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Scientific paper
ISSN 0351-9465, E-ISSN 2466-2585
https://doi.org/10.62638/ZasMat1871

Zastita Materijala 67 ()
(2026)

Integrating recycled rubber and slag for strength and low carbon footprint in sustainable high-performance concrete

ABSTRACT

This study investigates the development of sustainable high-performance concrete (HPC) by incorporating Granulated Blast Furnace Slag (GGBS) and recycled rubber powder (RRP) as partial replacements for cement and fine aggregate. The objective is to enhance the mechanical and durability properties of concrete while promoting environmental sustainability. Various concrete mixes were prepared with different percentages of GGBS (10–30%) and RRP (5–15%). Workability was evaluated using slump tests, while compressive, split tensile, and flexural strengths were determined at 7, 14, and 28 days. Durability performance was assessed through Rapid Chloride Penetration Test (RCPT) and sulphate resistance tests, along with microstructural analysis using SEM. The results indicated that GGBS improves workability, long-term strength, and durability due to pore refinement and additional C–S–H formation. In contrast, RRP reduces strength and workability at higher contents due to weak interfacial bonding. However, moderate incorporation of RRP enhances sustainability without significantly compromising performance. An optimum mix of 20% GGBS and 5% RRP was identified, providing a balanced combination of strength, durability, and eco-friendliness.

Keywords: *Rubber powder, GGBS, Cement, Silica sand, High-performance concrete*

1. INTRODUCTION

The construction industry is currently undergoing a significant transformation driven by the urgent need to reduce carbon emissions, conserve natural resources, and adopt sustainable materials and technologies. As one of the largest consumers of raw materials globally, the construction sector has a substantial environmental footprint. Among construction materials, concrete remains the most widely used due to its versatility, strength, and cost-effectiveness. However, conventional concrete production is closely associated with environmental degradation, primarily because of cement manufacturing.

Cement production alone is responsible for approximately 7–8% of global carbon dioxide (CO_2) emissions [1, 2].

This high emission level is mainly attributed to the calcination of limestone and the energy-intensive kiln processes involved in producing clinker. On average, the production of one ton of clinker releases nearly 0.8–1 ton of CO_2, making cement one of the most carbon-intensive industrial products [2]. In addition to emissions, the rapid expansion of construction activities has led to excessive extraction of natural aggregates, especially river sand, resulting in riverbed erosion, groundwater imbalance, habitat destruction, and long-term ecological instability [3].

In response to these environmental concerns, the development of sustainable high-performance

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Paper received: 02. 05. 2026.
Pape accepted: 07. 06. 2026.

concrete (HPC) has gained considerable attention from researchers and engineers [2, 4]. High-performance concrete is characterized not only by superior mechanical strength but also by enhanced durability, workability, and resistance to environmental degradation. A key strategy for improving sustainability in HPC is the partial replacement of ordinary Portland cement with supplementary cementitious materials (SCMs). Among these, Granulated Blast Furnace Slag (GGBS), a by-product of the iron and steel industry, has emerged as one of the most promising alternatives [3, 5]. GGBS is obtained by rapidly cooling molten slag from blast furnaces, resulting in a glassy, granular material that exhibits latent hydraulic properties. When used as a partial cement replacement, typically in the range of 20–30%, GGBS significantly reduces the demand for Portland cement and consequently lowers CO_2 emissions [2, 5]. Beyond environmental benefits, GGBS contributes positively to the performance of concrete by enhancing workability due to its smoother particle texture and improving long-term strength development through the formation of additional calcium silicate hydrate (C–S–H) gel during hydration [6]. This densification of the microstructure results in reduced porosity, improved impermeability, and greater resistance to aggressive chemical environments such as chloride and sulphate attacks [7, 8].

Alongside cement replacement strategies, the incorporation of alternative aggregates has also become an important focus in sustainable concrete research [9, 10]. One such material is recycled rubber powder (RRP), derived from waste tires. The disposal of used tires is a major global environmental issue, with more than one billion waste tires generated annually [4]. These materials are non-biodegradable and often accumulate in landfills or are illegally dumped, posing significant fire and pollution hazards. Recycling waste tires into rubber powder for use in concrete provides a viable solution for waste management while contributing to material sustainability [11, 12]. Typically, recycled rubber powder is used to replace fine aggregates such as sand in proportions ranging from 5% to 15% [4, 13]. The inclusion of rubber particles in concrete has been shown to improve mechanical properties such as ductility, flexibility, impact resistance, and energy absorption capacity [14, 15]. These improvements are attributed to the elastic nature of rubber, which enables better absorption of dynamic loads and reduces sudden brittle failure. However, higher rubber content can reduce compressive strength by 10–25% due to weak interfacial bonding between hydrophobic rubber particles and the cementitious matrix [16, 17]. Despite this limitation, rubberized concrete is considered highly beneficial for applications requiring enhanced toughness and vibration resistance [13, 18].

