



VALORIZATION OF WASTE TIRE RUBBER IN CONCRETE: INFLUENCE OF PARTICLE SIZE DISTRIBUTION ON MECHANICAL PERFORMANCE

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Abstract

The valorization of waste tire rubber presents a sustainable approach to reducing environmental impact while fostering the development of innovative construction materials. In this study, concrete mixtures were produced by partially replacing natural aggregates with three types of recycled rubber: fine powder (PR, 0/2 mm), rubber sand (SR, 0.3-0.4 mm), and coarse rubber aggregates (GR, 3/7 mm), at substitution levels ranging from 5% to 20%. Mechanical performance was assessed through standardized compression and tensile (splitting) tests carried out on laboratory-prepared concrete specimens.

The results indicate that incorporating rubber leads to a gradual reduction in mechanical strength compared to the reference concrete (26.8 MPa in compression and 2.39 MPa in tension). At 20% substitution, compressive strengths decreased to 20.4 MPa (PR), 21.4 MPa (SR), and 22.1 MPa (GR), corresponding to reductions of 24%, 20%, and 17%, respectively. Tensile strengths followed a similar trend, with values of 1.80 MPa, 1.88 MPa, and 1.95 MPa for PR, SR, and GR, respectively. These results clearly indicate that rubber particle size strongly influences mechanical performance: the coarser the particles, the better the strength retention. Additionally, all rubberized concretes exhibited higher peak strains, indicating improved ductility.

Overall, the incorporation of recycled rubber appears to be a promising solution for producing more ductile and environmentally sustainable concretes, particularly suitable for non-structural applications or elements requiring enhanced energy absorption capacity.

1. Introduction

The rapid increase in waste tire generation has become a major global environmental concern. Their disposal is particularly problematic due to their non-biodegradable nature, the accumulation in landfills, and the elevated risk of fire outbreaks. In response to these issues, the recycling of tire rubber into construction materials has emerged as an innovative, eco-friendly, and economically viable strategy that simultaneously mitigates environmental impact and enhances certain properties of concrete.

Over the past two decades, numerous studies have investigated the incorporation of rubber particles into cement-based materials [1, 2]. These investigations have demonstrated that rubber can improve concrete ductility, enhance energy absorption, and reduce impact sensitivity [3, 4]. However, most existing research has focused on a single particle size or a limited substitution range, which restricts a comprehensive understanding of the combined influence of particle size distribution and replacement rate on the global mechanical behaviour of rubberized concrete.

The originality of the present study lies in its comparative evaluation of three distinct rubber particle size fractions-fine powder (PR, 0/2 mm), rubber sand (SR, 0.3-0.4 mm), and coarse rubber aggregates (GR, 3/7 mm)-incorporated at substitution levels of 5%, 10%, 15%, and 20%. The objective is to provide a detailed analysis of their effect on the mechanical properties of concrete, particularly compressive strength, tensile strength, and ductility. The study seeks not only to quantify the strength reductions associated with each rubber type but also to identify the most suitable particle size distributions for non-structural applications or situations requiring improved energy dissipation.

Through its systematic and comparative approach, this work contributes to a deeper understanding of the role of rubber particle size in governing the mechanical behaviour of concrete and provides practical insights for the sustainable and optimized valorisation of waste tires in cement-based materials.

2. Experimental Methodology

2.1. Materials

The materials used for producing the rubberized concrete mixtures (Table 1) are listed below:

- Cement: Portland cement CEM I 52.5R, compliant with the Moroccan standard NM EN 197-1, commonly used in civil engineering works in Morocco [2, 4].

- Mineral addition: Limestone filler (CaCO_3), incorporated to improve matrix compactness, in accordance with the NM EN 206 - Moroccan National Annex [5, 7].
 - Natural aggregates:
 - 0/3 mm sand from a local quarry, complying with the NM EN 12620 [5, 8].
 - 3/7 mm gravel, also compliant with the NM EN 12620 [5, 8].
 - Mixing water: Potable water meeting the requirements of the NM EN 1008 standard, used for cement hydration and mixing [5, 9].
 - Admixture: Polycarboxylate-based superplasticizer, compliant with Moroccan national regulations (approved by national metrology laboratories or validated by accredited testing laboratories) [5, 9].
 - Recycled tire rubber aggregates: Three granular fractions obtained through mechanical shredding of end-of-life tires, in accordance with national industrial waste management practices:
 - PR (Powder): fine particles, 0/2 mm,
 - SR (Rubber sand): 0/3-0/4 mm,
 - GR (Rubber gravel): 3/7 mm.

