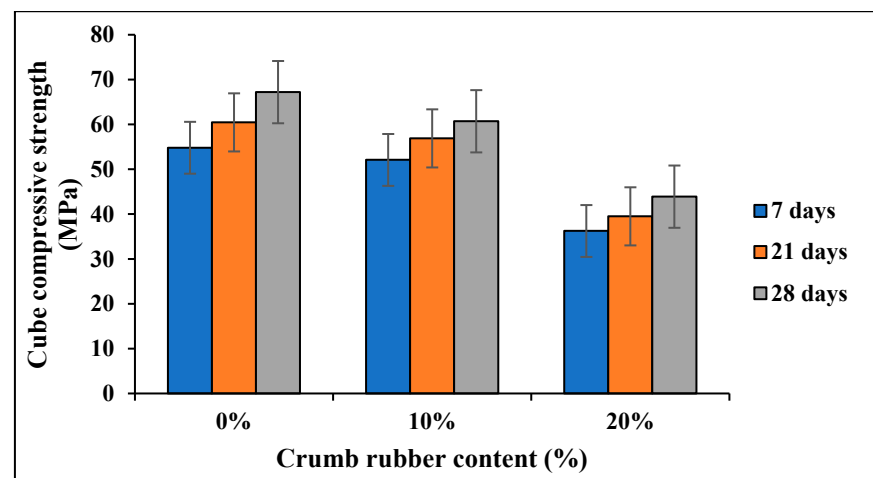


Figure 13. Relationship between cube compressive strength and crumb rubber content.

In nominal concrete, strength growth is attributed to the hydration process of cement and the creation of calcium–silicate–hydrate (C-S-H) gel, which occupies the voids in the concrete and improves its strength. Luhar et al. [27] reported that the process of hydration of the cement matrix is long and continuous, allowing the concrete pores to gradually get filled up, enhancing the concrete strength over a period of 365 days [85]. However, in GPC, the process of geopolymerization happens very fast because of the reaction that takes place between the binder and the AAS, resulting in an 80 to 95% gain of compressive strength at just 7 days [27,96–98]. The binder type, with respect to its chemical composition, molarity of NaOH, temperature of curing, and ratio of Na₂SO₃ to NaOH of GPC, plays a large role in determining the early strength growth and maximum strength. For this research, it can be seen from Table 3 that the combination of GGBFS and FA is in a ratio of 3:2, which means that there is a higher quantity of GGBFS in the mixture. From Table 1, the percentages of CaO and SiO₂ in GGBFS are 41.7% and 33.45%, while in FA, they are

6.57% and 62.4%, respectively. The large quantity of GGBFS and CaO in the aluminosilicate precursor accelerated the high early strength in the concrete, allowing the SiO₂ to have more effect after 7 days. Employing both GGBFS and FA is beneficial to RuGPC, as GGBFS supports high early strength [99–103], while FA aids in enhancing workability, reducing concrete pores and permeability and producing a denser concrete [104–108]. The strength growth in the latter days is not as fast as in the first 7 days because there is a reduction in the chemical of the geopolymer matrix as the age increases and the formation of a crystalline anatomy takes place [109].

The compressive strength of GPC decreased as CR percentage replacement increased in the concrete, as shown in Figure 13. It reduced by an average of 9.64% and 34.67% at 10% and 20%, respectively. The following factors are responsible for this: First and foremost, the weak ITZ developed because of the hydrophobic characteristics of CR's frail adhesive bond with other concrete constituents (geopolymer gel) [78,110–112]. Secondly, the rubber aggregates possess an elastic modulus much lower than that of the geopolymer mixture, and this escalates their stress within the RuGPC sample, preempting the possibility of microcracks developing around them, which would reduce their compressive strength [29,110,112,113]. Thirdly, the rubber's irregular and rough surface causes the material to retain additional air bubbles, which increases the porosity in RuGPC with the increased rubber content, thereby resulting in a loss of its compressive strength [29,78,111,112,114].

Surprisingly, the compressive strength of RuGPC at 10% and 20% crumb rubber replacement was able to surpass the design strength, recording values of 60.725 MPa and 43.9 MPa, respectively, at 28 days, and this is largely attributed to the treatment of the rubber aggregates with NaOH before adding them to the mixture. The hydrophobic nature of rubber becomes hydrophilic after treatment with NaOH, which improves its adhesive qualities with the geopolymer matrix and other concrete ingredients [115–118]. The presence of zinc stearates on the surface of rubber aggregate, which prevents it from bonding properly with the geopolymer matrix, was removed after CR pre-treatment with NaOH [29,35,111,114,119]. In addition, the sodium hydroxide treatment also affects the surface texture of the CR by forming needle-like crystals on the surface, which enables the rubber aggregates and the geopolymer matrix to interlock efficiently, thus eradicating unwanted pores within the concrete, reducing entrapped air, and improving the overall microstructure of the concrete [29,120].

The cube strength results of RuGPC vary from 67.2 to 43.9 MPa at 28 days for RuGPC at 0% and 20%, respectively. Under the BS 8110 [121] concrete design strength requirement, RuGPC with CR at 20% can be employed for the construction of structural elements. This strength can be further enhanced by further improving the adhesive bond between CR and the geopolymer matrix so that RuGPC can be employed in high-strength concrete. Conversely, the quantity of rubber in RuGPC can be increased for structural applications where the compressive strength requirement is between 25 and 30 MPa.

Correlation Between Density and 28-Day Cube Compressive Strength

Figure 14 shows the correlation between the experimental density results and the 28-day cube compressive strength of RuGPC with different percentages of CR replacement. The linear relationship between the concrete density and compressive strength indicates that both concrete properties are directly proportional. This result is in accordance with reports from previous research [47]. The numerical expression between both parameters can be represented as follows:

$$y = 0.3603x - 734.46$$

where y represents the 28-day strength, and x is the concrete density.

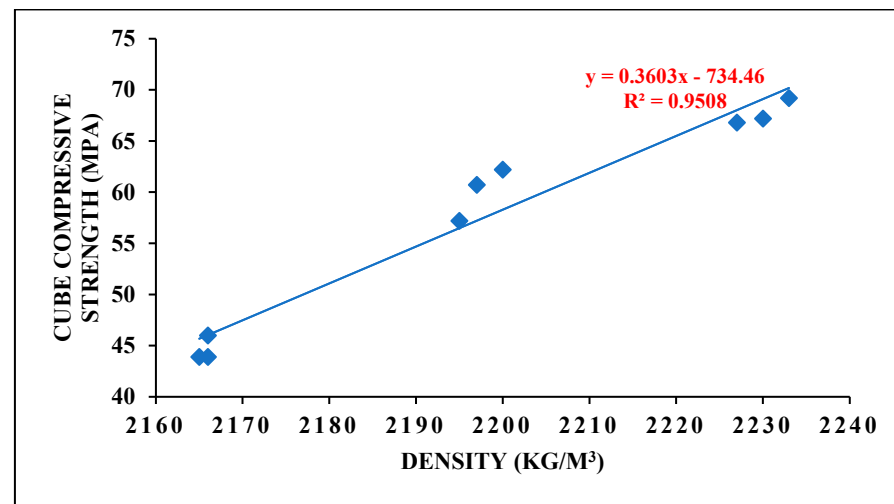


Figure 14. Correlation between density and 28-day cube compressive strength of RuGPC mixes.

The straight-line curve of concrete density and compressive strength showed an average correlation (R^2) of 0.95, which indicates a strong correlation between both parameters. A positive slope suggests a direct relationship between density and compressive strength.

3.5. Stress–Strain Relationship

The stress–strain curve for nine RuGPC specimens (three specimens per batch) of 100 mm diameter and 200 mm height after 28 days with different percentages of CR was drawn with data obtained from the load cell, along with axial displacement recorded by the LVDTs. Compressive longitudinal strains were measured and reported as positive values, while tensile transverse strains (hoop strains) were presented as negative values. The stress–strain results of three specimens for each concrete batch are illustrated in Figure 15a–c for 0%, 10%, and 20% RuGPC specimens. Overall, from Figure 15a–c, the results displayed from the three-cylinder samples for each mix batch were consistent. This confirms that good quality control was strictly adhered to in the process of material selection, concrete production, and experimental testing. The small volume of concrete also helped to reduce deviation in the stress–strain results.

The stress–strain results of all the concrete samples are presented in Table 6. The average stress–strain results of three cylinders for each batch were used to define the strain performance of RuGPC with different percentages of CR under uniaxial compressive stress. The test results for 0%, 10%, and 20% RuGPC specimens are illustrated graphically in Figure 16.

Table 6. Stress–strain relationship of RuGPC specimens.

CR (%)	No.	Peak Stress (MPa)	Yield Strain	Peak Strain	Ultimate Strain	MoE	Poisson's Ratio	Toughness (N.m/m ³)	Ductility Index
0%	C001	50.265	0.00230	0.00330	0.00356	23.265	0.146	10.21	1.55
	C002	50.248	0.00225	0.00328	0.00332	23.036	0.145	10.01	1.48
	C003	50.910	0.00229	0.00322	0.00339	23.818	0.145	10.07	1.48
	AVG	50.474	0.00228	0.00327	0.00342	23.373	0.145	10.10	1.50
10%	C101	33.096	0.00143	0.00346	0.00450	16.314	0.156	11.39	3.07
	C102	33.089	0.00143	0.00345	0.00432	16.581	0.152	10.67	3.02
	C103	33.082	0.00141	0.00344	0.00430	16.314	0.152	10.69	3.04
	AVG	33.089	0.00142	0.00345	0.00437	16.403	0.153	10.92	3.04

Table 6. Cont.

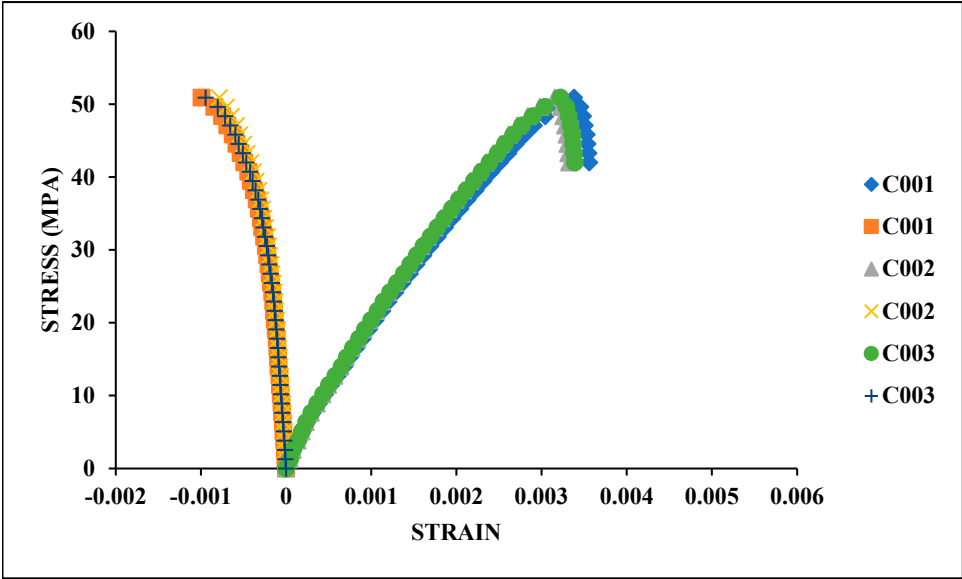
CR (%)	No.	Peak Stress (MPa)	Yield Strain	Peak Strain	Ultimate Strain	MoE	Poisson's Ratio	Toughness (N.m/m ³)	Ductility Index
20%	C201	27.274	0.00138	0.00357	0.00542	13.422	0.199	13.71	3.93
	C202	28.273	0.00139	0.00352	0.00526	13.141	0.167	11.86	3.78
	C203	27.252	0.00136	0.00356	0.00531	13.110	0.201	11.54	3.85
AVG	-	27.775	0.00138	0.00355	0.00533	13.224	0.189	12.37	3.85

The stress–strain curve shown in Figure 16 is divided into the pre-peak (ascending) and post-peak (descending) phases. All the specimens displayed linear behavior at the start of the pre-peak phase, but the linearity of the curvature of 10% and 20% RuGPC specimens started to reduce as the curve approached peak stress, indicating a decrease in peak stress with an increase in CR content. This is because RuGPC specimens with CR have less resistance to the applied compression force compared to the control specimen, owing to the higher stiffness of fine aggregate over CR. The post-peak phase presents an entirely different characteristic. After failure at the peak stress of the control specimen, the load dropped and collapsed at a very quick rate with a very steep slope. This confirms the quick brittle failure of GGBFS GPC immediately after the peak stress that was reported by Thomas and Peethamparan [31]. RuGPC specimens with CR displayed higher peaks and ultimate concrete strains than the control specimens. The introduction of CR into RuGPC enhanced the deformation capability and changed the failure mode from brittle to ductile as the descending segment of the stress–strain curve became less steep [18,120,122,123]. This is because CR increases the ductility of concrete under loading, thus delaying the failure process. This makes rubberized GPC suitable for applications where concrete flexibility is required.

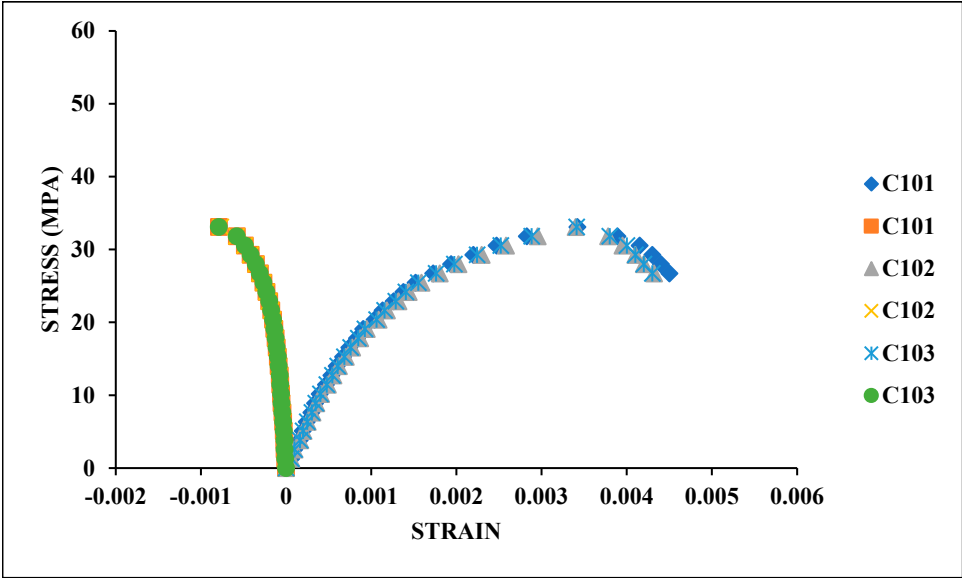
Figure 17 shows how to calculate the yield strain, ultimate strain, and energy absorption capacity from the stress–strain curve. The yield strain Δ_{yield} is indicated by the dashed vertical lines and corresponds to 75% of the secant stiffness of the peak stress. It is the strain in alignment with the intersection point between the elastic segment extension and the tangential line drawn from the peak stress point on the stress–strain curve [124]. The ultimate strain (Δ_u) is the strain at 80% of the peak stress on the strain axis in the post-peak region of the stress–strain curve [124].