Another important component in high-performance concrete systems is silica sand, widely used due to its high purity, uniform grading, and excellent mechanical strength [3, 19]. Silica sand contributes to improved packing density and enhances the overall strength of concrete. However, large-scale extraction of silica sand raises environmental concerns, including land degradation and depletion of natural reserves [20]. To address this issue, researchers have explored partial replacement of natural sand with industrial by-products and recycled materials [21]. Such substitutions not only reduce environmental impact but also support waste valorization and circular economy principles. When combined with SCMs like GGBS and alternative aggregates such as rubber powder, silica sand-based systems can be optimized to achieve both mechanical performance and sustainability goals [10, 22].

Recent studies have highlighted the synergistic effects of combining multiple waste-derived and supplementary materials in concrete [14, 23]. For instance, the combined use of GGBS and recycled rubber powder has been reported to enhance durability characteristics such as reduced water absorption, lower chloride ion permeability, and improved resistance to sulphate attack [13, 24]. GGBS contributes to matrix densification, while rubber particles introduce flexibility and crack-bridging capabilities [25]. This dual mechanism leads to a more balanced performance, where brittleness is reduced without significantly compromising strength. However, most existing studies focus on single or binary material replacements, and limited research has investigated ternary systems involving GGBS, recycled rubber powder, and high-quality fine aggregates such as silica sand, particularly for achieving high-strength concrete grades such as M80 or above [5, 26].

This research gap is important because modern infrastructure requires materials that combine high strength, durability, and sustainability. High-strength concrete such as M80 is used in structures like high-rise buildings, bridges, and industrial facilities, where reliable performance is critical. However, achieving this strength while incorporating industrial by-products and recycled materials is challenging due to factors such as particle interaction, mix design, interfacial transition zone (ITZ) behavior, and hydration processes, all of which must be carefully optimized to maintain structural integrity.

Therefore, this study aims to develop and evaluate a sustainable M80 grade high-performance concrete using 10–30% GGBS as a cement replacement and 5–15% recycled rubber powder as a fine aggregate replacement. The investigation focuses on fresh properties such as workability, hardened properties including compressive, split tensile, and flexural strength, and durability aspects such as water absorption, chloride resistance, and sulphate resistance [11], [14], [15]. Microstructural analysis (SEM) will also be used to study bonding and pore structure evolution within the concrete matrix [9], [15].

The expected outcome is an optimized mix that balances strength, durability, and sustainability. GGBS is expected to improve long-term strength and durability, while rubber powder enhances ductility and energy absorption [13], [18]. Although early-age strength may slightly decrease due to rubber content, overall performance is expected to remain suitable for high-strength structural applications [11], [20].

2. MATERIALS

Ordinary Portland Cement (OPC) provides high compressive strength and reliable setting, though it generates moderate heat. Granulated Blast Furnace Slag (GGBS) enhances durability, reduces heat of hydration, and improves long-term strength. Silica sand acts as a strong, inert fine aggregate, improving packing density and durability. Recycled rubber powder lowers density, increases flexibility and impact resistance, but may reduce strength at higher contents. Polycarboxylate-based super plasticizer significantly reduces water demand, improves workability, enhances strength, and ensures better dispersion of cement particles, making it suitable for high-performance and sustainable concrete mixtures.

2.1 Cement

Ordinary Portland Cement (OPC) is the most commonly used binding material in construction, produced by grinding clinker with gypsum. It provides high compressive strength, making it suitable for structural applications. OPC exhibits good initial and final setting times, ensuring ease of handling and placement. However, it generates moderate to high heat of hydration, which may lead to thermal cracking in mass concrete. It offers satisfactory durability under normal conditions but can be vulnerable to sulfate and chemical attacks if not modified. Additionally, OPC contributes to the workability and plasticity of fresh concrete when mixed with water. Figure 1 shows the XRD image of cement.