Table 1. Physical characteristics of the materials used

Material	Moroccan standard/reference	Particle size (mm)	Typical density (kg/m^3)	Notes
CEM I 52.5R Portland cement	NM EN 197-1/national standard for high-strength cement	–	~3150	Typical value for Portland cement
Limestone filler (CaCO_3)	Meets requirements for mineral additions in NM EN 206/local specification	< 0.08	~2700	Depends on limestone origin
Natural sand 0/3	National aggregate standard/NM EN 206	0–3	~2650	Local washed sand
Natural gravel 3/7	National aggregate standard/NM EN 206	3–7	~2700	Dense local rock
Mixing water	NM EN 1008 or equivalent Moroccan water quality standard	–	~1000	Potable laboratory water

Superplasticizer (PCE)	Compliant with locally recognized admixture specifications/certified laboratories	–	~1100–1250	Density depends on formulation
Recycled rubber PR (0/2 mm)	Recycled material; controlled according to national industrial waste regulations	0–2	~1200–1400	Composite density of shredded rubber
Recycled rubber SR (0/4 mm)	Same	0–4	~1100–1300	Higher void content → lower density
Recycled rubber GR (3/7 mm)	Same	3–7	~900–1100	Coarser particles with more internal pores

Role of admixtures in our study

In studies involving concrete incorporating recycled tire aggregates, researchers commonly use a polycarboxylate-based superplasticizer for two main reasons:

- Improving workability

Recycled rubber particles are lightweight, hydrophobic, and exhibit poor adhesion to the cement paste, which reduces the compactness of the fresh mixture.

Without an admixture, achieving adequate slump would require adding excessive water, which increases the water-to-cement ratio (w/c) and consequently leads to a significant loss of mechanical strength.

- Maintaining mechanical performance despite rubber incorporation

The superplasticizer allows the mixture to remain workable while keeping a low w/c ratio, thereby preserving compressive strength and durability even when rubber is added.

The use of admixtures to maintain workability while preserving mechanical strength despite rubber addition follows established practices in fiber- and cork-reinforced earth materials [5, 7, 9].

2.2. Concrete mix designs

In this study, a series of Self-Compacting Concrete (SCC/SCSC) mixtures were prepared by partially replacing natural aggregates with

different fractions of recycled tire rubber, following a volumetric substitution approach. The objective is to assess the influence of both the substitution rate and particle size of the rubber on the mechanical, thermal, and durability-related properties of the concrete [2, 4, 8].

Mix design objectives

- Maintain a fluid consistency to ensure proper placement without vibration, in accordance with EFNARC (2002) recommendations and the Moroccan standard NM EN 206.

- Keep a constant water-to-cement ratio ($w/c = 0.50$) across all mixtures by using a polycarboxylate-based superplasticizer (PCE) dosed at 0.8% of cement mass, ensuring that any variation in performance is solely due to rubber incorporation.

- Evaluate three granular classes of recycled rubber:

- PR (powder, 0/2 mm),
- SR (rubber sand, 0/4 mm),
- GR (rubber gravel, 3/7 mm).

For each class, four volumetric substitution levels were tested: 5%, 10%, 15%, and 20%, in addition to a control mix CTRL-0 without rubber (Table 2).

All concrete mixtures were cast into $100 \times 100 \times 100 \text{ mm}^3$ specimens, in compliance with the Moroccan standard NM EN 12390-1 governing the preparation and curing of concrete specimens. This single specimen format was selected for all tests conducted in the study-including mechanical (compression, flexural), physical (density, porosity, water absorption), thermal (conductivity), and durability tests (immersion in aggressive environments) [5, 6].

Choosing a single specimen geometry ensured consistent comparison across all properties while minimizing material consumption.