3.5.1. Peak Stress

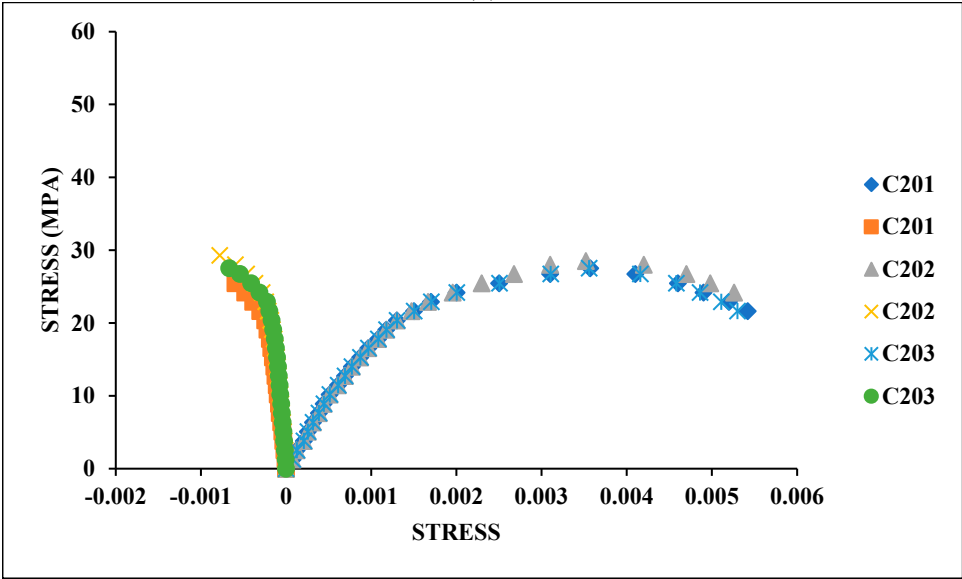
Analysis of the results from the stress–strain curve presented in Table 6 indicates that peak stress was reduced by 34.44% and 44.97% for 10% and 20% CR replacement with reference to the control specimen. As a result, the concrete became less rigid overall, which lowered the peak stress. This is because of the reduced adhesive bond between CR and the geopolymer matrix due to its hydrophobic properties compared to the bond between nominal fine aggregate and the geopolymer paste, and because CR aggregates are not as stiff as fine aggregates. Another reason is the reduction in the load-carrying capacity of CR aggregates. Furthermore, crumb rubber has a higher Poisson's ratio and lower modulus of elasticity compared to nominal fine aggregate [18,125,126].



(a)



(b)



(c)

Figure 15. (a) Stress–strain relationship of 0% RuGPC specimens. (b) Stress–strain relationship of 10% RuGPC specimens. (c) Stress–strain relationship of 20% RuGPC specimens.

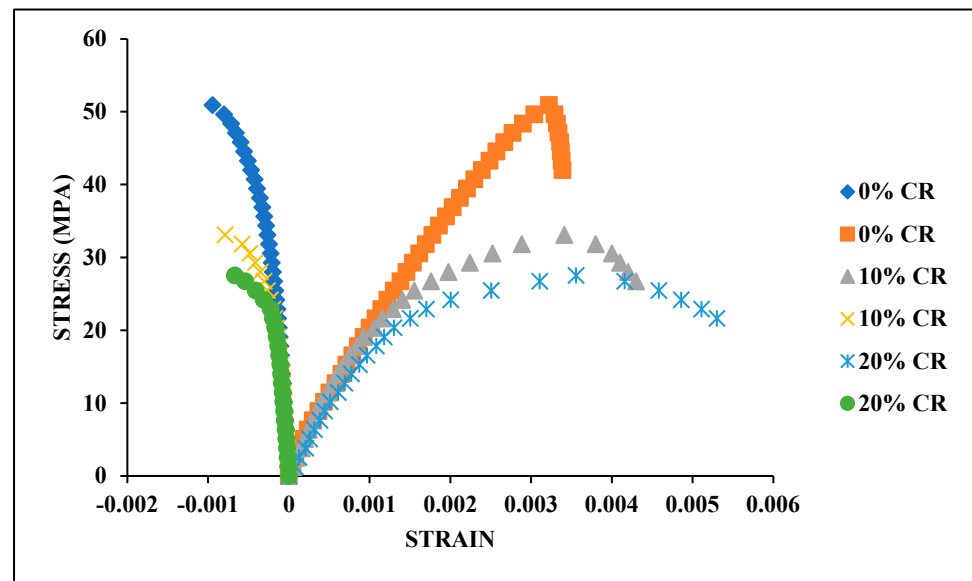


Figure 16. Summary of the stress–strain relationship of RuGPC specimens.

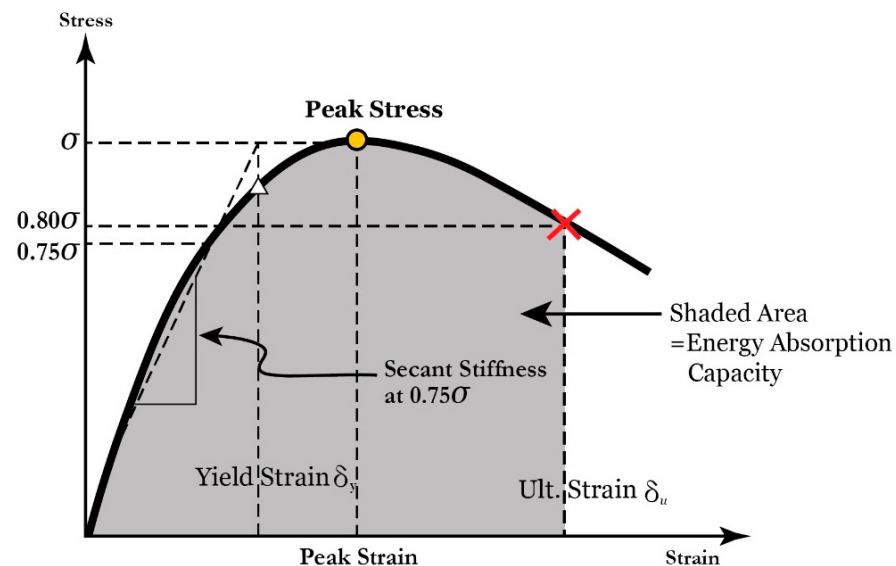


Figure 17. Definition of concrete strains.

3.5.2. Correlation Between the Cube and Cylinder Compressive Strength

From Figure 13 and Table 6, the ratios of the compressive strength at 28 days of the concrete cylinder to that of the cube are 0.75, 0.54, and 0.63 for the 0%, 10%, and 20% specimens, implying that the strength of the cube supersedes that of the cylinder by 1.33, 1.84, and 1.58 times. For nominal concrete, BS-EN 12504-1 [127] stipulates that the compressive strength of a cylinder is equal to 0.8 times the strength of the cube, and the literature review shows that the strength of the cube should be approximately 1.25 times that of the cylinder [128]. The superiority of geopolymer concrete to Portland cement concrete is due to its denser microstructure, which helps it to exhibit enhanced compressive strength because of increased sodium silicate bonding. The influence of this bonding is significant in the cylinder specimen but is only particularly pronounced in concrete cubes due to increased friction and minimized stress distribution. Additionally, it was found that the process of geopolymerization is very sensitive to temperature and time; that is why the setting time of geopolymer concrete is very short. Cube concrete specimens take a shorter time to cast compared to cylinder specimens, indicating that cube specimens

receive a higher efficiency of compaction than cylinder specimens. This is why the ratio of cube to cylinder compressive strength of rubberized geopolymer concrete is higher than that of NC. Padmakar et al. [129] found that the ratio of the strength of the cylinder to the cube specimen of GPC made with 70% GGBFS and 30% silica fume was in the range of 0.67 to 0.96, implying the strength of the cube was 1.05 to 1.5 times that of the cylinder. This finding aligns closely with what was achieved in this study. Thus, the statement that the compressive strength of a cylinder is 0.8 times that of the compressive strength of a cube is not significant for rubberized geopolymer concrete.

3.5.3. Strain Values

Figure 18 shows how the average strain values changed with an increase in CR percentage replacement in RuGPC. The control specimen had an average yield strain of 0.00228. The value of the average strain began to decline with an increase in rubber content, with 10% and 20% RuGPC specimens recording values of 0.00142 (about 37.72% reduction) and 0.00138 (about 39.47% reduction), respectively. The yield strain is the first point where the concrete samples begin to yield. The reason why the control specimen has the highest yield strain is because its resistance to yield is much higher than that of all the other concrete samples (resulting from its high adhesive bond and corresponding high compressive strength). This resistance to yield stress decreases with the introduction of CR and a corresponding increase in percentage replacement, due to the reduction in the adhesive bond between CR and the other concrete constituents because of its hydrophobic nature. This weak bond reduces the bond at the interfacial transition zone, prompting the concrete to start yielding earlier [125,130,131]. The peak strain corresponding to the peak stress was found to increase as the percentage of CR increased. The control specimen recorded 0.0033, which is close to the 0.003 suggested by ACI 318-11 [132], while values of 0.00345 and 0.00355 were recorded at 10% and 20% CR replacement, respectively. This is attributed to the increase in the deformation of RuGPC because of the deformable properties of CR, which positively affects the ductility of the concrete [131,133].

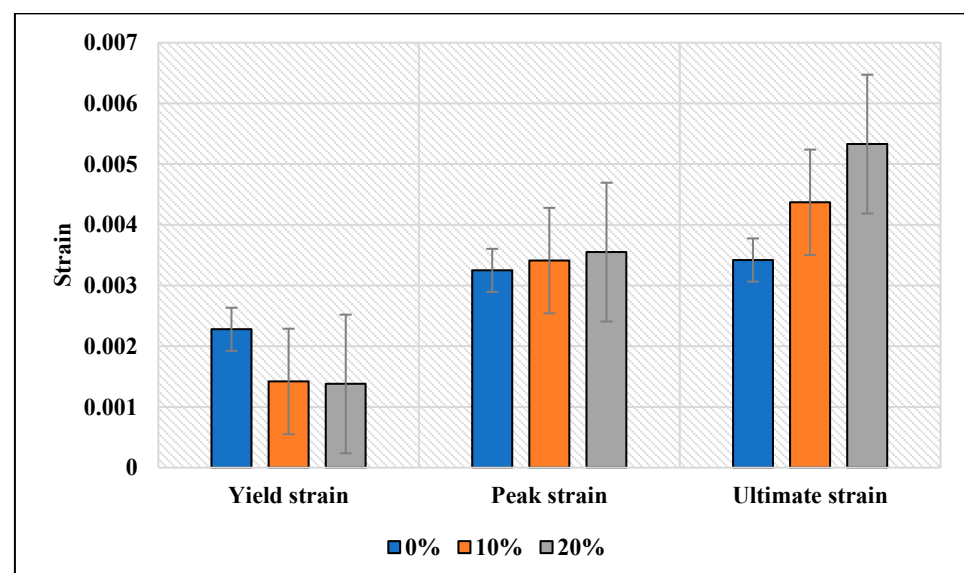


Figure 18. Strain values of RuGPC specimens.

The ultimate strain is thought to be more significant in the setting of rubberized geopolymer concrete than any other strain value. This is the strain at which the failure of the RuGPC specimen takes place [6,27,120]. The 0%, 10%, and 20% RuGPC specimens had average ultimate strains of 0.0034, 0.0044, and 0.0053, respectively, which are 27.78%

and 55.84% increments for 10% and 20% RuGPC in comparison to the control specimen. The ultimate strain performance of the RuGPC specimen is directly proportional to the percentage of CR in the specimen, since rubber aggregates effectively undergo deformation, lessen sudden failure (prevent brittle failure), and prolong the damage to the concrete. This phenomenon is consistent with most rubberized concretes, whether nominal or geopolymer concrete. In rubberized concrete research by Aleem et al. [134] where CR replaced fine aggregate at 0%, 5%, 10%, 15%, and 20%, it was discovered that the ultimate strain increased as the rubber content increased [135]. For RuGPC with treated CR, some investigations reported a decrease in ultimate strain at 10% CR replacement, but most reported an increase in ultimate strain at 20% CR replacement [6,29,136].

3.5.4. Modulus of Elasticity

A material's stiffness is dependent on its elastic modulus. It is a key variable in the design of geopolymer and rubberized geopolymer concrete. The modulus of elasticity (MoE) is used to check the displacement and strain distribution characteristics of concrete structural elements. In this investigation, the modulus of elasticity of RuGPC is expressed as the secant modulus obtained from the coefficient of x in the mathematical equation of the stress–strain curve, which represents 40% of the concrete cylinder average compressive strength (f_{cm}). Figure 19 clearly shows that there is a trending correlation between the compressive strength of RuGPC and the modulus of elasticity.

