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Waste glass powder on the properties of treated granular rubber modified concrete

Polvo de vidrio de desecho en las propiedades del hormigón modificado con caucho granulado tratado

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ABSTRACT: The valorization of solid waste and efficient use of natural resources directly contribute to achieving Sustainable Development Goals (SDGs) No. 11 "Sustainable Cities and Communities" and No. 12 "Responsible Consumption and Production." This study aims to determine the optimal substitution ratio of sand with treated granular rubber (TGR) and subsequently evaluate the effect of replacing cement with waste glass powder (WGP) on the physical and mechanical properties of concrete. The experimental methodology followed two phases: First, fine aggregate was replaced with TGR at 2.5%, 5%, 7.5%, and 10% to identify the best-performing mixture. Second, using the optimal TGR proportion, cement was partially substituted with WGP at 4%, 10%, 16%, and 22%. Nine mix designs were prepared, totaling 180 specimens, with evaluations of workability, fresh density, temperature, air content, compressive strength, flexural strength, and modulus of elasticity at 7, 14, and 28 days of curing. Results indicate that TGR-modified concrete exhibited reduced density and improved workability, a trend that reversed in hybrid mixtures combining optimal TGR dosage with WGP as partial cement replacement. The 2.5% TGR + 16% WGP hybrid combination achieved mechanical performance improvements up to 54.76%, demonstrating viability for non-structural applications while promoting sustainable development through waste valorization.

RESUMEN: La valorización de residuos sólidos y el uso eficiente de los recursos naturales contribuyen directamente al cumplimiento de los Objetivos de Desarrollo Sostenible (ODS) N.º 11 “Ciudades y comunidades sostenibles” y N.º 12 “Producción y consumo responsables”. En este contexto, la presente investigación tiene como objetivo determinar la proporción óptima de sustitución de arena por caucho granular tratado (CGT) y, a partir de esta, evaluar el efecto de reemplazar el cemento por polvo de vidrio de desecho (PVD) sobre las propiedades físicas y mecánicas del concreto. Inicialmente, se sustituyó el árido fino por CGT en proporciones de 2.5%, 5%, 7.5% y 10% para identificar la mezcla con mejor comportamiento. Posteriormente, con la proporción óptima de CGT, se sustituyó el cemento por PVD en 4%, 10%, 16% y 22%. Se elaboraron nueve diseños de mezcla, con un total de 180 especímenes, evaluando la trabajabilidad, densidad en estado fresco, temperatura, contenido de aire, resistencia a la compresión, resistencia a la flexión y módulo de elasticidad a los 7, 14 y 28 días de curado. Los resultados muestran que los concretos modificados con caucho granular tratado presentaron una menor densidad y una mayor trabajabilidad, tendencia que se invirtió en las mezclas híbridas que incorporaron óptima dosis de CGT y polvo de vidrio de desecho como sustituto parcial del cemento. La combinación híbrida 2.5% CGT + 16% PVD logró incrementos de hasta 54.76% en el desempeño mecánico, demostrando su viabilidad para aplicaciones no estructurales, contribuyendo al desarrollo sostenible mediante la valorización de residuos.

1. Introduction

Over the years, the evolution of global waste production has become a very serious threat to the ecology. In particular, around 270 million used tires are disposed of in illegal stockpiles or landfills, and the figure is expected to reach 1.2 billion tires annually by 2030 [1]. Burning tires is the easiest way to dispose of them, but this causes serious health problems and releases toxic gases into the environment. Waste management is the priority for many countries [2], [3], [4].

On the other hand, other waste such as glass is an inert material; it does not decompose and remains in the soil for many years [5]. In reality, recycled glass cannot be converted into new usable products, as a result of the disparate chemical compositions in the collected glass. Not least, the cement industry contributes between 5% and 8% of total anthropogenic CO_2 emissions [6], the aim is to raise awareness in society to mitigate this material and look for an alternative partial replacement, such as waste glass powder. Meanwhile, glass powder shows pozzolanic properties of great value due to its high content of silica dioxide [7]. It should be noted that in Peru, 25% of the 260 thousand tons of glass produced contain recycled glass and 3.2% of the waste generated in the home is glass; that is, 682 tons per day [8]. Only a small fraction of solid waste is recycled directly to the primary market, i.e., the bottling and packaging industry.

From an economic and environmental standpoint, these alternative materials to concrete offer a double advantage: they save costs by reducing the need for natural aggregates and cement, while addressing environmental concerns through waste recovery and ecological preservation. This sustainable approach demonstrates how industrial by-products can be transformed into valuable resources for construction, creating a win-win situation for both budget-conscious projects and environmentally friendly construction practices [9, 10, 11, 12, 13]. Replacements of fine aggregates (conventional sand) and cement being materials such as foundry sand wastes [14], graphite tailings [15], ceramic waste [16], expanded perlite and pumice [17], waste glass powder [18], steel slag [19], sandstone cutting waste [20], sea sand [21], alum sludge [22], shredded rubber and silica fume [23], low-density polyethylene [24], glass dust [25], glass dust and coconut shell [26] in concrete production, as well as the use of alternative sands for a cleaner and more sustainable environment.