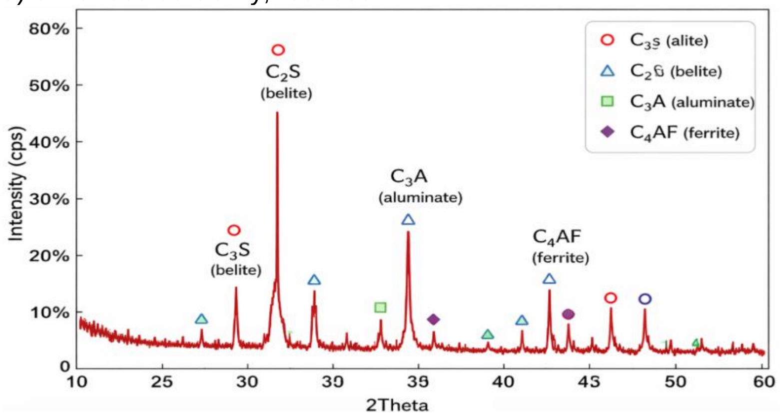

Figure 1. XRD of cement

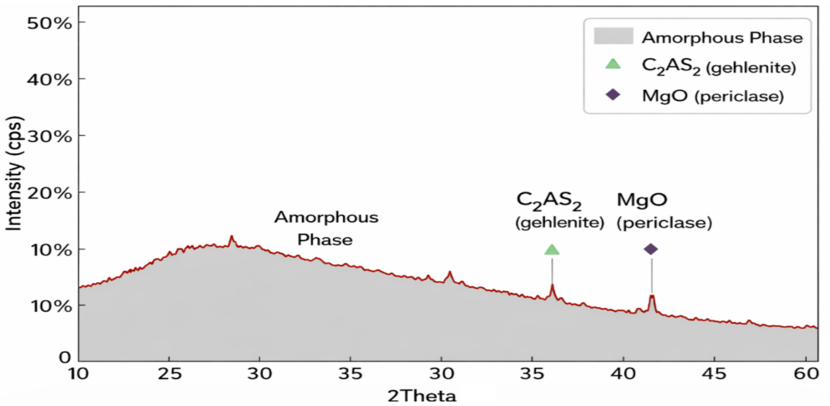

Figure 2. XRD of GGBS

2.2. Granulated Blast Furnace Slag (GGBS)

Granulated Blast Furnace Slag (GGBS) is a by-product of iron manufacturing, formed by rapidly cooling molten slag. It possesses latent hydraulic properties and reacts with water in the presence of activators like OPC to form cementitious compounds. GGBS improves concrete durability by enhancing resistance to sulfate attack, chloride ingress, and alkali-silica reaction. It produces low heat of hydration, reducing the risk of thermal cracking in large structures. Although early strength gain is slower, it contributes to higher long-term strength. Its use significantly lowers the carbon footprint of concrete, making it an eco-friendly and sustainable material. Figure 2 shows the XRD of GGBS.

2.3. Silica Sand

Silica sand is a fine aggregate primarily composed of silicon dioxide (SiO_2), widely used in concrete mixtures. It is known for its high hardness and strength, which contribute to the overall mechanical performance of concrete. Due to its chemical inertness, silica sand resists weathering and chemical reactions, ensuring durability. Its uniform particle size distribution improves packing density and minimizes voids, resulting in a denser and stronger matrix. Silica sand also enhances the workability and finishability of fresh concrete. Additionally, it provides excellent abrasion resistance and long-term stability, making it suitable for various construction applications. Figure 3 shows the XRD of silica sand.

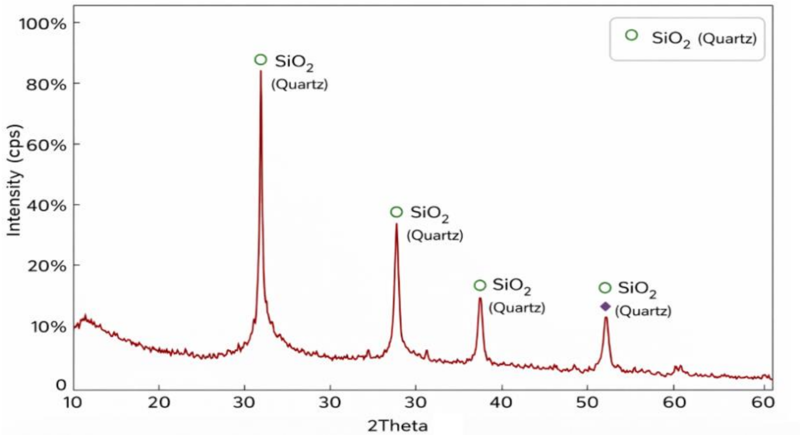

Figure 3. XRD of silica sand

2.4. Recycled Rubber Powder

Recycled rubber powder (RRP) is obtained from waste tires and used as a partial replacement for fine aggregates in concrete. It has a lower density, which helps produce lightweight concrete. The material enhances flexibility, ductility, and impact resistance due to its elastic nature. It also improves energy absorption, making concrete more resistant to shock and vibration. However, excessive use may reduce compressive strength due to weaker bonding with cement paste. Recycled rubber powder contributes to better thermal and acoustic insulation. Its use promotes sustainability by reducing environmental pollution and providing an effective solution for waste tire management. Figure 4 shows the XRD of recycled rubber powder.

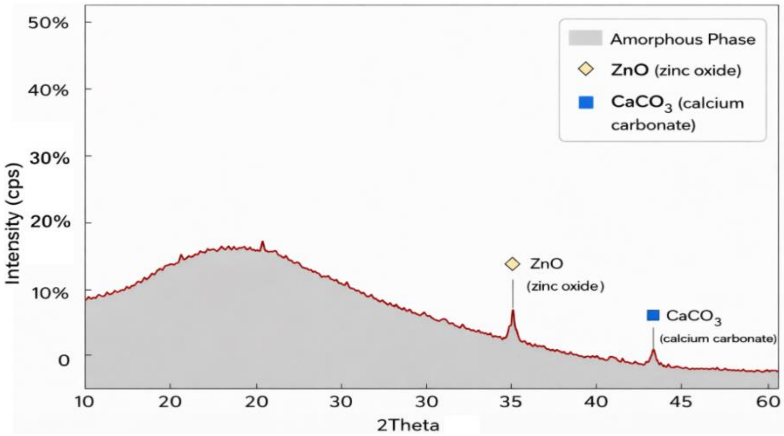

Figure 4. XRD of recycled rubber powder

2.5. Coarse Aggregate

In this study, 20 mm nominal size coarse aggregate is used, which is commonly preferred for structural concrete. It consists of crushed angular stones that provide good interlocking and bonding with the cement matrix. The aggregate typically has a specific gravity of about 2.6–2.8 and a bulk density of 1400–1600 kg/m³. Its angular shape enhances strength, while proper grading ensures reduced voids and improved workability. The 20 mm size aggregate offers an optimal balance between strength and workability, making it suitable for reinforced concrete works. It is durable, resistant to abrasion, and contributes significantly to the overall strength and stability of concrete.