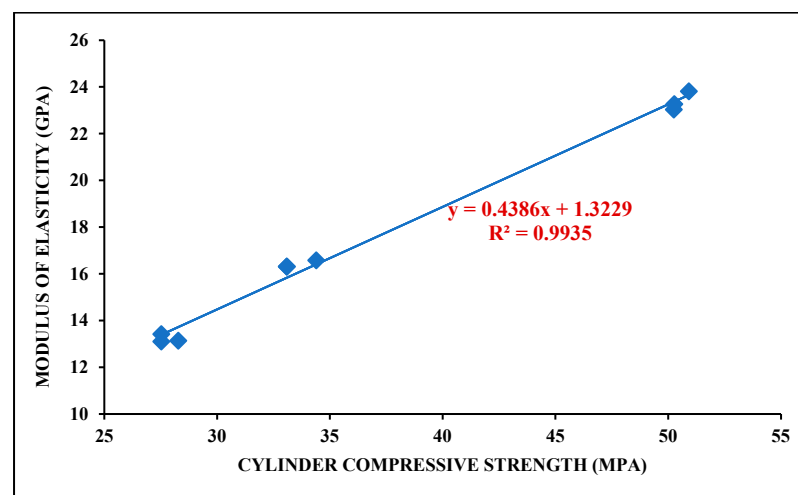


Figure 19. Relationship between MoE and compressive strength (f_{cm}) of RuGPC.

The modulus of elasticity of RuGPC samples was determined at 28 days as the average from three mixes of the same batch, as presented in Table 6. The MoEs of RuGPC in the 0%, 10%, and 20% CR replacement specimens were 23.37 GPa, 16.40 GPa, and 13.22 GPa, respectively.

From Figure 16, the rigidity of RuGPC with 10% and 20% CR is lower compared to that of RuGPC with 0% CR; hence, it can be concluded that the introduction of CR into GPC brings about a reduction in the MoE of the concrete. Similar results were reported by Luhar et al. [27], Hassan et al. [29], and Alaloul et al. [137]. The modulus of elasticity of the control samples was 29.82% and 43.42% higher than that of RuGPC specimens with 10% and 20% CR replacement, respectively. The reduction in the MoE of RuGPC can be attributed to several factors. First and foremost, the microstructure of the rubberized geopolymer concrete is a key factor that determines the MoE of the concrete, irrespective of the materials' source and aggregate. The microstructure is dependent on the strength of the interfacial transition zone (ITZ) and the porosity of the concrete. A weak interfacial

transition zone reduces the MoE of RuGPC because of the weak adhesive bond, resulting in more pores, and a less porous concrete is likely to have higher MoE. As the percentage of CR in RuGPC increases, the homogeneity of GPC decreases, resulting from increased porosity and weaker ITZ, leading to a reduction in the MoE. Another contributing factor to the reduction in MoE is that rubber aggregates have higher ductility and flexibility properties than granite. This is the reason why, in most cases, RuGPC experiences a higher deformation before failure compared to GPC, which makes RuGPC a more ductile concrete.

3.5.5. Poisson's Ratio

Poisson's ratio is the ratio of the vertical and horizontal strains (hoop strains) at 40% of the concrete cylinder's average compressive strength and is expressed with the formula in Equation (1) from ASTM C469 [138].

$$\mu = \frac{(\varepsilon_{t2} - \varepsilon_{t1})}{\varepsilon_2 - 0.000050} \quad (1)$$

where μ = Poisson's ratio, S_2 = stress at 40% of the ultimate load, S_1 = stress at 50 millionth (MPa) of vertical strain, ε_2 = vertical strain at S_2 , ε_{t2} = horizontal strain at S_2 , ε_{t1} = horizontal strain at S_1 .

Poisson's ratio of RuGPC ranges from 0.14 to 0.19 (Table 6). For nominal concrete, the value of Poisson's ratio ranges from 0.11 to 0.21; in most cases, values of 0.15 and 0.22 are adopted for high- and low-strength concrete, respectively [139]. The results obtained for RuGPC also fall within these ranges. From the results in Table 6, it can be observed that the concrete's Poisson's ratio increased with an increase in CR content. This is because CR has a Poisson's ratio of approximately 0.48 to 0.5, much higher than that of the fine aggregate. In addition, Poisson's ratio is also affected by the concrete's MoE. As MoE reduces with an increase in the percentage of CR, its stress resistance reduces with an increase in CR during loading, leading to an increase in the Poisson's ratio of the concrete. The Poisson's ratio of the 10% and 20% CR specimens increased by 5.52% and 30.34% in comparison to the control specimen. The 0% RuGPC can be classified as high-strength concrete, and the 20% RuGPC as medium-strength concrete, implying that both types of concrete can be used for structural purposes depending on the required design strength.

3.5.6. Toughness/Energy Absorption

A material's ability to resist plastic deformation and absorb energy without breaking is referred to as toughness. A material's toughness is dependent on its ductile characteristics and strength. Toughness can be calculated by integrating the entire area under the stress-strain curve [140,141]. From the results in Table 6, the control specimen displayed an average toughness of 10.11 N.m/m³. The toughness results of RuGPC specimens were seen to increase by 8.1% and 22.4% at 10% and 20% CR replacement, respectively, compared to the control. RuGPC displayed higher toughness characteristics than the control specimen, and it increased with an increase in rubber content. This implies that CR enhances GPC's toughness, and if the toughness is enhanced, it means its energy absorption capacity is also enhanced. Du et al. [142] reported a 31.9% increase in the toughness of concrete with the addition of 30% rubber aggregate of sizes 0.1–20 mm. Rubber aggregate was also reported as a material with high toughness characteristics in another investigation [143].

3.5.7. Ductility Index

Ductility index (*DI*) is the ability of concrete to tolerate distortion over the yield point before finally collapsing. The brittleness of GPC can be considerably decreased and transformed into a ductile concrete by the introduction of rubber (RuGPC). The ductility

index is the ratio of the concrete's ultimate strain (strain at 80%) to the yield strain [134], as presented in Equation (2).

$$DI = \frac{\Delta_u}{\Delta_{yield}} \quad (2)$$

The DI of each specimen is collected from the stress–strain curve and presented in Table 6. The ductility index of the control specimen was 1.91. The introduction of CR increased the ductility index by 102.67% and 156.67% at 10% and 20% CR, respectively, in comparison to 0% RuGPC. This proves that an increase in CR increased the ductility of concrete. In research by Abdo et al. [135], where CR was used as a surrogate to fine aggregate at 5%, 10%, 15%, and 20%, the concrete ductility was recorded to increase by 25.20% with the introduction of CR. Pham et al. [120] and Dong et al. [18] also confirmed the increase in the ductility index of RuGPC and attributed it to the CR's combined properties of a smaller elastic modulus and lower stiffness [144,145]. Table 6 provides the results of the MoE, Poisson's ratio, toughness, peak stress, ultimate strain, peak strain, and yield strain of the stress–strain curves.

3.6. Failure Mode

The failure mode of concrete cylinders when subjected to axial compression load is usually diagonal; usually, the cylinders experience shear fracture diagonally when the bond strength between the concrete constituents is strong. The failure mode of the concrete cylinder specimens with different percentages of CR is shown in Figure 20. All the specimens displayed normal crack failures, implying that the introduction of CR does not change the failure pattern of RuGPC. In the testing process, small fractures started to appear at the top of bottom corners of the concrete cylinder and later started to appear inside the concrete cylinder as the stress increased. Before the applied stress reached the peak load, the fractures generated by the specimens were roughly parallel to the direction of the axial compression load. The failure across all the concrete specimens was shear failure with diagonal fractures running through each sample. Specifically, the compression of the specimens is vertical, which indicates that Poisson's ratio influences the lateral formation of tensile strain. The destruction of the specimens occurs the moment the concrete's ultimate tensile strain is reached by the lateral tensile strain, thus forming the above-mentioned modes of failure.

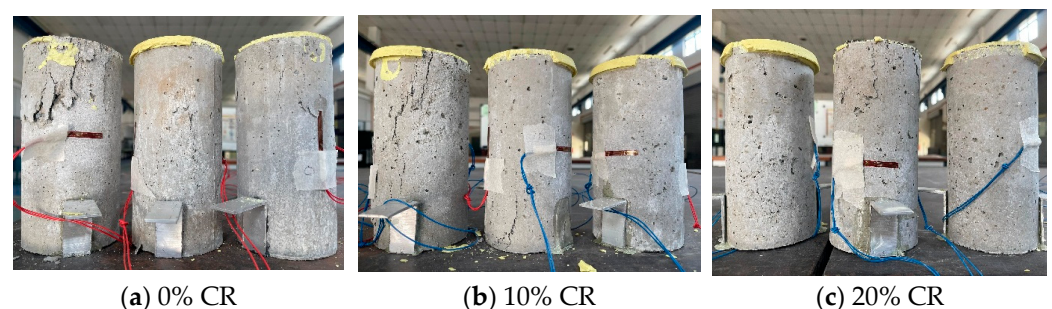


Figure 20. Failure modes of RuGPC specimens: (a) 0% RuGPC, (b) 10% RuGPC, (c) 20% RuGPC.

The control specimen had more pronounced cracks, as shown in Figure 20a, characterized by brittle failure. The 10% RuGPC specimen displayed more uniform and moderate cracks. In the case of RuGPC with CR, as the concrete strain progressively increased there was a reduction in the stress on the crack until the concrete failed, and even after unloading the specimen the cracked cylinder remained intact without splitting, as can be seen in Figure 20b. In the 20% RuGPC concrete cylinder, the cracks that appeared were smoother with very narrow crack width (see Figure 20c). The failure pattern noticed in Figure 20b,c is

because of the CR present in the concrete. The utilization of CR in GPC inhibits the spread of cracks, increases its resistance to abrupt failure, and leverages the ductile characteristics of rubber [146]. Normally, the brittle fracture in nominal GPC is very high, and CR helps to delay the creation of fractures as well as minimize their development or spread due to deformable properties [84]. As the percentage of CR in concrete increases, there is a change in the mode of failure to a smoother pattern, and the cracks developed in the concrete become much smaller [12]. From the findings of the experimental investigation, RuGPC is suggested to be a concrete with great qualities for adoption in structures where impact resistance and energy absorption are paramount, while simultaneously enhancing concrete's sustainability.

4. Correlation with Standard Codes

4.1. Modulus of Elasticity (MoE)

The MoE of RuGPC from the experimental results was compared with the numerical predictions by standard codes for the MoE of OPC concrete to see how well they can predict the MoE of ambient-cured GGBFS/FA-based RuGPC.

ACI 318-19 [124]: $E_c = 4700\sqrt{f_c}$, ACI 363R-10 [147]: $E_c = 3320\sqrt{f_c} + 6900$, BS EN 19-1-1 [44]: $f_{cm} = f_{ck} + 8$, $E_c = 22[(f_{cm})/10]^{0.3}$, EC 2 (2004) [148]: $E_c = 200 \times f_c + 20,000$. Previous researchers have also proposed models through regression analysis of experimental results for calculating the MoE of GPC. Noushini et al. [149]: $E_c = -11400 + 4712\sqrt{f_c}$, Hassan et al. [29]: $E_c = 463f_c + 188$.

E_c and f_c represents the modulus of elasticity and cylinder compressive strength of concrete.

Since the mentioned universal codes for nominal concrete concern $150 \times 150 \times 150$ mm cubes and $150 \text{ mm} \times 300 \text{ mm}$ cylinders, while this investigation tested cubes with 100 mm and $100 \text{ mm} \times 200 \text{ mm}$ cylinders, a conversion factor of 0.96 was applied as proposed by ASTM C 39 [150] and ASHTO T 22 [151].

The data from the experimental results and numerical calculations are plotted graphically in Figure 21. Table 7 presents the ratio of experimental data to numerical predictions of MoE results by standard codes and models proposed from previous investigations.

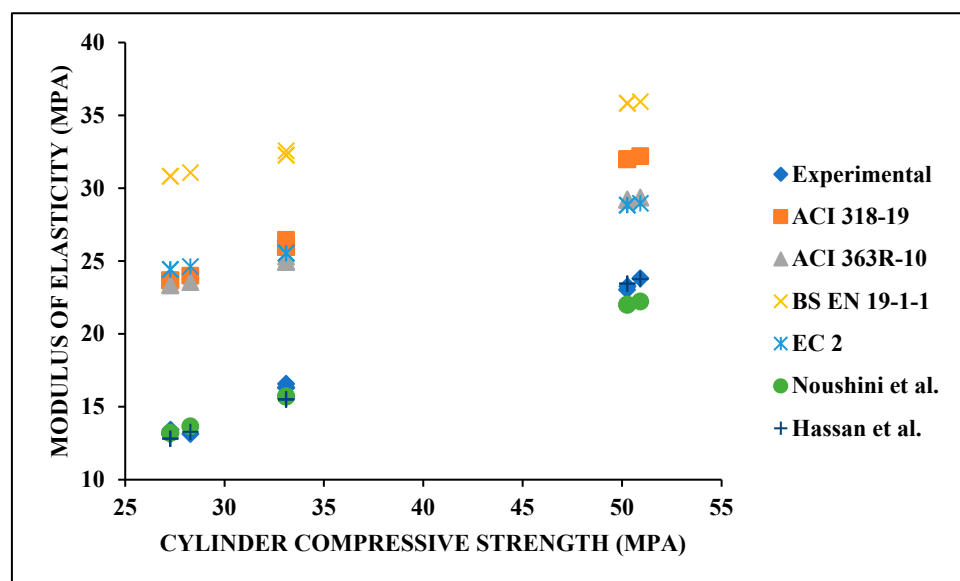


Figure 21. Modulus of elasticity versus compressive strength predictions by standard codes/literature studies [29,149].

Table 7. The ratio of experimental data to numerical predictions of MoE results by standard codes/literature studies.

No.	CS	EXP. MoE	ACI 318-19	ACI 363R-10	BS EN 19-1-1	EC2	Noushini et al. [149]	Hassan et al. [29]
C001	50.27	23.27	0.73	0.80	0.65	0.81	1.06	0.99
C002	50.25	23.04	0.72	0.79	0.64	0.80	1.05	0.98
C003	50.91	23.82	0.74	0.81	0.66	0.82	1.07	1.00
C101	33.10	16.31	0.63	0.65	0.51	0.64	1.04	1.05
C102	33.09	16.58	0.63	0.65	0.51	0.65	1.06	1.07
C103	33.08	16.31	0.63	0.65	0.51	0.64	1.04	1.05
C201	27.27	13.42	0.57	0.57	0.44	0.55	1.02	1.05
C202	28.27	13.14	0.55	0.56	0.42	0.53	0.96	0.99
C203	27.25	13.11	0.55	0.56	0.43	0.54	0.99	1.02
AVG	-	-	0.64	0.67	0.53	0.66	1.03	1.02
S. D	-	-	0.08	0.10	0.10	0.12	0.03	0.03
COV	-	-	11.85	15.24	18.62	17.77	3.38	3.20

Note: CS represents the compressive cylinder strength.