Thus, the partial substitution of aggregates with recycled materials can lead to the conservation of large amounts of natural resources, there is an urgent need to find reasonable options that can replace sand [27, 28, 29, 30, 31]. Additionally, the use of cement would be reduced, lowering the costs per cubic meter that this currently represents for many constructions at a national and international level [32, 33]. In Peru, there are no rigorous controls on the extraction of minerals for construction, which will result in a shortage of this stone mineral due to the considerable increase in construction that is currently taking place. Sustainable construction technology is a new approach adopted in the built environment [34].

Meanwhile, the glass particles trap air due to their irregular shape, and more importantly, the sharp edges of the glass particles transport air into the concrete [35]. The combined dosages of waste rubber (WR) by 10%, 20%, and 30% in replaced sand and waste glass (WG) were replaced with coarse aggregate at 10%, 20%, and 30%, on a volume basis. It also showed that the combination of WR and WG improved the strengths of rubber concrete, especially at 10% WR and 20% WG; moreover, rubber concrete with the addition of glass particles had more encouraging slump results concerning plain rubber concrete and control mix [27].

The integration of rubber into concrete without pretreatment is ineffective, and the effect of some easily applied treatment methods such as sodium hydroxide (NaOH) [36], potassium permanganate ($KMnO_4$), and cement coating were investigated; however, $KMnO_4$ and cement treatment methods resulted in a remarkable improvement [37]. On the other hand, the use of rubber heat treated at 200 °C for 2 h shows compressive strength recoveries [38, 39]. With a rubber content of 20% using heat-treated rubber and passing the No. 40 mesh (0.420 mm), the compressive strength recovered by 60.3% [40]. The size of granular rubber to be used in the research should be taken into account [41], there are different types according to the size such as granulated rubber (0.425-4.75 mm), crushed rubber (length 300-430 mm and width 100-230 mm) and ground rubber (0.075-0.475 mm), where usually 5%, 7.5% and 10% of fine aggregates are replaced. Some studies show that the combination strengthens the resistance with an increase with the incorporation of glass powder and rubber aggregates, especially with contents of 10% and 20% [1]. However, these rubberized concrete with a small amount of rubber provided sufficient compressive strength results (greater than 50 MPa). Due to the pozzolanic reaction, we see that the compressive strength results after 56 days for samples modified with glass powder increased by 11 to 13% compared to the 28-day compressive strengths [5]. The properties of the hardened concrete showed that the combination of powdered glass waste and plastic waste increased the compressive strength up to 25%, beyond which the strength decreased [42].

This study introduces an innovative approach to sustainable concrete by combining two waste valorization strategies: (1) thermal treatment of crumb rubber for enhanced aggregate compatibility and (2) multi-factor ANOVA optimization of hybrid replacements (treated rubber for sand + glass powder for cement). The research contributes to circular construction practices by developing a systematic methodology to determine optimal waste material incorporation rates, specifically designed for implementation in developing countries with abundant natural resources. By addressing both aggregate and cement replacement simultaneously through statistically designed experiments, this work advances SDG-compliant concrete technology while providing a replicable framework for reducing construction's environmental footprint without compromising material performance.

2. Materials and methods

2.1. Materials

2.1.1 Aggregates

Natural aggregates from quarries in the Lambayeque region of Peru located at the geographical coordinates 6° 35' 00" south latitude and 79° 21' 00" west longitude were used; the fine aggregate passed through a 4.75 mm sieve and was retained in a 0.149 mm sieve. Crushed granite stones with a maximum size of 19 mm were used as coarse aggregate; tests were carried out to characterize their properties, which are shown in **Table 1**.

Table 1 Physical properties of natural aggregates

Stone aggregate	Module fineness	Max. particle size (mm)	Specific gravity	Absorption (%)	Moisture content (%)	Loose unit weight (kg/m^3)	Compacted unit weight (kg/m^3)
Fine	3.01	4.75	2.54	0.80	0.60	1500	1609
Coarse	-	19.00	2.61	1.40	0.23	1351	1460

2.1.2. Ordinary Portland Cement

In the present investigation, ordinary Portland cement of common use (42.5 kg bag) was used, a commercial material from the study area, made according to the international standard ASTM C150 [43]. It contains a density of 3.10 g/cm^3 and an initial and final setting time (minutes) of 45 and 345. Some chemical characteristics of cement are shown in **Table 2**.

Table 2 Chemical properties of type I cement

Description	Results	National regulations
MgO	1.7	NTP 334.086
SO_3	2.82	NTP 334.086
Alkali equivalent (%)	0.8	NTP 334.086
Loss on ignition (%)	2.8	NTP 334.086
Insoluble residue (%)	0.6	NTP 334.086

2.1.3. Rubber granules

The rubber used was obtained commercially from the city of Lima (Peru). It was collected in hermetically sealed 40 kg bags. Then it was washed with potable water for five minutes to proceed with the chosen heat treatment. Some characteristics of the untreated rubber granules are shown in **Table 3** below.