2.6. Polycarboxylate-Based Superplasticizer

Polycarboxylate-based superplasticizer is a high-range water-reducing admixture used to enhance concrete performance. It significantly reduces the water-cement ratio while maintaining or improving workability. This results in higher strength and durability of hardened concrete. It improves flowability, making it suitable for producing self-compacting and high-performance concrete. The admixture ensures better dispersion of cement particles, preventing flocculation and improving hydration efficiency. It also provides extended workability retention, allowing longer handling time.

Table 1. Physical properties of materials

Material	Form	Specific Gravity	Bulk Density (kg/m³)	Particle Size	Color	Fineness
OPC	Fine powder	3.15	1436	< 75 µm	Grey	330 m²/kg
GGBS	Fine powder	2.88	1189	< 45 µm	Off-white	542 m²/kg
Silica Sand	Granular	2.67	1604	> 1.36 mm	White	Low
Recycled Rubber Powder	Powder/Granules	1.14	514	< 600 µm	Black	Low
Superplasticizer (PCE-based)	Liquid	1.09	1169	Liquid form	Light yellow	-
Coarse Aggregate (20 mm)	Crushed angular stones	2.75	1548	20 mm	Grey	-

Table 2. Chemical properties of materials

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Others
OPC	65.13	21.65	4.18	2.56	1.86	1.79	2.83
GGBS	41.28	34.15	15.09	-	6.83	-	2.65
Silica Sand	-	97.87	0.98	0.56	-		0.59
Recycled Rubber Powder	-	-	-	-	-	-	100 (Rubber + Carbon black + additives)

Additionally, it is highly compatible with supplementary cementitious materials like GGBS, making it ideal for modern, sustainable concrete mixtures. Table 1 and 2 show sthe physicalk and chemical properties of materials.

3. METHODOLOGY

The materials were first characterized based on their physical and chemical properties. Mix design was carried out as per relevant standards to achieve the desired strength. Concrete mixtures were prepared with different percentages of GGBS and rubber powder. The dry materials were thoroughly mixed, followed by the addition of water and superplasticizer to obtain a homogeneous mix.

Fresh concrete tests such as slump were conducted to evaluate workability. The concrete was then cast into standard moulds for compressive strength, split tensile strength, and flexural strength tests. Specimens were demoulded after 24 hours and cured in water for 7, 14, and 28 days.

Hardened concrete tests were performed at specified curing periods. Additionally, durability properties like RCPT and sulphate resistance and microstructural analysis such as SEM was carried out to study phase composition. The results obtained were analyzed to evaluate the effect of recycled rubber and GGBS on strength and durability properties of concrete. Figure 5 shows the graphical methodology.