It can be seen from Figure 21 and Table 7 that the results predicted by Hassan et al. [29] were the closest to the experimental results, with ratios in the range of 0.98 to 1.07 and a standard deviation and coefficient of variation of 0.03 and 3.2%, respectively. Noushini et al.'s [149] formula also gave very similar results to those of the experimental results, with ratios ranging between 0.96 and 1.07 and a standard deviation and coefficient of variation of 0.03 and 3.38, respectively. All the other standard codes overestimated the MoE of GGBFS/FA-based RuGPC [44,124,147,148].

4.2. Peak Strain

The peak strain of RuGPC is very important in analyzing the stress–strain relationship. According to Popovics [152], the strain at the peak stress ϵ'_c indicates the degree of micro-cracking that takes place up until the peak stress. Hassan et al. [29] reported that when the calculated strain of RuGPC was put into the CEB-FIB [153] model, its prediction of the stress–strain curve accurately matched that of the experimental results. This investigation will evaluate the model for analyzing strain at peak stress proposed by previous researchers for geopolymers concrete, as presented in Table 8. Some scholars have put forth linear formulas that depend on the compressive strength of concrete to forecast the peak strain. Hardjito [97] & Sarker [154] used regression analysis from experimental GPC results to propose Equation (3), while Noushini et al. [149] & Hassan et al. [29] proposed Equation (4) (the equation for MoE in Equation (4) was proposed by Noushini et al. [149]). The modulus of elasticity E_c is a metric for the linearity of ascending part of the stress–strain curve.

$$\epsilon'_c = \frac{f'_c}{E_c} \frac{n}{n-1} \quad (3)$$

where $E_c = 2707\sqrt{f'_c} + 5300$, $n = 0.8 + \frac{f'_c}{12}$

$$\epsilon'_c = \frac{2.23 \times 10^7 (E_c)^{1.74}}{(f'_c)^{1.98}} \quad (4)$$

$$E_c = -11,470 + 4712\sqrt{f'_c}$$

E_c and f'_c represents the modulus of elasticity (MPa) and peak stress (MPa), respectively.

Table 8. The ratios of experimental data to numerical predictions of peak strain results by the previous literature.

No.	Practical Results			Noushini et al. [149]	Hardjito et al. [97]
	CS	MoE	Strain	Exp/Num	Exp/Num
C001	50.265	23.265	0.0033	1.60	1.29
C002	50.248	23.036	0.00328	1.59	1.28
C003	50.910	23.818	0.00322	1.58	1.25
C101	33.096	16.314	0.00346	1.32	1.57
C102	33.089	16.581	0.00345	1.32	1.56
C103	33.082	16.314	0.00344	1.32	1.56
C201	27.274	13.422	0.00357	1.26	1.72
C202	28.273	13.141	0.00352	1.26	1.68
C203	27.252	13.11	0.00356	1.26	1.71
AVG	-	-	-	1.39	1.51
S. D	-	-	-	0.15	0.19
COV	-	-	-	11.01	12.64

As can be seen from Table 8, the models proposed by Hardjito [97] and Noushini et al. [29] underestimated the peak strain of the concrete with respect to the experimental results with a coefficient of variation of 11.01% and 12.64%, respectively. This is because the strength of the ITZ between CR and the geopolymer determines the peak strain. The surface texture and size of CR determine the strength of the ITZ as well as the method of CR pre-treatment. Some investigations reported that the peak strain decreased [155–157], while others reported that the peak strain increased [112,135,158] as the percentage of CR in the concrete increased. Zhang et al. [6] found that the peak strain increased up to 10% of CR, after which it decreased, and Hassan et al. [29] found that the peak strain of 5% untreated CR RuGPC was higher than the control specimen, but the strain after 5% was lower. These irregularities are also reflected in the failure mode of the specimens. The number of cracks and intensity increased with an increase in CR in some reports [29], while the reverse is the case in some other reports (see Figure 20). For this reason, it is suggested that a model for peak strain be formulated from the regression of the experimental results from every test with CR.

5. Proposed Models

5.1. Cube Compressive Strength

In this investigation, a model to forecast the compressive strength of RuGPC was put forward from the regression analysis of the experimental results. The numerical equation is expressed in Equation (5).

$$f_{cu} = 0.9508[0.3603\rho - 734.46] \text{ (MPa)} \quad (5)$$

where f_{cu} represents the 28-day compressive strength, and ρ is the concrete density.

Figure 22 demonstrates how the suggested model and the experimental results fit. To validate the degree of efficiency of the accuracy of Equation (3) in predicting the compressive strength of RuGPC samples with respect to density, it will be used to predict the compressive strength of experimental results from previous literature, as presented in Table 9.

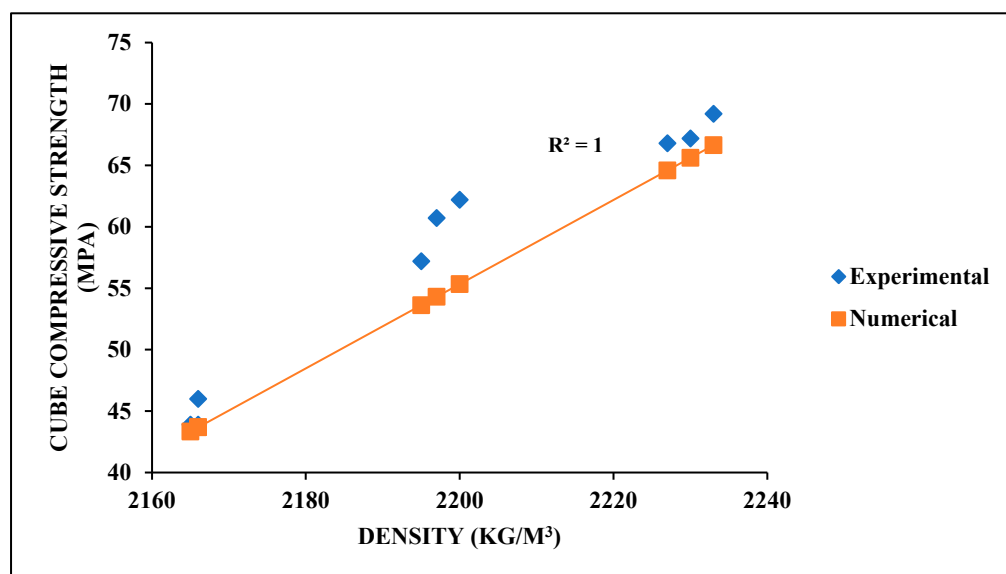


Figure 22. Cube compressive strength vs. density of RuGPC for proposed numerical and experimental results.

Table 9. Correlation of experimental results from previous investigations and proposed numerical equation results.

Ref.	Conc. Type	Desc.	CR (%)	Density	Exp. CS	Num. CS	Exp/Num
Fine aggregate replacement							
Experimental		NaOH	0	2230	67.50	66.30	1.02
			10	2200	60.70	55.34	1.10
			20	2165	43.90	43.35	1.01
Saloni et al. [17]	GPC	No treatment	0	2380	62.60	117.00	0.54
			10	2250	53.20	72.47	0.73
			20	2195	46.50	53.62	0.87
		water	10	2260	54.50	75.89	0.72
			20	2210	47.70	58.76	0.81
		NaOH	10	2250	57.60	72.47	0.79
			20	2200	54.60	55.34	0.99
		Cement	10	2300	55.70	89.59	0.62
			20	2230	49.60	65.61	0.76
		UFC	10	2290	58.20	86.17	0.68
			20	2220	54.60	62.19	0.88
		Azmi et al. [77]	GPC	R.T	0	2230	65.00
5	2120				33.00	27.93	1.18
10	2103				28.00	22.11	1.27
Metwally et al. [159]	GPC	0–1	0	2240	51.33	69.04	0.74
			10	2180	41.60	48.49	0.86
			20	2090	35.55	17.65	2.01
		1–4	30	2080	28.80	14.23	2.02
			10	2180	44.61	48.49	0.92
			20	2110	34.29	24.50	1.40
		4	30	2040	28.06	0.52	53.46
			10	2190	44.34	51.91	0.85
			20	2130	35.84	31.36	1.14
		1–4	30	2020	28.71	−6.33	−4.54
			10	2190	43.82	51.91	0.84
			20	2120	36.78	27.93	1.32
			30	2010	28.87	−9.75	−2.96

Table 9. Cont.

Ref.	Conc. Type	Desc.	CR (%)	Density	Exp. CS	Num. CS	Exp/Num
Hassan et al. [29]	GPC	0	0	2160	41.91	41.63	1.01
		NaOH	5	2150	35.09	38.21	0.92
			15	2120	33.20	27.93	1.19
			25	2110	31.08	24.50	1.27
		No treatment	5	2140	33.53	34.78	0.96
			15	2130	29.78	31.36	0.95
			25	2120	27.72	27.93	0.99
Fadiel et al. [160]	NC	C40	0	2340	39.00	103.30	0.38
			5	2265	32.00	77.60	0.41
			10	2230	30.00	65.61	0.46
			15	2215	29.50	60.48	0.49
		C60	20	2180	29.00	48.49	0.60
			0	2539	57.37	171.47	0.33
			10	2439	52.29	137.21	0.38
Nouran et al. [86]	NC	C60	15	2390	42.44	120.43	0.35
			20	2302	40.64	90.28	0.45
			0	2401	36.44	124.19	0.29
		C40	10	2307	33.87	91.99	0.37
			15	2257	27.03	74.86	0.36
			20	2190	25.59	51.91	0.49
			Coarse aggregate replacement				
Hassan et al. [29]	GPC	NaOH	5	2150	20.41	38.21	0.53
			15	2145	19.15	36.50	0.52
			25	2135	18.72	33.07	0.57
		No treatment	5	2155	19.10	39.92	0.48
			15	2140	17.19	34.78	0.49
			25	2130	16.55	31.36	0.53

CS = cube compressive strength.

The ratio of experimental to proposed numerical results ranged from 0.81 to 1.27 and had a coefficient of variation of 16% for RuGPC specimens with 0%, 10%, 20%, and 25% CR fine aggregate, whose densities were in the range of 2100 to 2230 kg/m³. There is a strong correlation between the experimental and numerical results from this investigation. This exempts RuGPC specimens with cement-coated CR. This is because Portland cement had more effect on the unit weight of the concrete than it did on the compressive strength; hence, the compressive strength was overestimated. The average mean ratio of experimental to proposed numerical results was 0.60 for RuGPC specimens with densities above 2230 kg/m³. This implies that the numerical formula overestimated the compressive strength by an average of 48.20%. RuGPC specimens with densities below 2100 kg/m³ were massively underestimated; 2080 to 2100 kg/m³ was underestimated by approximately 50.45%, while the underestimation was above 100% when the density was below 2080 kg/m³. The numerical expression is unsuitable for RuGPC with CR coarse aggregate replacement, as the average ratio for experimental to numerical results was 0.52, meaning it overestimated the compressive strength.

The numerical expression is also unsuitable for nominal concrete regardless of the design strength or percentage of CR replacement. This is because the compressive strength of nominal concrete was overestimated by an average of 156.31%, which is why the experimental to numerical results ratio was as low as 0.41. This is attributed to the fact that GPC has higher compressive strength than NC of the same concrete grade [106]; also, CR has a better bond strength with GPC than NC, especially when the CR is treated with NaOH [47,125]. This is a result of the high percentage of Al₂O₃ in the binder required

for geopolymerization. The strength of GPC is dependent on the alkaline geopolymer matrix formed from dissolved Al and Si ions in the AAS, which is further increased by the concentration of NaOH.

5.2. Modulus of Elasticity

In this paper, a regression analysis of the results from the experiment is used to suggest a model to calculate the MoE of RuGPC. The numerical equation is expressed in Equation (6).

$$E_c = 993.5[0.4386f_{cm} + 1.3229] \text{ (MPa)} \quad (6)$$

where f_{cm} represents the mean compressive strength of an RuGPC cylinder specimen in MPa.

The suggested model and experimental results have a well-fitted connection, as shown in Figure 23. The degree of accuracy of the proposed formula in predicting the MoE of RuGPC is evaluated in Table 10 by calculating its standard deviation and coefficient of variation with results from previous studies. The results from the models proposed for GPC by Hassan et al. [29] and Noushini et al. [149] came very close to the experimental results; hence, the data from the proposed model in this investigation will be compared to those of Hassan et al. [29] and Noushini et al. [149] to see which formula has a higher accuracy. Table 9 presents the MoE of this investigation and other investigations and analyzes the ratio of the experimental results to the numerical results from the proposed models as well as models proposed by Hassan et al. [29] and Noushini et al. [149].

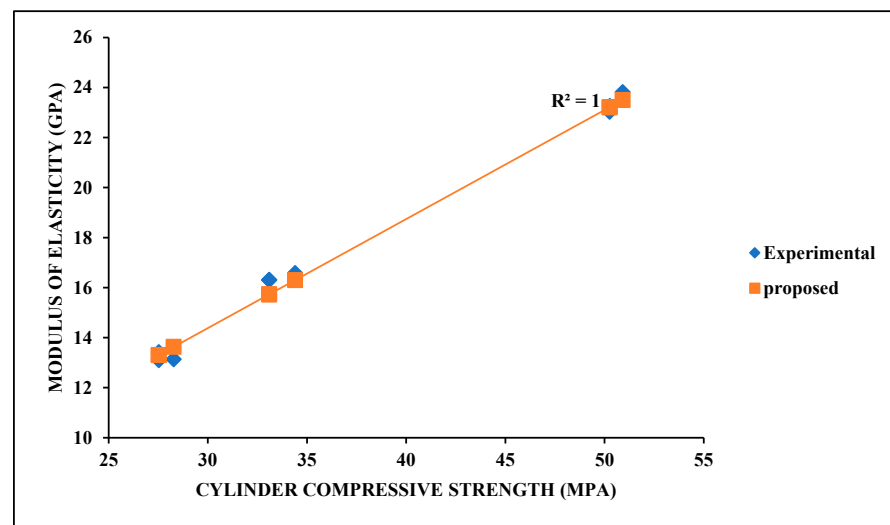


Figure 23. Relationship between MoE and compressive strength (f_{cm}) of RuGPC.