2.1.4. Waste glass powder

Recycled bottles were used, and glass was obtained from commercial glassworks in the city of Chiclayo (Peru). They were previously washed and disinfected for a subsequent drying process in the sun for 2 to 3 hours. Then the pieces obtained were placed in the Los Angeles abrasion machine for 5 to 10 minutes for the first grinding and the second grinding for 15 to 20 minutes until obtaining a size similar to the cement replacement as shown in **Figure 1**, some characteristics are shown in **Table 3**. Some chemical components of WGP are: SiO_2, Al_2O_3, Fe_2O_3, CaO, Na_2O, MgO, K_2O and LOI corresponding to percentage results of 73.3%, 0.89%, 0.66%, 8.66%, 10.03%, 4.21%, 0.14% and 2.48%.

Table 3 Physical properties of rubber granules and waste glass powder

Description	Rubber granules	Waste glass powder
Fineness modulus	2.03	1.34
Color	Black	White and Gray
Particle size (mm)	4.50 - 5	0.075
Water absorption (%)	0.03	0.12
Density (g/cm^3)	1.71	2.87

Figure 1 Glass crushing process and final sample in retained powder 0.075 mm.

2.2. Methods

2.2.1. Rubber granule heat treatment process

The heat treatment was carried out in a laboratory muffle furnace with a maximum capacity of 1200°C and a control accuracy of ±1°C. The working temperature of 200°C ±1°C and the exposure times (30, 45, and 60 minutes) were selected through a rigorous experimental process and literature review [38], [40], [39]. This specific temperature, achieved with a maximum variation error of 0.5% in the muffle furnace, allows for controlled surface oxidation of the rubber, improving its adhesion to the cement matrix (by increasing its roughness and chemical reactivity) without causing thermal degradation, while the treatment times were optimized to ensure homogeneous modification of the 500 g sample. The purpose of the heat treatment was to improve the texture of the granule surface to have a more solid adhesion between the cementitious paste in the concrete; in addition, the concrete compressive strength test was performed to determine the ideal time of subjection to heat, using a dose of 2.5% of heat-treated rubber granules under the considerations [44]. Concrete specimens were prepared with each rubber sample at different times treated and analyzed at 7, 14, and 28 days for rupture, the treated granulated rubber is shown in **Figure 2**.

Figure 2 Texture of treated granulated rubber.

Heat treatment of rubber improves its adhesion to the cement matrix mainly by modifying its surface, reducing the presence of hydrophobic compounds and increasing its roughness. These physical and chemical changes promote mechanical and chemical interaction with the cement paste. During heating, weak organic bonds on the rubber surface can be broken, removing volatile substances and manufacturing residues (such as oils or plasticizers), resulting in a more active surface. In addition, increased surface roughness promotes more effective mechanical anchoring with the hardened paste.

2.2.2. Design, preparation, and processing of samples

A control group with a target compressive strength of 21 MPa, labeled as T1, was prepared following the ACI 211.1 method [45], using a water-to-cement ratio (w/c) of 0.68 for all mixtures and without incorporating superplasticizers. The mix design is detailed in **Table 4**. The concrete was prepared using river sand as fine aggregate, crushed stone as coarse aggregate, Type I Portland cement, and potable water, mixed for approximately 5 minutes in an 11-cubic-foot mechanical mixer.

The experimental procedure was divided into two phases. The objective of the first phase was to determine the optimal replacement ratio of river sand with thermally treated rubber granules (2.5%, 5%, 7.5%, and 10% by weight of fine aggregate), based on compressive strength performance at 7, 14, and

28 days of curing. This phase aimed to identify the proportion that best balances mechanical strength and workability. The doses selected in this study were based on those studies [2], [1], [46].
In the second phase, the optimal rubber dosage identified in the first stage was used as a constant, while the cement was partially replaced with waste glass powder at 4%, 10%, 16%, and 22% by weight. The goal of this phase was to evaluate the synergistic effect of combining both waste materials on the physical and mechanical behavior of the concrete. Specimens were cast in standard cylindrical (15 × 30 cm) and prismatic (15 × 15 × 55 cm) molds. After 24 hours, they were demolded and cured by immersion in potable water, with tests performed at 7, 14, and 28 days for both fresh and hardened state properties.

Table 4 Quantity in volume and percentage for each experimental design

ID Mix	w/c	Cement (kg/m³)	Water (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	TRG (%)	WGP (%)
T1	0.68	370	252	882	910	0	0
T-GR1	0.68	370	252	864	910	2.5	0
T-GR2	0.68	370	252	846	910	5	0
T-GR3	0.68	370	252	829	910	7.5	0
T-GR4	0.68	370	252	811	910	10	0
T2	0.68	365	252	864	910	Optimal dose	4
T3	0.68	357	252	864	910		10
T4	0.68	349	252	864	910		16
T5	0.68	341	252	864	910		22

2.2.3. Laboratory testing standards

The properties considered are the workability under international considerations ASTM C143M [47] using Abrams cone; the unit weight ASTM C138M [48], using Washington pot equipment and used to find the air content, respectively ASTM C231 [49]; the temperature of fresh concrete measured with a calibrated thermometer under parameters of ASTM C1064M [50]. Tests such as compressive strength according to ASTM C39M [51], flexural strength according to ASTM C78 [52], and modulus of elasticity ASTM C469 [53].