Table 2. Mix proportions of the concrete mixtures

Mix	Substitution (%)	Cement (kg/m ³)	Water (kg/m ³)	Filler (kg/m ³)	PCE (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Rubber (kg/m ³)	w/c
CTRL-0	0	350.0	175.0	100	2.80	775.0	947.2	0.0	0.50
PR-5	5	350.0	175.0	100	2.80	736.6	947.2	190.5	0.50
PR-10	10	350.0	175.0	100	2.80	698.2	947.2	404.4	0.50
PR-15	15	350.0	175.0	100	2.80	659.8	947.2	626.6	0.50
PR-20	20	350.0	175.0	100	2.80	621.4	947.2	857.2	0.50
SR-5	5	350.0	175.0	100	2.80	736.6	947.2	160.9	0.50
SR-10	10	350.0	175.0	100	2.80	698.2	947.2	342.6	0.50
SR-15	15	350.0	175.0	100	2.80	659.8	947.2	532.9	0.50
SR-20	20	350.0	175.0	100	2.80	621.4	947.2	731.5	0.50
GR-5	5	350.0	175.0	100	2.80	775.0	900.3	187.7	0.50
GR-10	10	350.0	175.0	100	2.80	775.0	853.3	387.7	0.50
GR-15	15	350.0	175.0	100	2.80	775.0	806.3	606.1	0.50
GR-20	20	350.0	175.0	100	2.80	775.0	759.4	832.6	0.50

2.3. Preparation and curing of concrete specimens

The concrete mixtures were prepared in a controlled laboratory environment to ensure the homogeneity of the mixes and the comparability of results across all formulations. The dry constituents (cement, limestone filler, natural aggregates, and recycled rubber aggregates) were first prepared as follows:

- Natural aggregates were washed and conditioned to a saturated surface-dry (SSD) state to avoid undesired water absorption during mixing.
- Rubber aggregates were cleaned, air-dried, and sieved to obtain the three predefined particle-size fractions: PR (0/2 mm), SR (0/4 mm), and GR (3/7 mm).

The mixing water used complied with Moroccan standard NM EN 1008, and a polycarboxylate-based superplasticizer (PCE) was incorporated at 0.8% of cement mass to ensure adequate workability while maintaining a constant water-to-cement ratio of 0.50.

Mixing was performed using a laboratory vertical-axis mixer following this sequence:

- Dry mixing of aggregates, filler, and cement for 1 minute.

- Gradual addition of 70% of the mixing water, followed by 2 minutes of mixing.
- Addition of the remaining water containing the PCE, then mixing for an additional 2 minutes.
- One-minute rest period, followed by brief remixing to achieve full homogeneity.

The fresh concrete was then placed into $100 \times 100 \times 100$ mm steel cube molds without vibration, as the self-compacting nature of the mixtures ensured proper filling and encapsulation. The top surface was leveled and covered with plastic film to minimize early evaporation.

After 24 hours of curing at $20 \pm 2^\circ\text{C}$ under humid conditions, the specimens were demolded and immersed in lime-saturated water at $20 \pm 2^\circ\text{C}$, in accordance with NM EN 12390-2, until the testing ages of 7, 28, 180, and 365 days.

This wet curing procedure ensured complete cement hydration, prevented plastic shrinkage and early microcracking, and guaranteed identical curing conditions for all mixtures so that the observed differences in behavior were attributable solely to the rubber content and particle size.

3. Testing Methods

The mechanical tests were conducted on $100 \times 100 \times 100$ mm cubic specimens prepared according to the mix designs described above and cured in water at $20 \pm 2^\circ\text{C}$, in compliance with NM EN 12390-2. The aim of these tests was to evaluate the influence of incorporating recycled tire rubber aggregates of different particle sizes (PR, SR, GR) on the essential mechanical properties of concrete [2, 4, 7, 8, 9].

Two standardized tests were carried out:

- Compressive strength according to NM EN 12390-3, performed directly on the 100 mm cubes. This test assesses the load-bearing capacity of

the concrete and the evolution of strength as a function of rubber type and substitution rate [2, 4, 7].

- Splitting tensile strength (indirect tension) according to NM EN 12390-6, performed on the same cubes. This test evaluates the material's ability to resist crack opening and characterizes the influence of rubber on the internal cohesion of the concrete [2, 4, 8].

These two tests provide the fundamental mechanical indicators required to analyze the structural impact of replacing natural aggregates with recycled tire rubber in concrete [10-12].

4. Results and Discussion

The results presented in this section allow for a detailed evaluation of the effect of incorporating recycled rubber aggregates on the mechanical conduct of concrete. The PR, SR, and GR formulations, prepared with different substitution rates, are compared with the control concrete to identify variations in strength and changes in load-deformation behavior. The findings highlight the significant influence of rubber particle size and content on the global mechanical performance of the material.