Table 10. The ratio of MoE experimental to numerical results from the proposed model and previous research.

REF	CR	CS	MoE	Proposed	Noushini et al. [149]	Hassan et al. [29]
Experimental	0.00	50.27	23.27	1.00	1.06	0.99
	0.00	50.25	23.04	0.99	1.05	0.98
	0.00	50.91	23.82	1.01	1.07	1.00
	10.00	33.10	16.31	1.04	1.04	1.05
	10.00	33.09	16.58	1.05	1.06	1.07
	10.00	33.08	16.31	1.04	1.04	1.05
	20.00	27.27	13.42	1.02	1.02	1.05
	20.00	28.27	13.14	0.96	0.96	0.99
	20.00	27.25	13.11	0.99	0.99	1.02

Table 10. Cont.

REF	CR	CS	MoE	Proposed	Noushini et al. [149]	Hassan et al. [29]
Metwally et al. [159]	0.00	51.00	24.40	1.04	1.10	1.03
	RA10	41.60	20.70	1.06	1.09	1.06
	RA20	35.55	17.30	1.03	1.04	1.04
	RA30	28.80	14.60	1.05	1.05	1.08
	RB10	44.61	22.60	1.09	1.13	1.08
	RB20	34.29	18.20	1.12	1.12	1.13
	RB30	28.06	15.30	1.13	1.13	1.16
	RC10	44.34	22.10	1.07	1.11	1.07
	RC20	35.84	18.70	1.10	1.11	1.11
	RC30	28.71	15.40	1.11	1.11	1.14
	RD10	43.82	21.80	1.07	1.10	1.06
	RD20	36.78	19.20	1.11	1.12	1.12
	RD30	28.87	16.90	1.22	1.21	1.25
Hassan et al. [29]	0.00	54.00	31.50	1.27	1.36	1.25
	10.00	48.33	28.70	1.28	1.34	1.27
	20.00	40.00	24.20	1.29	1.32	1.29
Alsaif et al. [161]	N.M	38.00	20.70	1.16	1.17	1.16
	N.M	16.40	15.10	1.78	1.97	1.94
Alsaif et al. [162]	0.00	45.90	21.00	0.99	1.02	0.98
	10.00	39.00	20.70	1.13	1.15	1.13
	20.00	37.70	18.00	1.01	1.03	1.02
	30.00	36.70	17.30	1.00	1.01	1.01
	40.00	28.70	14.90	1.08	1.08	1.11
	50.00	16.90	11.80	1.36	1.48	1.47
Saloni et al. [17]	0.00	62.61	25.32	0.89	0.98	0.87
	10.00	53.22	23.34	0.95	1.02	0.94
	20.00	46.50	21.82	1.01	1.05	1.00
	30.00	39.91	20.22	1.08	1.10	1.08
	10.00	54.47	23.62	0.94	1.01	0.93
	20.00	47.74	22.11	1.00	1.05	0.99
	30.00	43.59	21.13	1.04	1.07	1.04
	10.00	57.60	24.29	0.92	1.00	0.90
	20.00	54.56	23.64	0.94	1.01	0.93
	30.00	46.05	21.71	1.02	1.06	1.01
	10.00	55.72	23.89	0.93	1.00	0.92
	20.00	49.60	22.54	0.98	1.03	0.97
	30.00	48.82	21.42	0.95	1.00	0.94
	10.00	58.23	24.43	0.92	0.99	0.90
	20.00	54.56	23.70	0.94	1.01	0.93
	30.00	45.43	21.57	1.02	1.06	1.02
Iqbal et al. [158]	0.00	59.00	34.00	1.26	1.37	1.24
	10.00	49.00	26.00	1.15	1.20	1.14
	20.00	40.00	20.00	1.07	1.09	1.07
	30.00	28.00	14.00	1.04	1.03	1.06
Albidah et al. [163]	0.00	45.90	21.00	0.99	1.02	0.98
	20.00	33.50	18.70	1.18	1.18	1.19
	40.00	21.10	15.50	1.47	1.51	1.56
Metwally et al. [164]	0.00	58.70	29.30	1.09	1.19	1.07
	3.00	58.10	28.30	1.06	1.15	1.04
	6.00	53.30	27.40	1.12	1.19	1.10
	9.00	51.50	26.40	1.11	1.18	1.10

Table 10. Cont.

REF	CR	CS	MoE	Proposed	Noushini et al. [149]	Hassan et al. [29]
Noushini et al. [149]	SAC	41.70	19.30	0.99	1.01	0.99
	HC-1	27.40	13.50	1.02	1.02	1.05
	HC-2	37.80	16.60	0.93	0.94	0.94
	HC-3	45.60	20.30	0.96	0.99	0.95
	HC-4	50.00	22.90	0.99	1.04	0.98
	HC-5	44.80	20.40	0.98	1.01	0.97
	HC-6	53.90	22.80	0.92	0.98	0.91
	HC-7	60.00	24.40	0.89	0.97	0.87
	HC-8	62.30	25.90	0.91	1.00	0.89
	HC-9	52.20	23.90	0.99	1.06	0.98
	HC-10	58.60	23.90	0.89	0.97	0.87
	HC-11	59.80	25.10	0.92	1.00	0.90
	HC-12	60.70	25.80	0.93	1.02	0.91
AVG				1.06	1.10	1.06
SD				0.14	0.15	0.16
COV				13.47	13.98	15.47

From Table 10, the results predicted by the proposed model in this investigation were the closest to the experimental results, with ratios in the range of 0.89 to 1.78, with a standard deviation and coefficient variation of 0.14% and 13.47%, respectively. Therefore, the modulus of elasticity of rubberized geopolymer concrete can be calculated using the numerical formula proposed in this investigation. The standard deviation between the experimental and numerical results for the modulus of elasticity proposed by this investigation, Noushini et al. (FA-GPC), and Hassan et al. (FA-GPC), was 0.14, 0.15, and 0.16. The average modulus of elasticity of metakalin-based GPC was 1.19, while that of FA-based RuGPC was 0.9 when predicted with the proposed experimental model. This implies that there is a strong correlation between the stress–strain parameters of RuGPC made with GGBFS/FA, FA, and Metakaolin.

5.3. Peak Strain

From Table 8, where the experimental data were compared with the proposed formulas, it is paramount to formulate a model that can predict the peak strain of the experimental results of NaOH-treated CR GGBGS/FA-based RuGPC. A numerical model is proposed in Equation (7) based on regression analysis from the experimental results illustrated in Figure 24. The degree of accuracy of the model was evaluated in Table 11 by verifying it with experimental results from the previous literature and checking the coefficient of variation with models proposed by Hardjito [97] and Noushini et al. [149].

$$\varepsilon'_c = 0.9762[-0.00001f_{cm} + 0.0039] \quad (7)$$

where f_{cm} represents the mean compressive strength (peak stress) of the RuGPC cylinder specimen in MPa

As shown in Table 11, the results predicted by the proposed model in this investigation were the closest to the experimental results, with ratios in the range of 0.76 to 1.75 and a standard deviation and coefficient variation of 0.08 and 6.54%, respectively. Therefore, the peak strain of rubberized geopolymer concrete can be calculated using the numerical formula proposed in this investigation. The standard deviation between the experimental and numerical results of the peak strain modulus from this investigation, Noushini et al. (FA-GPC), and Hassan et al. (FA-GPC) was 0.08, 0.15, and 0.19 with respect to the peak

stress. The small standard deviation implies that the binder type (GGBFS/FS, FA, or MK) has little effect on the peak strain of the material.

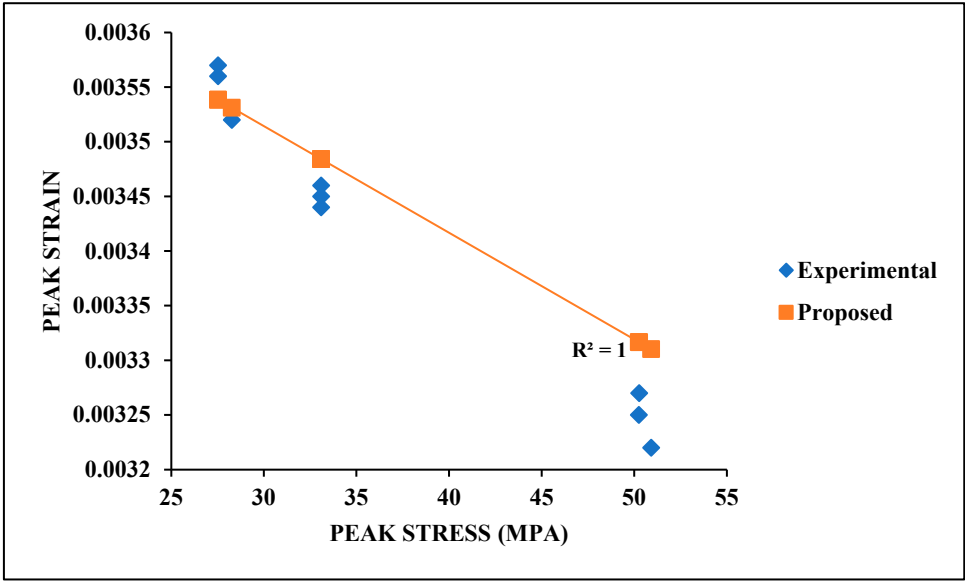


Figure 24. Relationship between peak strain and peak stress (f_{cm}) of RuGPC.

Table 11. The ratio of peak strain from experimental to numerical results from the proposed model and previous research.

Ref	CR	Practical Results			Proposed	Noushini et al. [149]	Hardjito et al. [97]
		PS	MoE	Strain	Exp/Num	Exp/Num	Exp/Num
Experimental	0	50.265	23.265	0.00330	1.00	1.60	1.29
	0	50.248	23.036	0.00328	0.99	1.59	1.28
	0	50.910	23.818	0.00322	0.97	1.58	1.25
	10	33.096	16.314	0.00346	0.99	1.32	1.57
	10	33.089	16.581	0.00345	0.99	1.32	1.56
	10	33.082	16.314	0.00344	0.99	1.32	1.56
	20	27.274	13.422	0.00357	1.01	1.26	1.72
	20	28.273	13.141	0.00352	1.00	1.26	1.68
	20	27.252	13.110	0.00356	1.01	1.26	1.71
Hassan et al. [29]	0	41.910	18.40	0.00333	0.98	1.45	1.39
	5	35.090	19.09	0.00299	0.86	1.18	1.33
	15	33.200	17.24	0.00305	0.88	1.17	1.38
	5	33.530	17.84	0.00363	1.04	1.40	1.64
Alsaif et al. [161]	0	38.000	20.70	0.00285	0.83	1.17	1.23
Alsaif et al. [162]	0	45.900	21.00	0.00320	0.95	1.47	1.29
	10	39.700	20.70	0.00280	0.82	1.18	1.19
	20	37.700	18.00	0.00330	0.96	1.35	1.43
	30	36.600	17.30	0.00275	0.80	1.11	1.21
Iqbal et al. [158]	0	59.000	34.00	0.00289	0.89	1.57	1.05
	10	49.000	26.00	0.00300	0.90	1.43	1.18
	20	40.000	28.00	0.00285	0.83	1.20	1.21
Albidah et al. [163]	0	45.900	21.00	0.00330	0.98	1.51	1.33
	20	33.500	18.70	0.00264	0.76	1.02	1.19

Table 11. Cont.

Ref	CR	Practical Results			Proposed	Noushini et al. [149]	Hardjito et al. [97]
		PS	MoE	Strain	Exp/Num	Exp/Num	Exp/Num
Zhang et al. [6]	0	39.400	12.80	0.00600	1.75	2.51	2.56
	5	43.800	19.40	0.00500	1.48	2.23	2.05
	10	46.900	19.60	0.00495	1.48	2.30	1.98
	15	42.300	18.00	0.00350	1.03	1.53	1.46
	20	38.800	14.10	0.00450	1.31	1.87	1.93
AVG					1.24	1.79	1.81
S. D					0.08	0.15	0.19
COV					6.54	8.56	10.55

6. Conclusions

This research investigated the effect of crumb rubber on the mechanical and stress–strain characteristics of rubberized geopolymer concrete, with crumb rubber replacing fine aggregate at 0%, 10%, and 20%. The results from the experimental program are concluded as follows:

1. The standard deviation between the experimental and numerical results of the modulus of elasticity proposed by this investigation, Noushini et al. (FA-GPC), and Hassan et al. (FA-GPC) was 0.14, 0.15, and 0.16, while that of the peak strain with respect to the peak stress was 0.08, 0.15, and 0.19. The average modulus of elasticity of metakalin-based GPC was 1.19, while that of FA-based RuGPC was 0.9 when predicted with the proposed experimental model. This implies that there is a strong correlation between the stress–strain parameters of RuGPC made with GGBFS/FA, FA, and Metakaolin.
2. The peak strain and ultimate strain increased by 8.56% and 55.84%, respectively, when the percentage of CR was raised to 20%, which shows that rubberized geopolymer concrete has higher deformability characteristics. This quality of rubberized geopolymer concrete was confirmed when the Poisson's ratio, toughness, and ductility index increased by 30.34%, 22.4%, and 156.67%. This makes rubberized geopolymer concrete very suitable for areas prone to vibration.
3. The concrete slump, density, compressive strength, peak stress, and modulus of elasticity of RuGPC reduced by 8.33%, 2.91%, 34.67%, 44.97%, and 43.42%, respectively, at 20% addition of CR replacement compared to the control specimen. This implies that the use of rubber aggregate negatively affects concrete workability and load-bearing capacity.
4. Numerical models were proposed for the cube compressive strength, modulus of elasticity, and peak strain of RuGPC at different percentages of crumb rubber. The findings demonstrate that the model's predictions fit the experimental data quite well. The model's calculated results, with R^2 values of 0.9508, 0.9935, and 0.9762, show a high degree of consistency with the experimental data. Formulas proposed by Hassan et al. and Noushini et al. can also predict the modulus of elasticity of rubberized geopolymer concrete with a high degree of accuracy.
5. The failure mode of geopolymer concrete with rubber aggregates showed fewer cracks, confirming the theory that rubber positively affects the energy absorption capacity and toughness of concrete. However, it reduces the workability and mechanical characteristics of concrete. It is paramount to balance the percentage of rubber in concrete with improved rubber pre-treatment to enable rubberized geopolymer concrete to attain the required workability and mechanical qualities while imposing its dominance in energy dissipation and toughness.