3. Results and discussions

3.1. Determination of heat treatment time of granulated rubber

As shown in **Table 5**, the average cracking results of 3 cylindrical concrete specimens for each heat exposure time of the granular rubber treated at 7, 14, and 28 days according to ASTM C39 procedure. In **Figure 3**, it is observed that it is possible to obtain the appropriate heat treatment time, the results are presented in the form of contour distributions. The results reveal that they are favorable for the times of 0, 30, 45, and 60 minutes, which translates into an increase in strength of 21.91, 22.68, 24.31, and 23.93 MPa, respectively for 28 days of rupture. It was determined that the highest compressive strength occurred at 45 minutes of heat treatment on the surface of the rubber granules with an increase in strength of up to 10.93%, with a constant temperature of 200 °C, for a granule size of 4.5 mm. While at a longer treatment time of 60 minutes, the resistance increased up to 9.18%, affecting the texture and cohesion between particles, since lumps were formed, directly affecting the mechanical resistance with the appearance of voids internally in the TRG-modified concrete specimens.

Table 5 Results of the effect of time in the treatment of granulated rubber on compression set resistance

Time (minutes)	7 d (MPa)	Sv	14 d (MPa)	Sv	28 d (MPa)	Sv
0	15.52	0.02	20.59	0.30	21.91	0.12
30	16.58	0.55	21.03	0.43	22.68	0.34
45	17.79	0.90	22.68	0.73	24.31	0.46
60	16.86	0.89	21.67	0.63	23.93	1.02

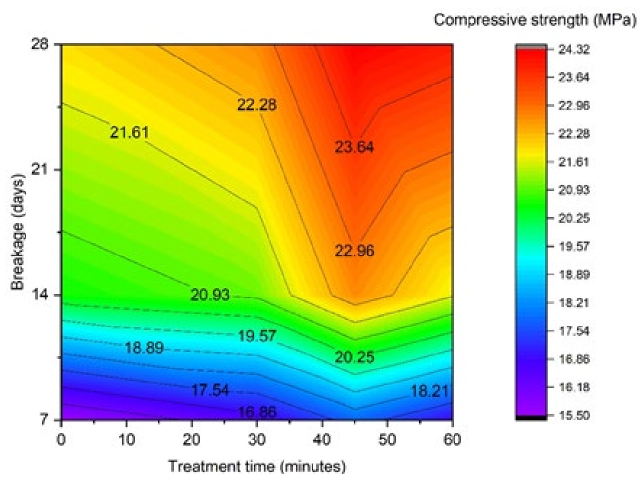

Figure 3 Contours of compressive strength values at 7, 14, and 28 days after breakage.

Abd-Elaal et al. [40] demonstrated that heat treatment at 200 °C for 2 h significantly improved the compressive strength of rubberized concrete, especially with finer particles. At 10%, 20%, and 40% rubber content, strength increased by 25%, 40%, and 128%, respectively. Using No. 40 mesh rubber at 20% replacement recovered 60.3% of the lost strength. Thermal pretreatment of rubber burned off most of the unwanted materials in the rubber aggregate, created a hard outer layer on the rubber particles and decreased the presence of zinc in the rubber from 8.32% to 1.89%, improving the compressive strength of granulated rubber concrete [39].

3.2. Determination of the optimum TRG dosage under compressive strength

Table 6 shows the compressive strength results of concrete with various dosages of treated granular rubber tested at 7, 14 and 28 days according to ASTM C39 procedure. **Figure 4** shows the 3D response surface plot generated by OriginPro for the compressive strength. It was determined that a T-GR1 content (2.5% TRG) as a substitute for fine aggregate, achieves the highest compressive strength of 24.24 MPa equivalent to an increase of 10.63% corresponding to the 28 days of failure, showing an optimum performance with respect to the control strength of 21.91 MPa (T1). Higher amounts of granulated rubber treated from 5, 7.5 and 10% has a minor effect on the progressive compressive strength increase of 23.40 MPa (6.76%), 22.90 MPa (4.48%), and 22.16 MPa (1.13%) for 5%, 7.5% and 10% TGR corresponding to 28 days of failure, but no sample was lower than the control sample.

This increase in concrete strength is due to better bonding between the heat-treated rubber particle and the cement paste, as the texture and size of the rubber granule are better coupled. Cylindrical concrete specimens with a small amount of rubber particles improve compressive strength [54]. Despite lower compressive strength than the control, replacing 2.5% fine aggregate with granulated rubber of particle size 0.18-1.25 mm produced acceptable results for high strength structural concrete [44].