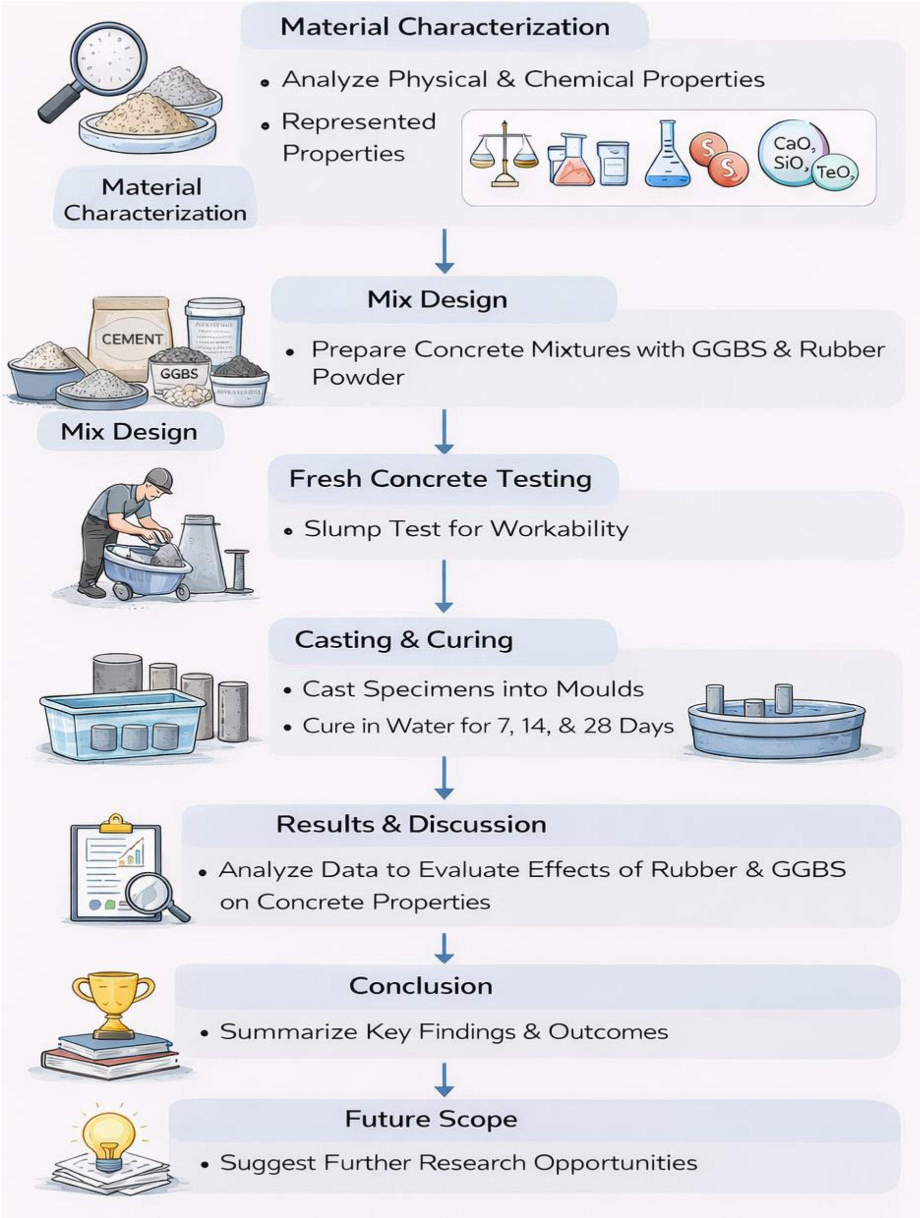

Figure 5. Graphical methodology

4. RESULTS AND DISCUSSION

4.1. Slump Cone Test

The slump test outcomes for the different high-performance concrete mixes are illustrated in figure 6. The measured slump values fall within the range of 74 mm to 84 mm, indicating that all mixtures achieved a consistent level of workability suitable for M80 grade concrete. The variation in slump values clearly reflects the influence of GGBS and recycled rubber powder (RRP) on fresh concrete behavior.

An increasing trend in workability was observed with the replacement of cement by GGBS. The slump value increased progressively from 80 mm to 84 mm as the GGBS content was raised from 10% to 30%. Compared to the control mix, which recorded a slump of 77 mm, the higher GGBS mixes exhibited improved flow characteristics. This enhancement can be explained by the finer particles and smooth surface of GGBS, which contribute to better packing density and reduced friction between particles.

On the other hand, the incorporation of recycled rubber powder resulted in a decline in slump values. With a constant GGBS content of 20%, increasing the RRP proportion from 5% to 15% reduced the slump from 80 mm to 74 mm. This behavior is mainly due to the non-absorbent and irregular nature of rubber particles, which restricts proper interaction with the cement paste and increases resistance to flow.

In summary, GGBS positively influences the workability of concrete, whereas RRP has an adverse effect. Nevertheless, when used in controlled proportions, their combined incorporation maintains workable mixes suitable for practical applications. Figure 7 shows the slump cone cone testing.

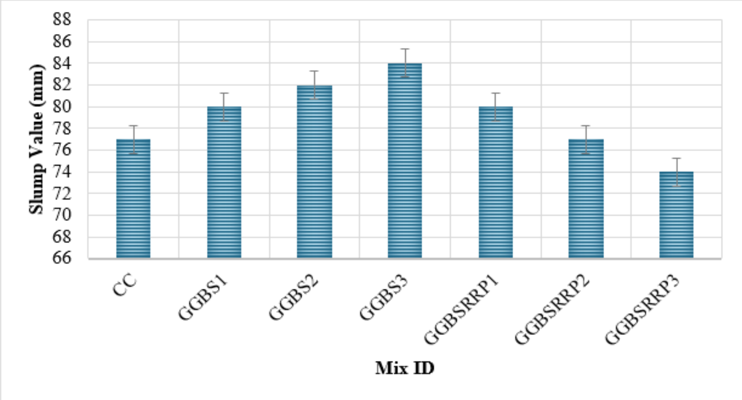

Figure 6. Slump value

Figure 7. Slump cone test

4.2. Compressive Strength Test

The compressive strength results of the various high-performance concrete mixes at 7, 14, and 28 days are presented in figure 8. The results show a clear variation in strength development with the incorporation of GGBS and recycled rubber powder (RRP).

At early curing age (7 days), the conventional concrete exhibited a strength of 54.60 MPa, which was higher than all GGBS-based mixes. As the percentage of GGBS increased from 10% to 30%, the 7-day strength gradually decreased from 52.50 MPa to 47.25 MPa. This reduction is attributed to the slower hydration rate of GGBS compared to Ordinary Portland Cement, resulting in delayed early strength gain.

However, at later ages, the trend reversed. At 28 days, the compressive strength increased significantly with higher GGBS content. The GGBS3 mix (30% replacement) achieved the highest strength of 94.50 MPa, compared to 86.10 MPa for conventional concrete. This improvement is due to the latent hydraulic properties of GGBS, which enhance long-term strength through secondary hydration reactions and formation of additional calcium silicate hydrate (C–S–H) gel.