6. The results show that rubberized geopolymer concrete can be used for the construction of structural elements subjected to lateral impact and where high energy absorption is required, e.g., columns in underground car parks and underneath bridges prone to vehicular collision, airport pavements, etc.

Author Contributions: Conceptualization, S.U.A. and F.N.A.A.A.; methodology, S.U.A.; formal analysis, S.U.A. and F.N.A.A.A.; investigation, S.U.A. and F.N.A.A.A.; resources, F.N.A.A.A., S.U.A. and E.B.M.; writing—original draft preparation, S.U.A.; writing—review and editing, F.N.A.A.A.; visualization, S.U.A. and F.N.A.A.A.; supervision, F.N.A.A.A. and R.S.M.R.; project administration, F.N.A.A.A. and E.B.M.; funding acquisition, F.N.A.A.A. and E.B.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Putra Malaysia under the Geran Putra-IPS (GP-IPS/2023/9769300) with Vot no: 9769300. The study was titled “Structural Application of Crumb rubber Geopolymer Concrete”.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to express their gratitude to Universiti Putra Malaysia, for providing financial support for this study under the Geran Putra-IPS (GP-IPS/2023/9769300) with Vot no: 9769300. The study was titled “Structural Application of Crumb rubber Geopolymer Concrete.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pourmohammadimojaveri, S. High Performance Rubber Concrete. Ph.D. Thesis, Sydney University, Sydney, Australia, 2019.
2. Thomas, B.S.; Gupta, R.C.; Kalla, P.; Cseteneyi, L. Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates. *Constr. Build. Mater.* **2014**, *59*, 204–212. [\[CrossRef\]](#)
3. Yadav, J.S.; Tiwari, S.K. The impact of end-of-life tires on the mechanical properties of fine-grained soil: A Review. *Environ. Dev. Sustain.* **2019**, *21*, 485–568. [\[CrossRef\]](#)
4. Sodupe-Ortega, E.; Fraile-Garcia, E.; Ferreira-Cabello, J.; Sanz-Garcia, A. Evaluation of crumb rubber as aggregate for automated manufacturing of rubberized long hollow blocks and bricks. *Constr. Build. Mater.* **2016**, *106*, 305–316. [\[CrossRef\]](#)
5. Rigotti, D.; Dorigato, A. Novel uses of recycled rubber in civil applications. *Adv. Ind. Eng. Polym. Res.* **2022**, *5*, 214–233. [\[CrossRef\]](#)
6. Zhang, B.; Feng, Y.; Xie, J.; Lai, D.; Yu, T.; Huang, D. Rubberized geopolymer concrete: Dependence of mechanical properties and freeze-thaw resistance on replacement ratio of crumb rubber. *Constr. Build. Mater.* **2021**, *310*, 125248. [\[CrossRef\]](#)
7. Ullah, H.; Iqbal, M.; Khan, K.; Jamal, A.; Nawaz, A.; Khan, N.; Jalal, F.E.; Almaliki, A.H.; Hussein, E.E. Experimental investigation of the stress–strain behavior and strength characterization of rubberized reinforced concrete. *Materials* **2022**, *15*, 730. [\[CrossRef\]](#)
8. Jokar, F.; Khorram, M.; Karimi, G.; Hataf, N. Experimental investigation of mechanical properties of crumbed rubber concrete containing natural zeolite. *Constr. Build. Mater.* **2019**, *208*, 651–658. [\[CrossRef\]](#)
9. He, S.; Jiang, Z.; Chen, H.; Chen, Z.; Ding, J.; Deng, H.; Mosallam, A.S. Mechanical properties, durability, and structural applications of rubber concrete: A state-of-the-art-review. *Sustainability* **2023**, *15*, 8541. [\[CrossRef\]](#)
10. Han, Y.; Lv, Z.; Bai, Y.; Han, G.; Li, D. Experimental Study on the Mechanical Properties of Crumb Rubber Concrete after Elevated Temperature. *Polymers* **2023**, *15*, 3102. [\[CrossRef\]](#)
11. Youssf, O.; Mills, J.E.; Benn, T.; Zhuge, Y.; Ma, X.; Roychand, R.; Gravina, R. Development of crumb rubber concrete for practical application in the residential construction sector—Design and processing. *Constr. Build. Mater.* **2020**, *260*, 119813. [\[CrossRef\]](#)
12. Khaloo, A.R.; Dehestani, M.; Rahmatatabadi, P. Mechanical properties of concrete containing a high volume of tire–rubber particles. *Waste Manag.* **2008**, *28*, 2472–2482. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Pacheco-Torgal, F.; Ding, Y.; Jalali, S. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. *Constr. Build. Mater.* **2012**, *30*, 714–724. [\[CrossRef\]](#)
14. Abd-Elal, E.-S.; Araby, S.; Mills, J.E.; Youssf, O.; Roychand, R.; Ma, X.; Zhuge, Y.; Gravina, R.J. Novel approach to improve crumb rubber concrete strength using thermal treatment. *Constr. Build. Mater.* **2019**, *229*, 116901. [\[CrossRef\]](#)
15. Chylík, R.; Trtík, T.; Fládr, J.; Bílý, P. Mechanical properties and durability of crumb rubber concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *236*, 012093. [\[CrossRef\]](#)
16. Ganjian, E.; Khorami, M.; Maghsoudi, A.A. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Constr. Build. Mater.* **2009**, *23*, 1828–1836. [\[CrossRef\]](#)

17. Pham, T.M.; Lim, Y.Y.; Malekzadeh, M. Effect of pre-treatment methods of crumb rubber on strength, permeability and acid attack resistance of rubberised geopolymer concrete. *J. Build. Eng.* **2021**, *41*, 102448.
18. Dong, M.; Elchalakani, M.; Karrech, A.; Yang, B. Strength and durability of geopolymer concrete with high volume rubber replacement. *Constr. Build. Mater.* **2021**, *274*, 121783. [[CrossRef](#)]
19. Shahzad, K.; Zhao, Z. Experimental study of NaOH pretreated crumb rubber as substitute of fine aggregate in concrete. *Constr. Build. Mater.* **2022**, *358*, 129448. [[CrossRef](#)]
20. Rajagopal, M.R.; Bhavya, M.; Kumari, G.J. Study on the impact of pre-treatment method and admixture on the mechanical and durability properties of crumb rubber concrete. *AIP Conf. Proc.* **2024**, *3010*, 020010.
21. Najim, K.B.; Hall, M.R. Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrainment and fracture toughness in self-compacting rubberised concrete (SCRC). *Mater. Struct.* **2013**, *46*, 2029–2043. [[CrossRef](#)]
22. Raghavan, D.; Huynh, H.; Ferraris, C.F. Workability, mechanical properties, and chemical stability of a recycled tyre rubber-filled cementitious composite. *J. Mater. Sci.* **1998**, *33*, 1745–1752. [[CrossRef](#)]
23. Lv, J.; Zhou, T.; Du, Q.; Wu, H. Effects of rubber particles on mechanical properties of lightweight aggregate concrete. *Constr. Build. Mater.* **2015**, *91*, 145–149. [[CrossRef](#)]
24. Xie, J.-H.; Guo, Y.-C.; Liu, L.-S.; Xie, Z.-H. Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber. *Constr. Build. Mater.* **2015**, *79*, 263–272. [[CrossRef](#)]
25. Li, L.; Ruan, S.; Zeng, L. Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles. *Constr. Build. Mater.* **2014**, *70*, 291–308. [[CrossRef](#)]
26. Zheng, L.; Huo, X.S.; Yuan, Y. Experimental investigation on dynamic properties of rubberized concrete. *Constr. Build. Mater.* **2008**, *22*, 939–947. [[CrossRef](#)]
27. Luhar, S.; Chaudhary, S.; Luhar, I. Development of rubberized geopolymer concrete: Strength and durability studies. *Constr. Build. Mater.* **2019**, *204*, 740–753. [[CrossRef](#)]
28. Prachasaree, W.; Limkatanyu, S.; Hawa, A.; Samakrattakit, A. Development of equivalent stress block parameters for fly-ash-based geopolymer concrete. *Arab. J. Sci. Eng.* **2014**, *39*, 8549–8558. [[CrossRef](#)]
29. Hassan, K.; Ibrahim, M.I.; Shill, S.K.; Al-Deen, S. Mechanical Properties of Rubberised Geopolymer Concrete. *Materials* **2024**, *17*, 1031. [[CrossRef](#)]
30. Hognestad, E. *Study of Combined Bending and Axial Load in Reinforced Concrete Members*; University of Illinois: Champaign, IL, USA, 1951; Engineering Experiment Station, Bulletin no. 399.
31. Thomas, R.J.; Peethamparan, S. Alkali-activated concrete: Engineering properties and stress–strain behavior. *Constr. Build. Mater.* **2015**, *93*, 49–56. [[CrossRef](#)]
32. Davidovits, J. False values on CO₂ emission for geopolymer cement/concrete published in scientific papers. *Tech. Pap.* **2015**, *24*, 1–9.
33. Shill, S.K.; Al-Deen, S.; Ashraf, M.; Hutchison, W. Resistance of fly ash based geopolymer mortar to both chemicals and high thermal cycles simultaneously. *Constr. Build. Mater.* **2020**, *239*, 117886. [[CrossRef](#)]
34. Vora, P.R.; Dave, U.V. Parametric studies on compressive strength of geopolymer concrete. *Procedia Eng.* **2013**, *51*, 210–219. [[CrossRef](#)]
35. Giri, Y.G.A.L.P.; Mohammed, B.S.; Liew, M.S.; Zawawi, N.A.W.A.; Abdulkadir, I.; Singh, P.; Ravindran, G. Mechanical and Microstructural Properties of Rubberized Geopolymer Concrete: Modeling and Optimization. *Buildings* **2023**, *13*, 2021. [[CrossRef](#)]
36. Moghaddam, S.C.; Madandoust, R.; Jamshidi, M.; Nikbin, I.M. Mechanical properties of fly ash-based geopolymer concrete with crumb rubber and steel fiber under ambient and sulfuric acid conditions. *Constr. Build. Mater.* **2021**, *281*, 122571. [[CrossRef](#)]
37. ASTM C136-06; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. American Society for Testing and Materials: Philadelphia, PA, USA, 2006.
38. ASTM C33/C33M-18; Standard Specification for Concrete Aggregates. American Society for Testing and Materials: Philadelphia, PA, USA, 2003.
39. ASTM C494; Standard Specification for Chemical Admixtures for Concrete. American Society for Testing and Materials: Philadelphia, PA, USA, 2013. Available online: www.concrete.org (accessed on 15 August 2024).
40. Pavithra, P.; Reddy, M.S.; Dinakar, P.; Rao, B.H.; Satpathy, B.; Mohanty, A. A mix design procedure for geopolymer concrete with fly ash. *J. Clean. Prod.* **2016**, *133*, 117–125. [[CrossRef](#)]
41. EN 206-1; Part 1: Method of Specifying and Guidance for Specifier. CEN European Committee for Standardization: Brussels, Belgium, 2006.
42. EN 12350-2: 2009; Testing Fresh Concrete. Slump-Test. British Standards: London, UK, 2009.
43. EN 12390-4; Testing Hardened Concrete, Compressive Strength, Specification for Testing Machines. British Standards: London, UK, 2025.
44. Narayanan, R.S. *Concise Eurocode 2: For the Design of In-Situ Concrete Framed Buildings to BS EN 1992-1-1: 2004 and Its UK National Annex: 2005*; A Cement and Concrete Industry Publication MPA; The Concrete Centre: London, UK, 2006.