Table 6 Average results of using TRG on the compressive strength of concrete

ID Mix	7 d (MPa)	Sv	14 d (MPa)	Sv	28 d (MPa)	Sv
T1	15.52	0.02	20.59	0.30	21.91	0.12
T-GR1	18.15	0.24	23.07	0.36	24.24	0.32
T-GR2	17.57	0.06	22.23	0.16	23.40	0.16
T-GR3	17.20	0.10	21.77	0.14	22.90	0.11
T-GR4	16.67	0.21	21.12	0.32	22.16	0.34

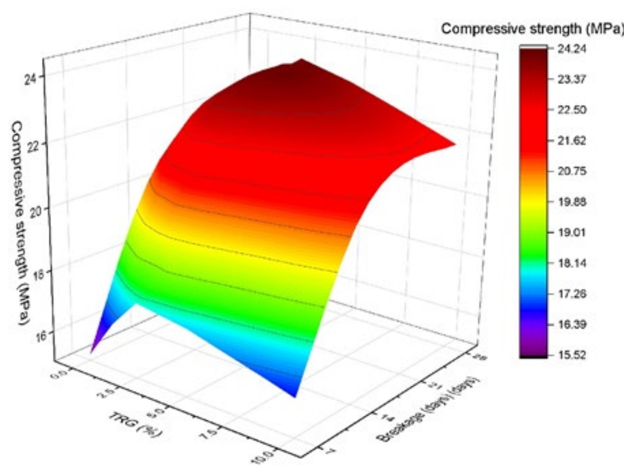

Figure 4 Effect of % TRG on compressive strength

3.3. Effect of optimum dosage of treated granulated rubber combined with dosage of waste glass powder on the fresh state tests of concrete.

Table 7 shows the results of each design T-GR1 to T-GR4, for the mixtures with granulated rubber treated with smaller particles, achieve better workability as the doses of treated granulated rubber increase. This is in agreement with studies on concrete with larger rubber particle size tending to have higher workability and fresh density than that with smaller particle size [55]. Unlike other studies where the finer rubber particles absorbed water to reach the dry saturated surface condition. This resulted in the reduction of free water, which made the overall concrete mix less workable [2]. In addition, the use of NaOH treatment on rubber influenced the slump by reducing by 50% with 15% replacement of CR [56]. The results on fresh concrete density and air content are interconnected. Indeed, when the air content increases, the density of fresh concrete decreases with respect to mixtures with TRG. Another relevant reason in the density decrease is the entrapped air content due to the nonpolar nature of rubber, which increases due to the high specific area of fine granulated rubber.

Table 7 Fresh state test values for all concrete mixtures.

ID Mix	Slump (mm)	Unit weight (kg/m^3)	Temperature (°C)	Air content (%)
T1	101.6	2362	30	2
T-GR1	101.6	2343	30	2.2
T-GR2	108.0	2319	29	2.4
T-GR3	114.3	2303	28	2.5
T-GR4	120.7	2277	28	2.6
T2	82.6	2315	30	0.70
T3	88.9	2323	29	0.60
T4	101.6	2330	26	0.50
T5	108.0	2339	28	0.35

3.4. Effects on the hardened state of hybrid concrete with optimum dosage of treated granulated rubber and waste glass powder

3.4.1. Compressive strength

Table 8 shows the results of the compressive strength of concrete with an optimum dosage of treated granular rubber combined with varying dosages of cullet glass powder tested at 7, 14, and 28 days according to the ASTM C39 procedure. According to the response surface in **Figure 5**, the compressive strength increases significantly as the concentration of cullet glass powder increases with an optimum concentration of 2.5%TRG. Increasing the amount of crushed glass particles can increase the mechanical strength value up to 26.95% with sample T4 (2.5%TRG +16%WGP); however, with a higher dosage, it tends to reduce its mechanical strength due to the presence of defects or voids in the concrete matrix caused by the crushed glass particles. In addition, it will depend on several factors, such as the size of the rubber particles, and the occurrence of internal pores in the concrete mix.

From the point of view of the matrix-aggregate interface, these effects contribute to reducing the formation of a weak transition zone, improving cohesion and reducing porosity in this critical region. As a result, thermally treated rubber concrete has better stress distribution and more ductile behavior under load compared to mixtures using untreated rubber.

Table 8 Average results of using TRG on the compressive strength of concrete

ID Mix	7 d (MPa)	Sv	14 d (MPa)	Sv	28 d (MPa)	Sv
T1	15.52	0.02	20.59	0.30	21.91	0.12
T2	19.06	0.25	24.16	0.34	25.54	0.37

T3	19.63	0.36	24.84	0.38	26.15	0.38
T4	20.90	0.29	26.46	0.36	27.82	0.43
T5	20.37	0.30	25.79	0.32	27.07	0.32

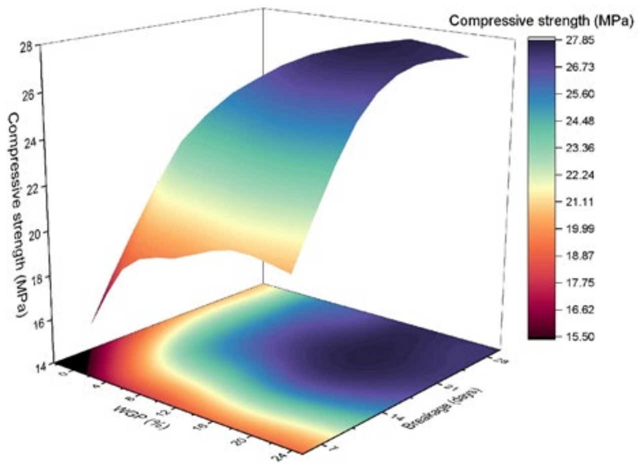

Figure 5 Effect of %WGP on the compressive strength of TRG-reinforced concrete.