4.1. Compressive strength results

The stress-strain curves of the PR series show a clear reduction in compressive strength as the proportion of rubber powder increases. The control concrete reaches a peak strength of approximately 26.8 MPa, while the PR mixtures achieve about 25.2 MPa (PR-5%), 23.6 MPa (PR-10%), 22.0 MPa (PR-15%), and 20.4 MPa (PR-20%).

This progressive loss of strength is attributable to the very fine particle size of the rubber powder (0/2 mm), which increases the rubber-cement paste interface area and leads to the formation of additional micro-voids. The weak adhesion between rubber and cement paste reduces the cohesion of the matrix, thereby lowering the load-carrying capacity of the material.

At the same time, a slight increase in the peak strain is observed, indicating a more ductile behavior compared with the control concrete CTRL-0 (Figure 1) [10, 11].

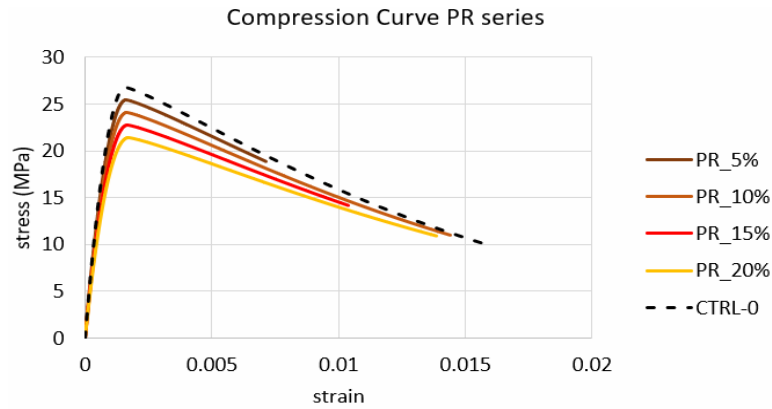


Figure 1. Stress-strain curves in compression for the PR series concretes (5%, 10%, 15%, 20%) compared with the control concrete CTRL-0.

The control concrete exhibits a maximum compressive strength of approximately 26.8 MPa, while the SR mixtures reach about 25.5 MPa (SR-5%), 24.1 MPa (SR-10%), 22.8 MPa (SR-15%), and 21.4 MPa (SR-20%).

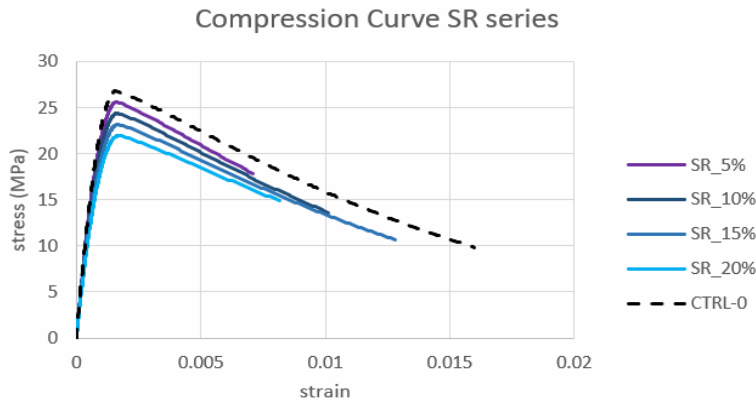


Figure 2. Stress-strain curves in compression for the SR series concretes (5%, 10%, 15%, 20%) compared with the control concrete CTRL-0.

The reduction in strength is less pronounced than that observed for the PR series, owing to the coarser particle size of the SR rubber (0/3-0/4 mm),

which induces less disruption within the cementitious matrix. The SR-5% and SR-10% mixtures remain close to the performance of the control concrete, whereas SR-15% and SR-20% show a moderate but consistent reduction in compressive strength. The stress-strain curves also display a more gradual post-peak response, indicating a less brittle failure mode and improved energy absorption capacity (Figure 2) [12, 13].

The control concrete reaches a maximum compressive strength of approximately 26.8 MPa, while the GR mixtures achieve about 25.6 MPa (GR-5%), 24.5 MPa (GR-10%), 23.3 MPa (GR-15%), and 22.1 MPa (GR-20%).