45. Chindaprasirt, P.; Ridditirud, C. High calcium fly ash geopolymers containing natural rubber latex as additive. *GEOMATE J.* **2020**, *18*, 124–129. [\[CrossRef\]](#)
46. Arunkumar, K.; Muthukannan, M.; Kumar, A.S.; Ganesh, A.C. Mitigation of waste rubber tire and waste wood ash by the production of rubberized low calcium waste wood ash based geopolymer concrete and influence of waste rubber fibre in setting properties and mechanical behavior. *Environ. Res.* **2021**, *194*, 110661. [\[CrossRef\]](#)
47. Azunna, S.U.; Aziz, F.N.A.B.A.; Al-Ghazali, N.A.; Rashid, R.S.; Bakar, N.A. Review on the mechanical properties of rubberized geopolymer concrete. *Clean. Mater.* **2024**, *11*, 100225. [\[CrossRef\]](#)
48. Elzeadani, M.; Bompá, D.; Elghazouli, A. Preparation and properties of rubberised geopolymer concrete: A review. *Constr. Build. Mater.* **2021**, *313*, 125504. [\[CrossRef\]](#)
49. Luhar, S.; Luhar, I.; Nicolaidis, D.; Gupta, R. Durability performance evaluation of rubberized geopolymer concrete. *Sustainability* **2021**, *13*, 5969. [\[CrossRef\]](#)
50. Puligilla, S.; Chen, X.; Mondal, P. Understanding the role of silicate concentration on the early-age reaction kinetics of a calcium containing geopolymeric binder. *Constr. Build. Mater.* **2018**, *191*, 206–215. [\[CrossRef\]](#)
51. Criado, M.; Fernández-Jiménez, A.; Palomo, A. Alkali activation of fly ash: Effect of the SiO₂/Na₂O ratio: Part I: FTIR study. *Microporous Mesoporous Mater.* **2007**, *106*, 180–191. [\[CrossRef\]](#)
52. Sanyin, Z.; Qijun, Y.; Fei, Q.; Jiaqi, H.; Suhong, Y.; Ziyun, W.; Guobang, G. Setting and strength characteristics of alkali-activated carbonatite cementitious materials with ground slag replacement. *J. Wuhan Univ. Technol. Sci. Ed.* **2006**, *21*, 125–128. [\[CrossRef\]](#)
53. Su, D.-Y.; Pang, J.-Y.; Han, C.-Y.; Huang, J.-Y.; Hu, X.-Y.; Shi, W. Influence of basalt/polypropylene fiber on permeability and uniaxial compressive properties of waste tire rubberized concrete. *Materials* **2023**, *16*, 481. [\[CrossRef\]](#)
54. Abdelaleem, A.; Moawad, M.; El-Emam, H.; Salim, H.; Sallam, H. Long term behavior of rubberized concrete under static and dynamic loads. *Case Stud. Constr. Mater.* **2024**, *20*, e03087. [\[CrossRef\]](#)
55. Fadiel, A.A.M.; Abu-Lebdeh, T.; Munteanu, I.S.; Niculae, E.; Petrescu, F.I.T. Mechanical Properties of Rubberized Concrete at Elevated Temperatures. *J. Compos. Sci.* **2023**, *7*, 283. [\[CrossRef\]](#)
56. Raffoul, S.; Garcia, R.; Pilakoutas, K.; Guadagnini, M.; Medina, N.F. Optimisation of rubberised concrete with high rubber content: An experimental investigation. *Constr. Build. Mater.* **2016**, *124*, 391–404. [\[CrossRef\]](#)
57. Uygunoğlu, T.; Topçu, I.B. The role of scrap rubber particles on the drying shrinkage and mechanical properties of self-consolidating mortars. *Constr. Build. Mater.* **2010**, *24*, 1141–1150. [\[CrossRef\]](#)
58. Guo, S.; Dai, Q.; Si, R.; Sun, X.; Lu, C. Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire. *J. Clean. Prod.* **2017**, *148*, 681–689. [\[CrossRef\]](#)
59. AbdelAleem, B.H.; Ismail, M.K.; Hassan, A.A. The combined effect of crumb rubber and synthetic fibers on impact resistance of self-consolidating concrete. *Constr. Build. Mater.* **2018**, *162*, 816–829. [\[CrossRef\]](#)
60. Siddique, R.; Naik, T.R. Properties of concrete containing scrap-tire rubber—An overview. *Waste Manag.* **2004**, *24*, 563–569. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Mhaya, A.M.; Shahidan, S.; Goel, A.; Huseien, G.F. Effect of metakaolin content and shape design on strength performance of lightweight rubberized geopolymer mortars incorporated slag-waste glass powders. *Constr. Build. Mater.* **2024**, *432*, 136500. [\[CrossRef\]](#)
62. Adebayo, I.W.; Long, G.; Tang, Z.; Ghone, M.O.; Zaland, S.; Garba, M.J.; Yang, K.; Akhunzada, K.; Oluwasina, U.A. Effect of crumb rubber and polyethylene fiber on the strength and toughness of fly ash/slag-based geo-polymer concrete. *Constr. Build. Mater.* **2024**, *455*, 139133. [\[CrossRef\]](#)
63. Aslani, F.; Ma, G.; Wan, D.L.Y.; Le, V.X.T. Experimental investigation into rubber granules and their effects on the fresh and hardened properties of self-compacting concrete. *J. Clean. Prod.* **2018**, *172*, 1835–1847. [\[CrossRef\]](#)
64. Al-Fasih, M.Y.M.; Huseien, G.F.; bin Ibrahim, I.S.; Sam, A.R.M.; Algaifi, H.A.; Alyousef, R. Synthesis of rubberized alkali-activated concrete: Experimental and numerical evaluation. *Constr. Build. Mater.* **2021**, *303*, 124526. [\[CrossRef\]](#)
65. Taha, M.R.; El-Dieb, A.; Abd El-Wahab, M. Fracture toughness of concrete incorporating rubber tire particles. In *International Conference on Performance of Construction Materials: A New Era of Building, Proceedings of the International Conference on Performance of Construction Materials in the New Millennium (ICPCM), Cairo, Egypt, 18–20 February 2003*; Elmaarefa: Cairo, Egypt, 2003; pp. 18–20.
66. Fallah, S.; Nematzadeh, M. Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume. *Constr. Build. Mater.* **2017**, *132*, 170–187. [\[CrossRef\]](#)
67. Manimaran, A.; Somasundaram, M.; Ravichandran, P.T. Experimental study on partial replacement of coarse aggregate by bamboo and fine aggregate by quarry dust in concrete. *Int. J. Civ. Eng. Technol.* **2017**, *8*, 1019–1027.
68. Patil, S.; Vaidya, R.; Math, V. Effect of curing compounds on strength and durability of concrete mixes. *Int. Res. J. Eng. Technol. (IRJET)* **2016**, *3*, 2874–2879.
69. Ephraim, M.E.; ThankGod, O.; Ezekwem, G.O. Performance Evaluation of Laterite Rock Concrete in Aggressive Environment. *Am. J. Eng. Res. (AJER)* **2018**, *7*, 93–101.

70. Gornale, A.; Quadri, S.I.; Quadri, S.M.; Ali, S.M.A.; Hussaini, S.S. Strength aspects of glass fibre reinforced concrete. *Int. J. Sci. Eng. Res.* **2012**, *3*, 1–5.
71. Okoye, F.; Durgaprasad, J.; Singh, N. Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete. *Ceram. Int.* **2016**, *42*, 3000–3006. [[CrossRef](#)]
72. Qureshi, M.; Li, J.; Wu, C.; Sheng, D. Mechanical strength of rubberized concrete: Effects of rubber particle size, content, and waste fibre reinforcement. *Constr. Build. Mater.* **2024**, *444*, 137868. [[CrossRef](#)]
73. Mansourghanaei, M.; Biklaryan, M.; Mardookhpour, A. Durability and mechanical properties of granulated blast furnace slag based geopolymer concrete containing polyolefin fibers and nano silica. *KSCE J. Civ. Eng.* **2024**, *28*, 209–219. [[CrossRef](#)]
74. Raheem, A.A.; Soyngbe, A.A.; Emenike, A.J. Effect of curing methods on density and compressive strength of concrete. *Int. J. Appl. Sci. Technol.* **2013**, *3*, 55–64.
75. Yahya, Z.; Abdullah, M.M.A.B.; Ramli, S.N.H.; Minciuna, M.G.; Razak, R.A. Durability of Fly Ash Based Geopolymer Concrete Infilled with Rubber Crumb in Seawater Exposure. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *374*, 012069. [[CrossRef](#)]
76. Opara, H.E.; Eziefula, U.G.; Eziefula, B.I. Comparison of physical and mechanical properties of river sand concrete with quarry dust concrete. *Sel. Sci. Pap. J. Civ. Eng.* **2018**, *13*, 127–134. [[CrossRef](#)]
77. Azmi, A.A.; Abdullah, M.M.A.B.; Ghazali, C.M.R.; Ahmad, R.; Musa, L.; Rou, L.S. The Effect of Different Crumb Rubber Loading on the Properties of Fly Ash-Based Geopolymer Concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *551*, 012079. [[CrossRef](#)]
78. Al Obeidy, N.F.; Khalil, W.I. Properties of modified metakaolin-based geopolymer concrete with crumbed rubber waste from damaged car tires. *Res. Eng. Struct. Mater.* **2024**, *10*, 209–231. [[CrossRef](#)]
79. Lu, S.; Yang, J.; Wang, J.; Huang, L.; Wang, L. Behavior of steel tubed rubberized geopolymer concrete columns under axial compression: Experimental study and analytical modeling. *Eng. Struct.* **2024**, *302*, 117389. [[CrossRef](#)]
80. Yang, G.; Chen, X.; Xu, J. Molecular dynamics simulation of interfacial mechanical properties of crumb rubber concrete. *Constr. Build. Mater.* **2024**, *438*, 137336. [[CrossRef](#)]
81. Zhao, J.; Xie, J.; Wu, J.; Zhao, C.; Zhang, B. Workability, compressive strength, and microstructures of one-part rubberized geopolymer mortar. *J. Build. Eng.* **2023**, *68*, 106088. [[CrossRef](#)]
82. Kuang, F.; Long, Z.; Kuang, D.; Guo, R.; Sun, J. Experimental study on high temperatures performance of rubberized geo-polymer mortar. *J. Build. Eng.* **2023**, *76*, 107091. [[CrossRef](#)]
83. Roychand, R.; Gravina, R.J.; Zhuge, Y.; Ma, X.; Youssf, O.; Mills, J.E. A comprehensive review on the mechanical properties of waste tire rubber concrete. *Constr. Build. Mater.* **2020**, *237*, 117651. [[CrossRef](#)]
84. Reda Taha, M.M.; El-Dieb, A.S.; Abd El-Wahab, M.A.; Abdel-Hameed, M.E. Mechanical, fracture, and microstructural investigations of rubber concrete. *J. Mater. Civ. Eng.* **2008**, *20*, 640–649. [[CrossRef](#)]
85. Güneyisi, E.; Gesoğlu, M.; Özturan, T. Properties of rubberized concretes containing silica fume. *Cem. Concr. Res.* **2004**, *34*, 2309–2317. [[CrossRef](#)]
86. Yasser, N.; Abdelrahman, A.; Kohail, M.; Moustafa, A. Experimental investigation of durability properties of rubberized concrete. *Ain Shams Eng. J.* **2023**, *14*, 102111. [[CrossRef](#)]
87. Liang, K.X.; Wang, Q.C.; Zhang, K.; Zhang, R.L.; Cui, X.N.; Wang, B.Z. Effect of pore structure of air-entrained concrete on strength and impermeability at low temperature (3 °C) condition. *Bull. Chin. Ceram. Soc.* **2018**, *37*, 6.
88. Lü, Q.; Qiu, Q.; Zheng, J.; Wang, J.; Zeng, Q. Fractal dimension of concrete incorporating silica fume and its correlations to pore structure, strength and permeability. *Constr. Build. Mater.* **2019**, *228*, 116986. [[CrossRef](#)]
89. Alaneme, G.U.; Olonade, K.A.; Esenogho, E.; Lawan, M.M. Proposed simplified methodological approach for designing geopolymer concrete mixtures. *Sci. Rep.* **2024**, *14*, 15191. [[CrossRef](#)]
90. Manzoor, T.; Bhat, J.A.; Shah, A.H. Advancements in geopolymer concrete: A state-of-the-art analysis of its mechanical and durability features. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2024**, *48*, 1777–1816. [[CrossRef](#)]
91. Kanagaraj, B.; Kiran, T.; N, A.; Al Jabri, K.; S, J. Development and strength assessment of eco-friendly geopolymer concrete made with natural and recycled aggregates. *Constr. Innov.* **2023**, *23*, 524–545. [[CrossRef](#)]
92. Azunna, S.U.; Aziz, F.N.A.A.; Abu Bakar, N.; Nasir, N.A.M. Mechanical properties of concrete with coconut shell as partial replacement of aggregates. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *431*, 032001. [[CrossRef](#)]
93. Azunna, S.U. Compressive strength of concrete with palm kernel shell as a partial replacement for coarse aggregate. *SN Appl. Sci.* **2019**, *1*, 342. [[CrossRef](#)]
94. Azunna, S.U.; Aziz, F.N.A.A.; Cun, P.M.; Elhibir, M.M.O. Characterization of lightweight cement concrete with partial replacement of coconut shell fine aggregate. *SN Appl. Sci.* **2019**, *1*, 649. [[CrossRef](#)]
95. Wang, J.; Guo, Z.; Yuan, Q.; Zhang, P.; Fang, H. Effects of ages on the ITZ microstructure of crumb rubber concrete. *Constr. Build. Mater.* **2020**, *254*, 119329. [[CrossRef](#)]
96. Wallah, S.E.; Rangan, B.V. *Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties*; Faculty of Engineering, Curtin University of Technology: Perth, Australia, 2006.