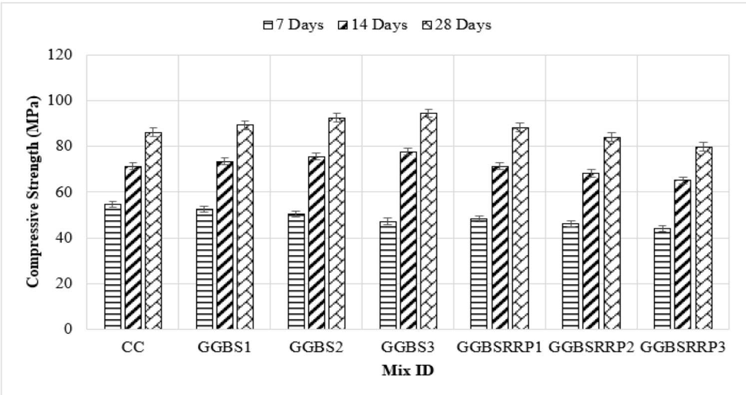

Figure 8. Compressive strength results

The inclusion of recycled rubber powder had a negative impact on compressive strength. At a constant GGBS content of 20%, increasing the RRP content from 5% to 15% reduced the 28-day strength from 88.20 MPa to 79.80 MPa. This decrease is mainly due to the weak bonding between rubber particles and the cement matrix, as well as the lower stiffness of rubber compared to mineral aggregates.

Figure 9. Compreissive Strength Test

Overall, the results indicate that GGBS improves long-term compressive strength, while RRP reduces strength with increasing content. An optimum combination is observed at 20% GGBS with 5% RRP, which provides a balance between strength and sustainability. Figure 9 shows the compressive strength test.

4.3. Split Tensile Strength Test

The split tensile strength results for all high-performance concrete mixes at 7, 14, and 28 days are presented in figure 10. The results indicate a gradual development of tensile strength with curing age and highlight the influence of GGBS and recycled rubber powder (RRP) on tensile behavior.

At 7 days, the conventional concrete exhibited a tensile strength of 5.59 MPa, which was higher than the GGBS-based mixes. As the GGBS content increased from 10% to 30%, the early-age strength decreased from 5.38 MPa to 4.84 MPa, due to the slower hydration rate of GGBS. However, at later ages, a significant improvement was observed. At 28 days, the tensile strength increased with higher GGBS content, reaching a maximum value of 8.62 MPa for the GGBS3 mix, compared to 7.85 MPa for conventional concrete. This enhancement is attributed to improved microstructure and additional formation of binding compounds.

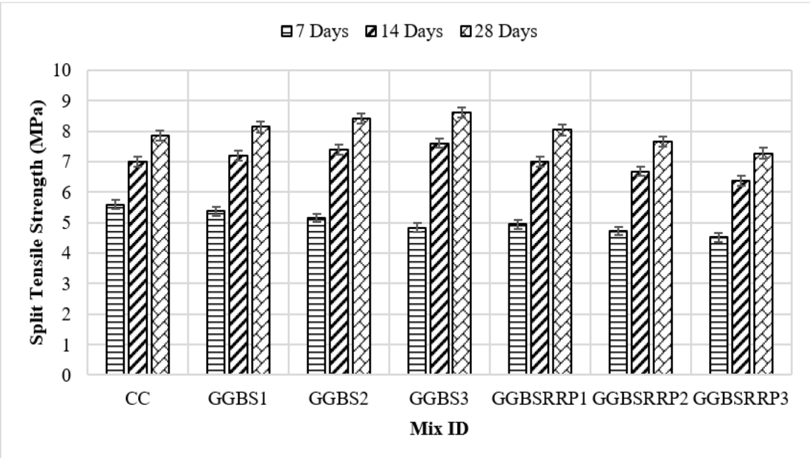

Figure 10. Split tensile strength results

The addition of recycled rubber powder showed a reduction in tensile strength. At a constant 20% GGBS replacement, increasing RRP content from 5% to 15% reduced the 28-day strength from 8.04 MPa to 7.28 MPa. This decrease is mainly due to the weak interfacial bonding between rubber particles and the cement matrix, which reduces the ability of concrete to resist tensile stresses.

Overall, GGBS contributes to improved long-term tensile strength, while higher proportions of RRP lead to strength reduction. An optimal combination is observed at 20% GGBS with 5% RRP, which provides a reasonable balance between tensile strength and sustainability benefits. Figure 11 shows the split tensile strength test.

Figure 11. Split tensile strength test

4.4. Flexural Strength Test

The flexural strength results of the high-performance concrete mixes at 7, 14, and 28 days are presented in figure 12. The results demonstrate a consistent increase in strength with curing age and highlight the influence of GGBS and recycled rubber powder (RRP) on flexural performance.

At 7 days, the conventional concrete showed a flexural strength of 4.98 MPa, which was higher than all GGBS-based mixes. As the GGBS content increased from 10% to 30%, the early strength decreased from 4.79 MPa to 4.31 MPa, due to slower hydration. However, at later ages, an improvement in flexural strength was observed.