Because of their coarser particle size (3/7 mm), GR rubber aggregates induce a more moderate and more uniform reduction in strength compared with the PR and SR series. The GR-5% and GR-10% mixtures remain very close to the performance of the control concrete, and even at higher substitution levels, the load-bearing capacity remains satisfactory. The larger particle size reduces the formation of weak interfacial zones and enhances energy dissipation, resulting in smoother post-peak behavior and a less brittle cracking mode [14, 10] (Figure 3).

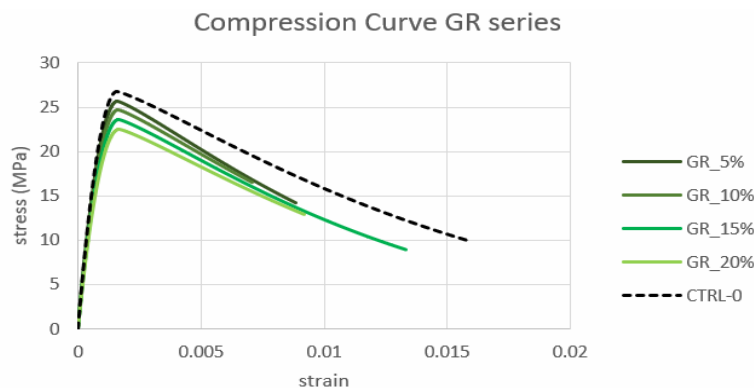


Figure 3. Stress-strain curves in compression for the GR series concretes (5%, 10%, 15%, 20%) compared with the control concrete CTRL-0.

The comparative analysis of the compressive curves for the substitution levels of 5%, 10%, 15%, and 20% (Figure 4) highlights the direct influence

of rubber particle size and substitution rate on the strength of concrete. The control concrete CTRL-0, with a maximum strength of 26.8 MPa, is used as the reference for assessing mechanical losses.

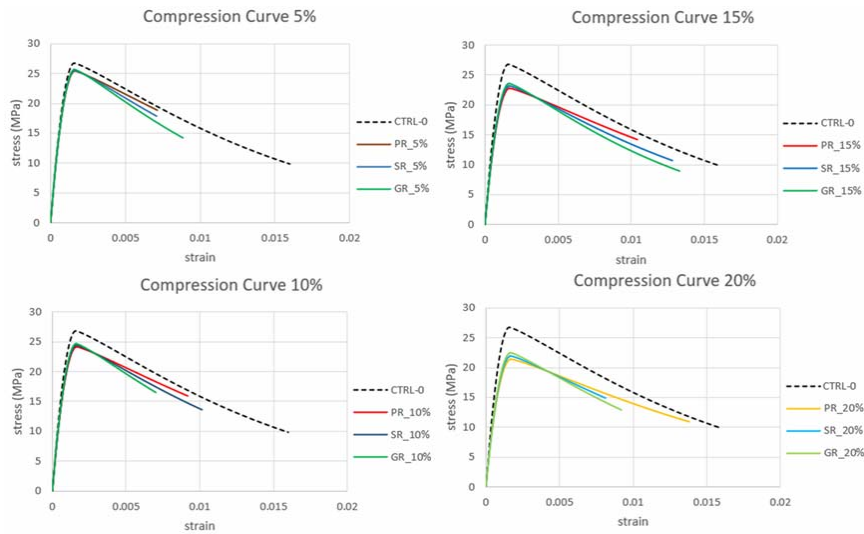


Figure 4. Comparison of the compressive stress-strain curves of the PR, SR, and GR series for substitution rates of 5%, 10%, 15%, and 20%.

At 5% incorporation, the three series remain relatively close to the control, with 25.2 MPa for PR-5%, 25.5 MPa for SR-5%, and 25.6 MPa for GR-5%. The reduction in strength is limited (−4% to −6%), indicating that low substitution levels do not significantly affect mechanical performance.

At 10%, the differences become more noticeable: PR-10% decreases to 23.6 MPa, SR-10% to 24.1 MPa, and GR-10% to 24.5 MPa. Strength losses reach −12% for PR, whereas SR and GR show more moderate reductions (−8% to −9%), reflecting the better compatibility of coarser rubber particles with the cementitious matrix.