By removing impurities through combustion, the hydration process of cement and its penetration into the rubber surface is improved, which leads to better interfacial adhesion and, consequently, higher compressive strength, as reported by Swilam et al. [38]. Similarly, the use of 10% residual glass powder combined with 5% granulated rubber contributed to a compressive strength increase of up to 6% in rubberized concrete [2]. This finding aligns with the mechanical improvements observed in this study. In contrast, the inclusion of untreated rubber has been shown to significantly deteriorate mechanical performance due to weak bonding with the cement matrix [46].

Moreover, the effect of glass powder is limited in the early stages of curing but becomes more pronounced over time due to its pozzolanic activity. This delayed reaction enhances properties such as compressive strength and also reduces unit weight, given that the specific gravity of glass powder is lower than that of cement, as noted by Khan et al. [7]. Finally, the hybrid incorporation of waste rubber (WR) and waste glass (WG) has proven to be a promising strategy for enhancing the performance of rubberized concrete [57], supporting the combined use of these materials in this research.

3.4.2. Flexural strength

Table 9 shows the results of the flexural strength of concrete with the optimum dosage of treated granular rubber combined with different dosages of residual glass powder tested at 7, 14, and 28 days according to the ASTM C78 procedure. The results according to the response surface in **Figure 6**, show that the effect of combining the TRG and the different doses of WGP has a significant influence in treatments T2, T3, T4, and T5 representing a significant increase of 36.18, 42.38, 54.76, and 48.56%, concerning T1 (at 28 days of failure). This behavior is generated by the characteristics of TRG, which is elastic, and the pozzolanic composition of WPG, being materials that contribute against the weakness of concrete under tensile stresses.

Seeboo et al. [58] demonstrated that crumb rubber's ductile nature reduces interfacial failures in rubber-concrete systems, particularly in tension zones, while fine glass powder enhances flexural strength up to an optimal threshold. Beyond this point, additional glass content decreases strength. The study also noted that excessive polymer content may compromise mechanical performance. Early-age flexural strength reduction was observed when combining glass powder with treated rubber [58]. In contrast, Gerges et al. [59] reported that a hybrid mixture—4% wood ash as cement replacement, combined with 30% wood ash, 30% fine crushed glass, and 2% crumb rubber as partial sand replacement—achieved a 28.72% increase in 28-day flexural strength. These findings highlight the importance of balanced waste-material ratios, where rubber improves ductility but requires complementary pozzolanic additives (e.g., glass or wood ash) to offset early-strength trade-offs.

Table 9 Flexural strength values for hybrid concrete mixes.

ID Mix	7 d (MPa)	Sv	14 d (MPa)	Sv	28 d (MPa)	Sv
T1	3.72	0.03	5.04	0.03	5.31	0.04
T2	5.42	0.06	6.87	0.07	7.23	0.08
T3	5.67	0.06	7.18	0.08	7.56	0.08
T4	6.16	0.07	7.80	0.08	8.22	0.09
T5	5.92	0.06	7.49	0.08	7.89	0.09

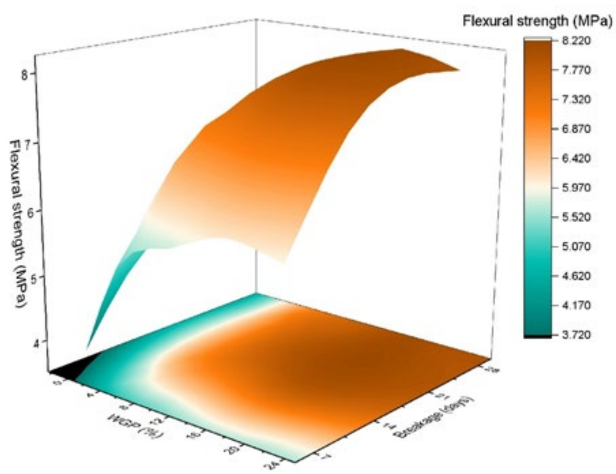

Figure 6 Effect of %WGP on the flexural strength of TRG-reinforced concrete.

3.4.3. Modulus of elasticity

Table 10 shows the results of the modulus of elasticity of concrete with the optimum dosage of treated granular rubber combined with varying dosages of residual glass powder tested at 7, 14, and 28 days according to the ASTM C469 procedure. **Figure 7** shows the 3D response surface plot with treatments

T2, T3, T4, and T5 showing a not-so-significant increase of 6.97, 9.84, 17.98, and 11.50%, respectively at 28 days of failure. With a content of 2.5%TRG and 16%WGP, the highest strength in modulus of elasticity was obtained indicating that at higher amounts of WGP, a great change in the internal structure of the strength of TRG-modified concrete occurs.