97. Wallah, S.E.; Hardjito, D.; Wallah, S.E.; Sumajouw, D.M.J.; Rangan, B.V. Introducing Fly Ash-Based Geopolymer Concrete: Manufacture and Engineering Properties. 2005. Available online: <https://www.researchgate.net/publication/43649846> (accessed on 17 August 2024).
98. Luhar, S. *Fly Ash and Slag Based Geopolymer Concrete: Experimental Facts*; LAP Lambert Academic Publishing: Saarbrücken, Germany, 2016.
99. Lin, J.-X.; Liu, R.-A.; Liu, L.-Y.; Zhuo, K.-Y.; Chen, Z.-B.; Guo, Y.-C. High-strength and high-toughness alkali-activated composite materials: Optimizing mechanical properties through synergistic utilization of steel slag, ground granulated blast furnace slag, and fly ash. *Constr. Build. Mater.* **2024**, *422*, 135811. [[CrossRef](#)]
100. Shen, Q.; Liu, J.; Li, Z.; Huang, S.; Wang, L.; Li, J.; Wu, X.; Song, W.; Li, L. Study on the early structural strength of a hardened GGBFS-based plugging slurry activated by alkali. *Constr. Build. Mater.* **2024**, *433*, 136586. [[CrossRef](#)]
101. Sundararaj, J.B.; Rajkumar, P.R.K. Effects of multiple precursors on strength, durability, and microstructural properties of ambiently cured geopolymer concrete. *Constr. Build. Mater.* **2024**, *442*, 137538.
102. Pradhan, J.; Panda, S.; Dwibedy, S.; Pradhan, P.; Panigrahi, S.K. Production of durable high-strength self-compacting geopolymer concrete with GGBFS as a precursor. *J. Mater. Cycles Waste Manag.* **2024**, *26*, 529–551. [[CrossRef](#)]
103. Oinam, Y.; Yonis, A.; Bae, Y.; Lee, C.; Pyo, S. Effect of curing temperature on hydration characteristics of GGBFS-based cementless high-strength concrete. *J. Build. Eng.* **2024**, *96*, 110514. [[CrossRef](#)]
104. Elyamany, H.E.; Elmoaty, A.E.M.A.; Diab, A.R.A. Properties of slag geopolymer concrete modified with fly ash and silica fume. *Can. J. Civ. Eng.* **2022**, *49*, 183–191. [[CrossRef](#)]
105. Özkılıç, Y.O.; Çelik, A.I.; Tunç, U.; Karalar, M.; Deifalla, A.; Alomayri, T.; Althoey, F. The use of crushed recycled glass for alkali activated fly ash based geopolymer concrete and prediction of its capacity. *J. Mater. Res. Technol.* **2023**, *24*, 8267–8281. [[CrossRef](#)]
106. Amin, M.; Elsakhawy, Y.; Abu el-Hassan, K.; Abdelsalam, B.A. Behavior evaluation of sustainable high strength geopolymer concrete based on fly ash, metakaolin, and slag. *Case Stud. Constr. Mater.* **2022**, *16*, e00976. [[CrossRef](#)]
107. Hamed, Y.R.; Elshikh, M.M.Y.; Elshami, A.A.; Matthana, M.H.; Youssf, O. Mechanical properties of fly ash and silica fume based geopolymer concrete made with magnetized water activator. *Constr. Build. Mater.* **2024**, *411*, 134376. [[CrossRef](#)]
108. Singh, R.P.; Vanapalli, K.R.; Jadda, K.; Mohanty, B. Durability assessment of fly ash, GGBS, and silica fume based geo-polymer concrete with recycled aggregates against acid and sulfate attack. *J. Build. Eng.* **2024**, *82*, 108354. [[CrossRef](#)]
109. Vijaya Rangan, B. Mix design and production of fly ash based geopolymer concrete. *Indian Concr. J.* **2008**, *82*, 7–15.
110. Sarkaz, A.M.H.; Danish, A.; Memiş, S.; Yaprak, H.; Gencel, O.; Ozbakkaloglu, T. Performance assessment and economic and ecological analysis of carbon-negative recycled crumb rubber-based geopolymers. *J. Clean. Prod.* **2024**, *434*, 139842. [[CrossRef](#)]
111. Alobeidy, N.F.; Khalil, W.I. Mechanical Properties of Modified Metakaolin-Based Geopolymer Concrete Containing Tires Rubber Waste and Reinforced with Recycled Steel Fibers. *Tikrit J. Eng. Sci. (TJES)* **2024**, *31*, 43–59. [[CrossRef](#)]
112. Iqbal, H.W.; Hamcumpai, K.; Nuaklong, P.; Jongvivatsakul, P.; Likitlersuang, S.; Pothisiri, T.; Chintanapakdee, C.; Wijeyewickrema, A.C. Enhancing fire resistance in geopolymer concrete containing crumb rubber with graphene nanoplatelets. *Constr. Build. Mater.* **2024**, *426*, 136115. [[CrossRef](#)]
113. Moghaddam, S.C.; Madandoust, R.; Jamshidi, M.; Nikbin, I.M. Evaluation of Geopolymer Concrete Based on Fly Ash Containing Steel Fibers and Rubber Crumbs Using Cement as a Partial Substitute for Fly Ash. *J. Civ. Eng. Res.* **2024**, *6*, 22–31. [[CrossRef](#)]
114. Wang, X.; Cheng, C.; Wang, D. Effect of rice husk ash on mechanical properties of rubber doped geopolymer recycled concrete. *Case Stud. Constr. Mater.* **2024**, *20*, e03406. [[CrossRef](#)]
115. Ferreira, R.A.d.R.; Grato, L.S.; Motta, L.A.d.C. Evaluation and optimization of the replacement of fine aggregate by waste tire rubber in geopolymer mortar with metakaolin. *Mech. Compos. Mater.* **2024**, *59*, 1223–1238. [[CrossRef](#)]
116. Zhu, Z.; Zhou, M.; Wang, B.; Xu, X. Enhancing permeability and mechanical properties of rubber cement-based materials through surface modification of waste tire rubber powder. *Constr. Build. Mater.* **2024**, *425*, 136098. [[CrossRef](#)]
117. Mohana, R.; Bharathi, S. Eggshell catalysed rubber aggregates for the sustainable green mortar constructions. *Constr. Build. Mater.* **2024**, *420*, 135475. [[CrossRef](#)]
118. Li, C.; Chi, S.; Sun, Y.; Zhong, J. Enhancing the interfacial properties of recycled rubber aggregate mortars through surface modifications with graphene oxide coating. *Constr. Build. Mater.* **2024**, *449*, 138338. [[CrossRef](#)]
119. Choudary, Y.S.; Singh, K.; Babu, T.S.; Deepthi, G. Impact on Mechanical and Durable Properties of Rubber and Copper Slag-based Geo-polymer Mortar using Various Sodium Hydroxide Molarities and Proportions of Alkali Activator Solutions. *J. Min. Environ.* **2023**, *14*, 853–870.
120. Pham, T.M.; Liu, J.; Tran, P.; Pang, V.-L.; Shi, F.; Chen, W.; Hao, H.; Tran, T.M. Dynamic compressive properties of lightweight rubberized geopolymer concrete. *Constr. Build. Mater.* **2020**, *265*, 120753. [[CrossRef](#)]
121. BS 8110-1: 1997; Structural Use of Concrete, Code of Practice for Design and Construction. British Standards: London, UK, 1997.
122. Yeluri, S.C.; Singh, K.; Babu, T.R.; Garikapati, D. Durability properties of rubber aggregates based geopolymer concrete- a review. *Mater. Today: Proc.* **2023**, *93*, 327–334. [[CrossRef](#)]

123. Al-Sodani, K.A.A. Mix design, mechanical properties and durability of the rubberized geopolymer concrete: A review. *Case Stud. Constr. Mater.* **2022**, *17*, e01480. [[CrossRef](#)]
124. *ACI 318-19*; Building Code Requirements for Structural Concrete. ACI: Farmington Hills, MI, USA, 2019.
125. Aly, A.M.; El-Feky, M.; Kohail, M.; Nasr, E.-S.A. Performance of geopolymer concrete containing recycled rubber. *Constr. Build. Mater.* **2019**, *207*, 136–144. [[CrossRef](#)]
126. Youssf, O.; Elchalakani, M.; Hassanli, R.; Roychand, R.; Zhuge, Y.; Gravina, R.J.; Mills, J.E. Mechanical performance and durability of geopolymer lightweight rubber concrete. *J. Build. Eng.* **2022**, *45*, 103608. [[CrossRef](#)]
127. *EN 12504-1*; Testing Concrete in Structures. Part 1. Cored Specimens: Taking, Examining and Testing in Compression. British Standards Institution: London, UK, 2000.
128. Kumari, R. Review paper based on the relation between the strength of concrete cubes and cylinders. *Int. J. Eng. Res. Appl.* **2015**, *5*, 52–54.
129. Padmakar, M.; Barhmaiah, B.; Priyanka, M.L. Characteristic compressive strength of a geo polymer concrete. *Mater. Today Proc.* **2021**, *37*, 2219–2222. [[CrossRef](#)]
130. Yolcu, A.; Karakoç, M.B.; Ekinci, E.; Özcan, A.; Sağır, M.A. Effect of binder dosage and the use of waste rubber fiber on the mechanical and durability performance of geopolymer concrete. *J. Build. Eng.* **2022**, *61*, 105162. [[CrossRef](#)]
131. Gill, P.; Jangra, P.; Roychand, R.; Saberian, M.; Li, J. Effects of various additives on the crumb rubber integrated geopolymer concrete. *Clean. Mater.* **2023**, *8*, 100181. [[CrossRef](#)]
132. *ACI 318-08*; Building Code Requirements for Structural Concrete (and Commentary: An ACI Standard). American Concrete Institute: Farmington Hills, MI, USA, 2008.
133. Youssf, O.; Mills, J.E.; Elchalakani, M.; Alanazi, F.; Yosri, A.M. Geopolymer Concrete with Lightweight Fine Aggregate: Material Performance and Structural Application. *Polymers* **2022**, *15*, 171. [[CrossRef](#)]
134. Aleem, M.A.U.; Siddique, M.S.; Farooq, S.H.; Usman, M.; Ahsan, M.H.; Hussain, M.; Hanif, A. Axial compressive behavior of concrete incorporating crumb rubber pretreated with waste quarry dust. *J. Build. Eng.* **2022**, *59*, 105086. [[CrossRef](#)]
135. Abdo, A.; El-Sisi, A.; El Sayed, S.; Hassan, H.; Ahmed, S. Properties and stress-strain curve of rubberized concrete cast with uncoated or pre-coated rubber with cement/waste materials. *Case Stud. Constr. Mater.* **2024**, *20*, e03226. [[CrossRef](#)]
136. Hamidi, F.; Valizadeh, A.; Aslani, F. The effect of scoria, perlite and crumb rubber aggregates on the fresh and mechanical properties of geopolymer concrete. *Structures* **2022**, *38*, 895–909. [[CrossRef](#)]
137. Alaloul, W.S.; Musarat, M.A.; Tayeh, B.A.; Sivalingam, S.; Rosli, M.F.B.; Haruna, S.; Khan, M.I. Mechanical and deformation properties of rubberized engineered cementitious composite (ECC). *Case Stud. Constr. Mater.* **2020**, *13*, e00385. [[CrossRef](#)]
138. *ASTM C469/C469M-22*; Test Method for Static Modulus of Elasticity and Poissons Ratio of Concrete in Compression. ASTM International: West Conshohocken, PA, USA, 2022. [[CrossRef](#)]
139. Neville, A.M. *Properties of Concrete, Volume 4*; Longman: London, UK, 1995.
140. Khan, M.; Cao, M.; Ali, M. Effect of basalt fibers on mechanical properties of calcium carbonate whisker-steel fiber reinforced concrete. *Constr. Build. Mater.* **2018**, *192*, 742–753. [[CrossRef](#)]
141. Eisa, A.S.; Elshazli, M.T.; Nawar, M.T. Experimental investigation on the effect of using crumb rubber and steel fibers on the structural behavior of reinforced concrete beams. *Constr. Build. Mater.* **2020**, *252*, 119078. [[CrossRef](#)]
142. Du, T.; Yang, Y.; Cao, H.; Si, N.; Kordestani, H.; Sktani, Z.D.I.; Arab, A.; Zhang, C. Rubberized Concrete: Effect of the Rubber Size and Content on Static and Dynamic Behavior. *Buildings* **2024**, *14*, 1541. [[CrossRef](#)]
143. Bu, C.; Zhu, D.; Liu, L.; Lu, X.; Sun, Y.; Yu, L.; OuYang, Y.; Cao, X.; Wang, F. Research progress on rubber concrete properties: A review. *J. Rubber Res.* **2022**, *25*, 105–125. [[CrossRef](#)]
144. Dong, M.; Elchalakani, M.; Karrech, A. Development of high strength one-part geopolymer mortar using sodium metasilicate. *Constr. Build. Mater.* **2020**, *236*, 117611. [[CrossRef](#)]
145. Tran, T.T.; Pham, T.M.; Hao, H. Rectangular Stress-block Parameters for Fly-ash and Slag Based Geopolymer Concrete. *Structures* **2019**, *19*, 143–155. [[CrossRef](#)]
146. Gupta, T.; Tiwari, A.; Siddique, S.; Sharma, R.K.; Chaudhary, S. Response assessment under dynamic loading and micro-structural investigations of rubberized concrete. *J. Mater. Civ. Eng.* **2017**, *29*, 04017062. [[CrossRef](#)]
147. *ACI 363R-10*; Report on High Strength Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2010.
148. *EN 1992-1-1*; Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings. British Standard Institution: London, UK, 2004.
149. Noushini, A.; Aslani, F.; Castel, A.; Gilbert, R.I.; Uy, B.; Foster, S. Compressive stress-strain model for low-calcium fly ash-based geopolymer and heat-cured Portland cement concrete. *Cem. Concr. Compos.* **2016**, *73*, 136–146. [[CrossRef](#)]
150. *ASTM C39/C39M*; Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens 1. ASTM International: West Coshohocken, PA, USA, 2005.
151. *ASTM C39/C39M*; Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International: West Coshohocken, PA, USA, 2021.

152. Popovics, S. A numerical approach to the complete stress-strain curve of concrete. *Cem. Concr. Res.* **1973**, *3*, 583–599. [[CrossRef](#)]
153. fib—Federation Internationale du Beton. *fib Model Code for Concrete Structures 2010*; John Wiley & Sons: Berlin, Germany, 2013.
154. Sarker, P.K. Analysis of geopolymer concrete columns. *Mater. Struct.* **2009**, *42*, 715–724. [[CrossRef](#)]
155. Xie, J.; Wang, J.; Rao, R.; Wang, C.; Fang, C. Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate. *Compos. Part B Eng.* **2019**, *164*, 179–190. [[CrossRef](#)]
156. Huang, X.; Pang, J.; Liu, G.; Chen, Y. The influence of equal amplitude high stress repeated loading on the mechanical and deformation characteristics of rubber concrete. *Constr. Build. Mater.* **2021**, *266*, 121135. [[CrossRef](#)]
157. Xu, J.; Niu, X.; Yao, Z. Mechanical properties and acoustic emission data analyses of crumb rubber concrete under biaxial compression stress states. *Constr. Build. Mater.* **2021**, *298*, 123778. [[CrossRef](#)]
158. Iqbal, H.W.; Hamcumpai, K.; Nuaklong, P.; Jongvivatsakul, P.; Likitlersuang, S.; Chintanapakdee, C.; Wijeyewickrema, A.C. Effect of graphene nanoplatelets on engineering properties of fly ash-based geopolymer concrete containing crumb rubber and its optimization using response surface methodology. *J. Build. Eng.* **2023**, *75*, 107024. [[CrossRef](#)]
159. Abd-Elaty, M.A.A.; Ghazy, M.F.; Khalifa, O.H. Mechanical and thermal properties of fibrous rubberized geopolymer mortar. *Constr. Build. Mater.* **2022**, *354*, 129192. [[CrossRef](#)]
160. Fadiel, A.A.M.; Mohammed, N.S.; Abu-Lebdeh, T.; Munteanu, I.S.; Niculae, E.; Petrescu, F.I.T. A Comprehensive Evaluation of the Mechanical Properties of Rubberized Concrete. *J. Compos. Sci.* **2023**, *7*, 129. [[CrossRef](#)]
161. Alsaif, A.S.; Albidah, A.S. Compressive and flexural characteristics of geopolymer rubberized concrete reinforced with recycled tires steel fibers. *Mater. Today Proc.* **2022**, *65*, 1230–1236. [[CrossRef](#)]
162. Alsaif, A.; Albidah, A.; Abadel, A.; Abbas, H.; Al-Salloum, Y. Development of metakaolin-based geopolymer rubberized concrete: Fresh and hardened properties. *Arch. Civ. Mech. Eng.* **2022**, *22*, 144. [[CrossRef](#)]
163. Albidah, A.; Alsaif, A.; Abadel, A.; Abbas, H.; Al-Salloum, Y. Role of recycled vehicle tires quantity and size on the properties of metakaolin-based geopolymer rubberized concrete. *J. Mater. Res. Technol.* **2022**, *18*, 2593–2607. [[CrossRef](#)]
164. Abd-Elaty, M.A.A.; Ghazy, M.F.; Khalifa, O.H. Mechanical and Impact Properties of Fibrous Rubberized Geopolymer Concrete. *MEJ Mansoura Eng. J.* **2023**, *48*, 5. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.