At 15%, the decrease becomes more pronounced, with 22.0 MPa for PR-15%, 22.8 MPa for SR-15%, and 23.3 MPa for GR-15%. The losses are significant: −18% for PR, −15% for SR, and −13% for GR, confirming the detrimental effect of fine particles which increase weak interfaces and internal micro-porosity.

At 20%, the differences between the series are even more marked: PR-20% drops to 20.4 MPa, while SR-20% reaches 21.4 MPa and GR-20% 22.1 MPa. Thus, the PR series shows the greatest reduction (−24%), whereas the GR series remains the most effective (−17%), owing to the coarser particle size which disrupts the granular skeleton less and enhances energy dissipation.

These numerical results clearly demonstrate that the finer the rubber particles, the greater the strength loss, and that GR aggregates exhibit the best mechanical behavior at all substitution levels, followed by SR, then PR.

4.2. Tensile strength results

The tensile strength decreases progressively as the proportion of PR rubber powder increases, falling from approximately 2.20 MPa to 1.80 MPa as the substitution level rises from 5% to 20%. This reduction is attributed to the very fine particle size of the rubber powder, which creates a larger number of weak interfaces within the matrix and facilitates crack initiation [13, 14] (Figure 5).

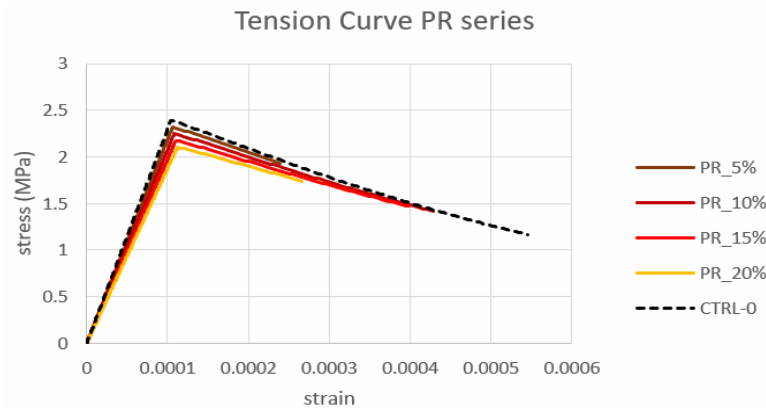


Figure 5. Tensile stress-strain curves for the PR series concretes (5%, 10%, 15%, 20%) compared with the control concrete CTRL-0.

The SR concretes exhibit a less pronounced decrease in tensile strength compared to the PR series. The tensile values range from approximately 2.25 MPa to 1.88 MPa for substitution rates between 5% and 20%.

The coarser SR particles induce less disruption within the cementitious matrix, thereby limiting the loss of strength (Figure 6).

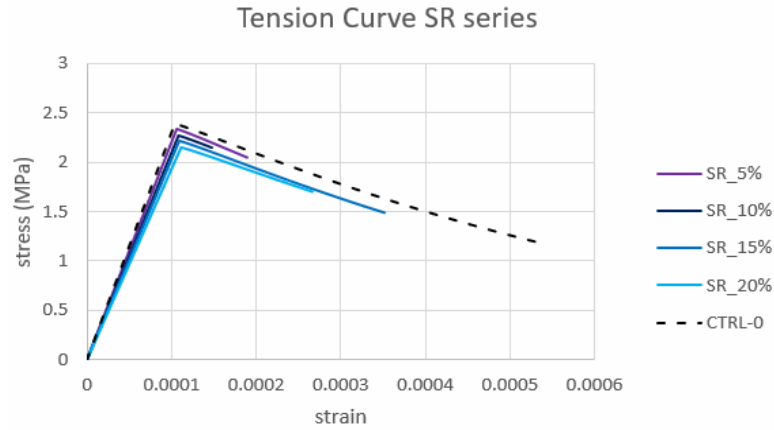


Figure 6. Tensile stress-strain curves for the SR series concretes (5%, 10%, 15%, 20%) compared with the control concrete CTRL-0.

The GR series exhibits the best retention of tensile strength, with values ranging from approximately 2.30 MPa to 1.95 MPa.

The coarse GR rubber aggregates enhance energy dissipation and reduce the number of weak interfacial zones, resulting in a less reduction in tensile strength (Figure 7).