Malek et al. [35] reported that mortar with 5–15% glass sand aggregate (GSA) by weight exhibited a significantly lower modulus of elasticity than reference samples. However, at 20% GSA, the modulus increased by ~3%, attributed to glass's inherently higher elasticity compared to sand [35]. Concurrently, concrete with 20% glass powder (CGP20) showed improved strength due to the pozzolanic reaction of CaO and SiO_2 in the glass, enhancing C-S-H gel formation [60]. These findings align with broader studies demonstrating that industrial waste (e.g., glass sand/powder) can effectively replace natural aggregates and cement, reducing resource depletion while maintaining performance [61]. The results underscore the importance of optimal dosages, as higher glass content (>20%) may compromise mechanical properties despite its microstructural benefits.

Table 10 Modulus of elasticity values for hybrid concrete mixes.

ID Mix	7 d (GPa)	Sv	14 d (GPa)	Sv	28 d (GPa)	Sv
T1	17.98	0.10	22.07	0.46	22.46	0.49
T2	21.65	0.21	23.30	0.27	24.02	0.35
T3	22.31	0.46	23.97	0.34	24.67	0.29
T4	22.93	0.65	24.88	0.35	26.49	1.04
T5	22.53	0.29	24.27	0.34	25.04	0.50

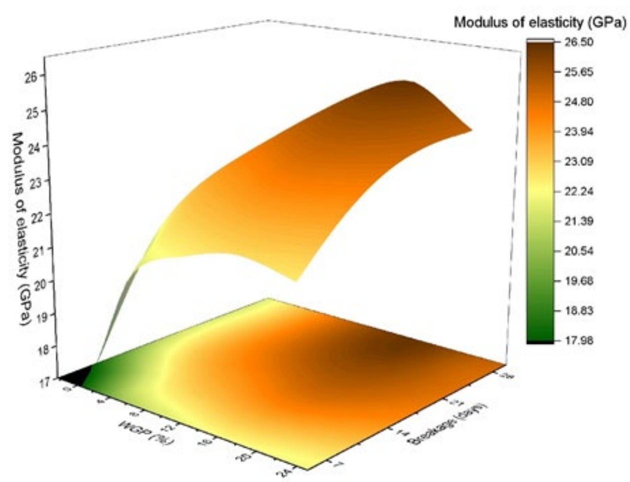

Figure 7 Effect of %WGP on the modulus of elasticity of TRG-reinforced concrete.

3.5. Multifactorial analysis of variance (ANOVA)

Considering the results from **Figure 8,** concerning the variable compressive strength, the ANOVA test yielded a significance p-value less than 0.05 (p=4.01e-06<0.05), indicating the rejection of the hypothesis of equal means. Additionally, Tukey's post hoc test revealed no significant difference between treatments T4 (2.5TRG%+16%WGP) and T5 (2.5TRG%+22%WGP). Both treatments facilitated maximizing compressive strength, with mean values of 27.81 MPa and 27.07 MPa, respectively, at 28 days of curing. Thus, treatment T4 (2.5TRG%+16%WGP) demonstrated the higher average compressive strength among samples.

Figure 9, concerning the variable flexural strength, the p-value of significance from the ANOVA test was found to be less than 0.05 ($p=8.23e-06<0.05$), indicating a significant difference between at least two evaluated treatments. Specifically, Tukey's multiple comparison test established that there is no significant difference between treatments T4 (2.5TRG%+16%WGP) and T5 (2.5TRG%+22%WGP). Treatment T4 (2.5TRG%+16%WGP) exhibited the highest average bending resistance among the samples, with a value of 8.22 MPa at 28 days of rupture.

Finally, in **Figure 10**, regarding the variable modulus of elasticity, the p-value of significance associated with the ANOVA test was found to be less than 0.05 ($p=6.1e-06<0.05$), indicating a significant difference between at least two treatments. Tukey's multiple comparison tests showed that treatments T4 (2.5TRG%+16%WGP) and T5 (2.5TRG%+22%WGP) did not exhibit a significant difference. Notably, the highest average modulus of elasticity among the samples was found in treatment T4 (2.5TRG%+16%WGP), with a value of 26.49 GPa at 28 days of rupture.

The lack of statistical significance ($p > 0.05$) between 16% and 22% WGP should be interpreted considering: 1) The effect size (standardized mean difference) between T4 and T5 was small ($d < 0.2$ for all variables), explaining the lack of statistical significance; 2) The statistical power (>80%) confirms that the study was sensitive enough to detect relevant differences; 3) The 95% confidence interval for the differences between means includes zero but leans toward T4. Technically, although statistically equivalent, 16% WGP shows consistent advantages: better mean (2.7-2.9% higher), lower standard deviation (greater uniformity), and greater material efficiency (37.5% less glass required). These practical factors justify selecting 16% as optimal.