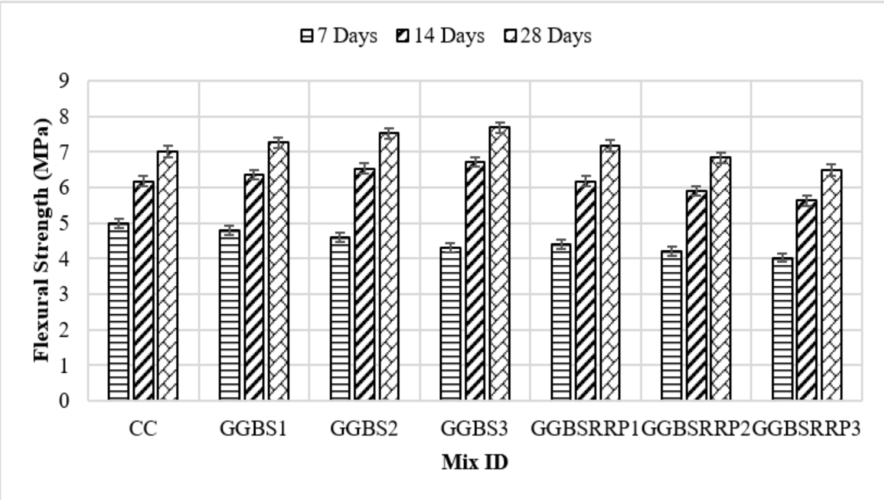

Figure 12. Flexural strength results

At 28 days, the strength increased with higher GGBS content, reaching a maximum of 7.69 MPa for the GGBS3 mix, compared to 7.00 MPa for conventional concrete. This enhancement is attributed to improved matrix densification and additional formation of binding gels.

The incorporation of recycled rubber powder led to a reduction in flexural strength. At a constant 20% GGBS content, increasing RRP from 5% to 15% decreased the 28-day strength from 7.17 MPa to 6.49 MPa. This reduction is mainly due to the lower stiffness of rubber particles and weaker bonding with the cement matrix.

Overall, GGBS improves long-term flexural strength, while higher RRP content reduces it. The mix with 20% GGBS and 5% RRP shows a balanced performance, maintaining adequate flexural strength along with sustainability benefits. Figure 13 shows the flexural strength test.

Figure 13. Flexural strength test

4.5. RCPT

The Rapid Chloride Penetration Test (RCPT) results for all concrete mixes at 28, 56, and 90 days are presented in figure 14. The measured charge passed values range from 2098 coulombs to 1285 coulombs, indicating a gradual improvement in durability with curing age and the incorporation of supplementary materials.

The conventional concrete recorded RCPT values of 2098, 1967, and 1843 coulombs at 28, 56, and 90 days, respectively, showing moderate resistance to chloride ion penetration. With the addition of GGBS, a consistent reduction in charge passed was observed. As the GGBS content increased from 10% to 30%, the RCPT values at 90 days decreased from 1657 coulombs to 1285 coulombs. The GGBS3 mix (30% replacement) exhibited the lowest permeability, indicating enhanced resistance to chloride ingress. This improvement can be attributed to the refinement of pore structure and the formation of additional calcium silicate hydrate (C–S–H) gel, which reduces connectivity of capillary pores.

The inclusion of recycled rubber powder showed a slight increase in RCPT values compared to the corresponding GGBS mixes. At a constant 20% GGBS content, increasing RRP from 5% to 15% increased the 28-day RCPT value from 1751 coulombs to 1955 coulombs. This indicates a marginal reduction in resistance to chloride penetration, likely due to the presence of microvoids and weaker interfacial bonding between rubber particles and the cement matrix.

Despite this, all mixes demonstrated improved durability over time, with decreasing RCPT values at longer curing periods. Overall, GGBS significantly enhances durability by reducing permeability, while higher RRP content slightly compromises it. The mix containing 20% GGBS and 5% RRP provides a balanced performance, maintaining good resistance to chloride penetration along with sustainability advantages. Figure 15 shows the RCPT.