Figure 7. Tensile stress-strain curves for the GR series concretes (5%, 10%, 15%, 20%) compared with the control concrete CTRL-0.

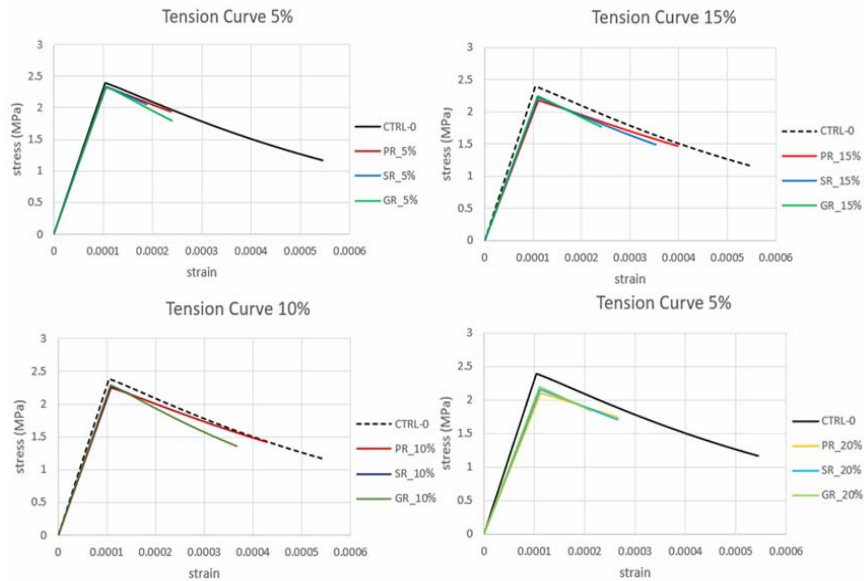


Figure 8. Comparison of the tensile stress-strain curves of the PR, SR, and GR series for substitution rates of 5%, 10%, 15%, and 20%.

At 5% incorporation, the three series (PR, SR, and GR) show only a slight decrease in tensile strength compared with the control. The values remain close: PR-5% \approx 2.20 MPa, SR-5% \approx 2.25 MPa, and GR-5% \approx 2.30 MPa, compared with 2.39 MPa for CTRL-0.

The reduction is limited (−4% to −8%), indicating that 5% rubber has only a minor effect on the material’s ability to resist crack initiation.

At 10%, the decrease becomes more noticeable: PR-10% \approx 2.05 MPa, SR-10% \approx 2.15 MPa, and GR-10% \approx 2.20 MPa. Strength losses range between −8% and −14%. The GR series remains the best-performing, while PR exhibits a more significant reduction due to its finer particle size.

At 20%, the reduction is the most pronounced: PR-20% \approx 1.80 MPa, SR-20% \approx 1.88 MPa, and GR-20% \approx 1.95 MPa. The losses reach −18% to −25%.

The GR aggregates maintain the highest level of tensile strength, whereas the PR series shows the greatest decrease.

5. Conclusion

This study investigated the effect of incorporating recycled tire rubber aggregates of three different particle-size fractions (PR, SR, and GR) on the mechanical performance of concrete. The results clearly show that the addition of rubber leads to a reduction in mechanical strength, although the extent of this reduction strongly depends on the particle size of the rubber.

The control concrete achieved 26.8 MPa in compression and 2.39 MPa in tension, serving as the reference for comparison. At a 20% substitution rate, the compressive strengths decreased to 20.4 MPa (PR), 21.4 MPa (SR) and 22.1 MPa (GR), corresponding to reductions of 24%, 20%, and 17%, respectively. Tensile strengths followed the same trend, with values of 1.80 MPa (PR), 1.88 MPa (SR) and 1.95 MPa (GR), confirming that coarser rubber particles preserve strength more effectively.

All rubberized concrete mixtures exhibited increased peak strain, indicating enhanced ductility, which is beneficial for applications requiring improved energy absorption or resistance to brittle cracking.

Although the incorporation of recycled rubber results in moderate reductions in strength, it provides significant advantages in terms of deformability, reduced density, and environmental impact, aligning with findings in fiber-reinforced and natural fiber-stabilized compressed earth blocks [10, 11, 15]. Coarse rubber aggregates (GR) appear to be the most suitable for non-structural or semi-structural applications where ductility and energy dissipation are of primary importance.

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