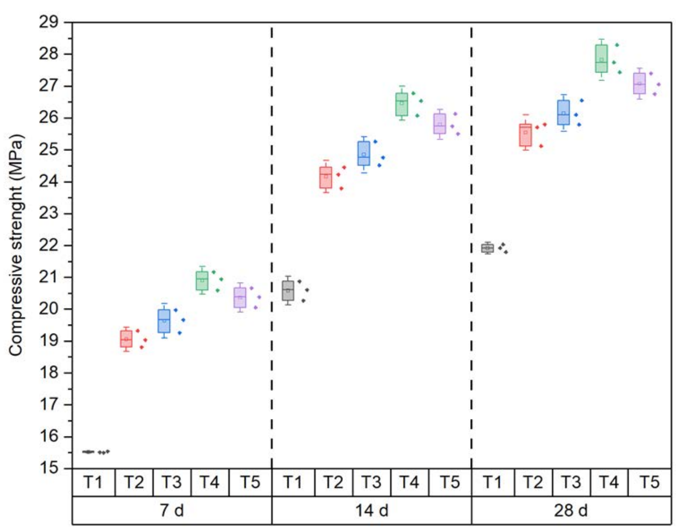

Figure 8 Boxplot of the compressive strength test of concrete

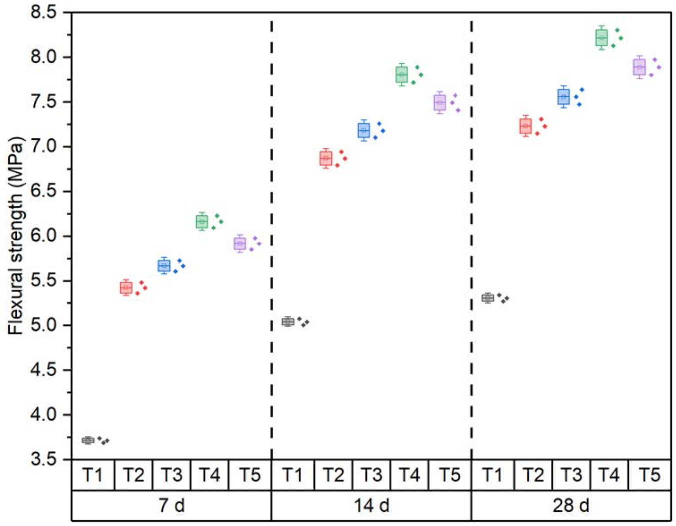

Figure 9 Boxplot of the flexural strength test of concrete

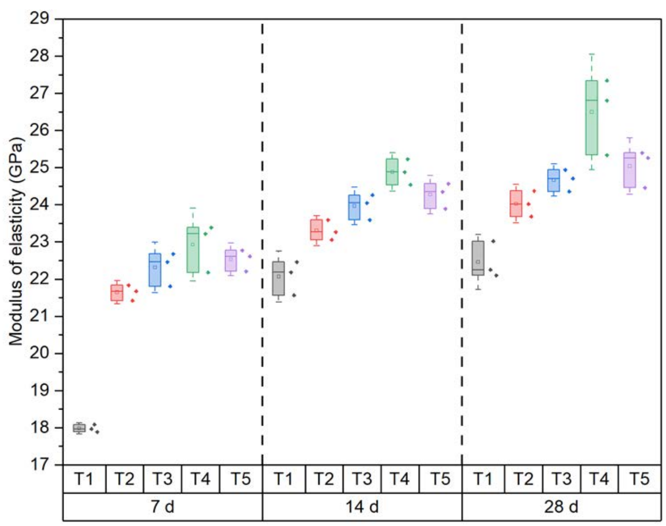

Figure 10 Boxplot of the modulus of elasticity test for concrete

4. Conclusions

In this study, the effect of the combination of the rubber granule with the optimal heat treatment with various doses of residual glass powder, the latter replacing cement, proved to be highly influential on the properties of the laboratory-produced concrete and favoring sustainable development, the following conclusions can be drawn from the study:

The use of rubber granules with heat treatment (at 200 °C for 45 minutes) showed a significant and ideal effect on compressive strength. The heat treatment evaluated at 30, 45, and 60 minutes increased the compressive strength by 3.49%, 10.93%, and 9.18%, respectively at 28 days.

The incorporation of treated rubber granules as received in concrete with contents of 2.5% increases its workability, and unit weight, and increases its air content. However, temperature showed a negligible effect, regardless of the volume of treated rubber used.
The hybrid mixtures had a reduction in their workability, air content, and increased unit weight; their temperature did not have much significance, being less than 30 °C.
The optimum percentage of treated rubber granules is 2.5% showed a significant effect on the improvement of compressive strength, flexural strength, and modulus of elasticity.
It is concluded that although statistically equivalent (*p* > 0.05), 16% WGP was selected over 22% due to: higher mechanical performance (2.7-2.9%), prevention of pozzolanic saturation, and material efficiency. This decision integrates statistical analysis with technical criteria, prioritizing optimization over statistical parity, according to established practices in materials science.
The optimal combination of 2.5% TRG + 16% WGP, validated through statistical analysis and technical criteria, is ideal for non-structural elements (lightweight pavements, curbs, building blocks, and street furniture). This solution directly contributes to three Sustainable Development Goals: SDG 9 (industrial innovation through waste recovery), SDG 11 (sustainable cities through eco-efficient materials), and SDG 12 (responsible production by reducing the consumption of virgin resources).

5. Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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7. Author contributions

G. CH. J. M. Conceived and designed the analysis. C. G. K. M. H. and M. M. E. A. Collected the data. C. G. K. M. H. and M. M. E. A. Contributed data or analysis tools. M. M. E. A. Performed the analysis. G. CH. J. M., and C. G. K. M. H. Wrote the paper

8. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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