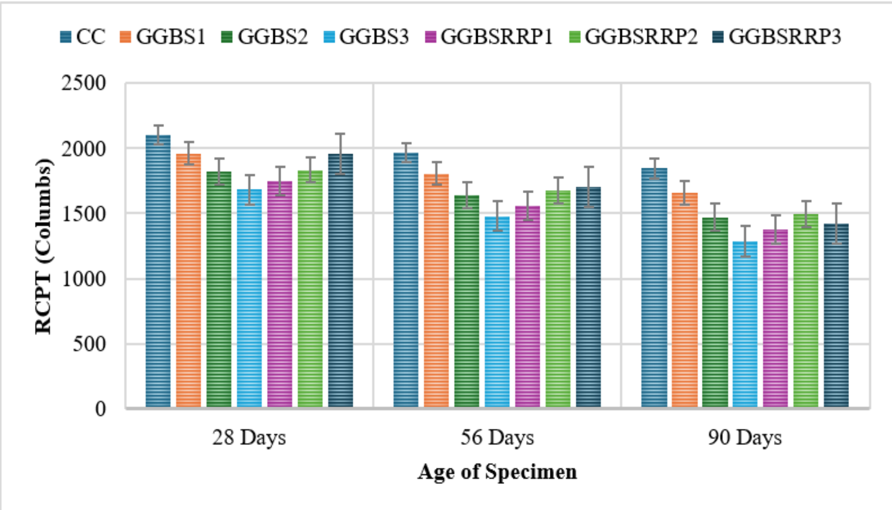

Figure 14. RCPT results

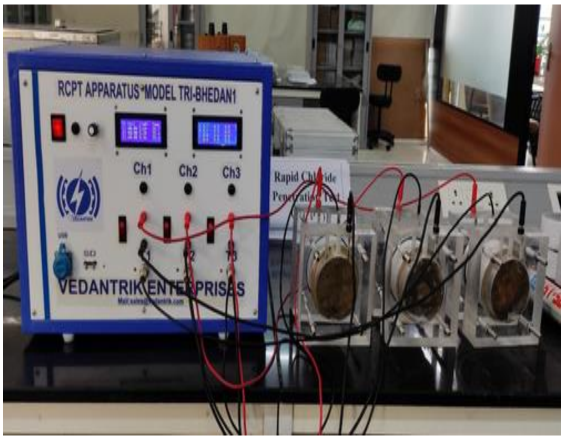

Figure 15. RCPT

4.6. Sulphate Attack Test

The results of the sulphate attack test for all concrete mixes at 28, 56, and 90 days are presented in figure 16. The values indicate the percentage deterioration of concrete under sulphate exposure, with lower values representing better resistance.

The conventional concrete exhibited percentage losses of 4.80%, 4.15%, and 3.59% at 28, 56, and 90 days, respectively. A gradual reduction in deterioration with age is observed for all mixes, which may be attributed to continued hydration and densification of the concrete matrix over time.

The incorporation of GGBS significantly improved sulphate resistance. As the GGBS content increased from 10% to 30%, the percentage loss decreased consistently. At 90 days, the GGBS3 mix (30% replacement) showed the lowest deterioration value of 2.24%, compared to 3.59% for conventional concrete. This enhanced performance is due to the reduced permeability and refined pore structure resulting from the secondary hydration of GGBS, which limits the ingress of sulphate ions.

The addition of recycled rubber powder resulted in a slight increase in deterioration compared to the corresponding GGBS mixes. At a constant GGBS content of 20%, increasing RRP from 5% to 15% increased the 90-day deterioration from 2.84% to 3.44%. This behavior is mainly attributed to the कमजोर interfacial bonding and increased void content introduced by rubber particles, which may facilitate sulphate penetration.

Overall, the results indicate that GGBS enhances sulphate resistance, while higher RRP content slightly reduces durability. However, the mix with 20% GGBS and 5% RRP demonstrates a balanced performance, offering improved resistance compared to conventional concrete along with sustainability benefits. Figure 17 shows sulphate attack test.

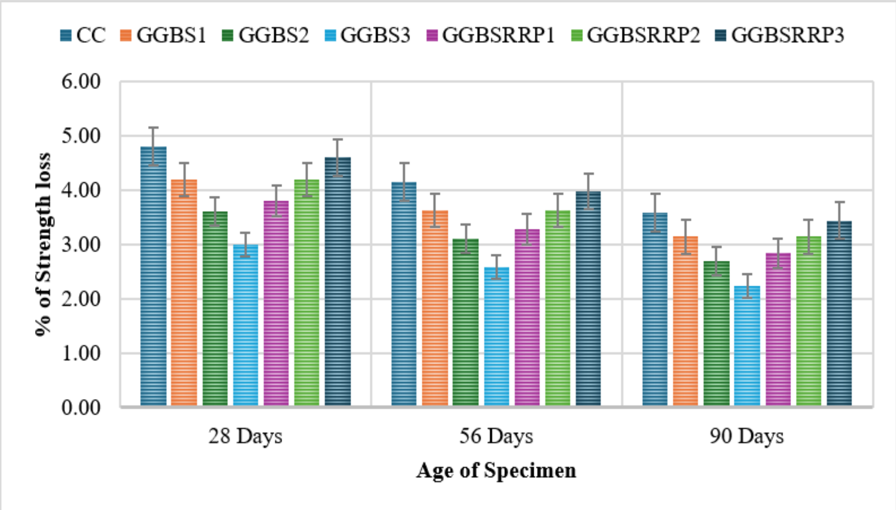

Figure 16. Percentage of strength loss in sulphate attack results

Figure 17. Sulphate attack test

4.7. SEM Analysis

The microstructural characteristics of the various concrete mixes were examined using Scanning Electron Microscopy (SEM) to understand the influence of GGBS and recycled rubber powder (RRP) on matrix densification and interfacial bonding. The SEM images for all mixes are presented figure 18.

The conventional concrete (CC) exhibited a relatively heterogeneous microstructure with visible capillary pores and microcracks. The presence of loosely packed hydration products and unhydrated cement particles indicates a comparatively lower degree of matrix densification.

With the incorporation of GGBS, a significant refinement in microstructure was observed. The GGBS-based mixes (GGBS1, GGBS2, and GGBS3) showed a denser and more uniform matrix with reduced porosity. The formation of secondary calcium silicate hydrate (C–S–H) gel due to the pozzolanic reaction of GGBS contributed to improved particle packing and pore refinement. Among these, the GGBS3 mix exhibited the most compact microstructure, with minimal voids and a well-developed C–S–H network, which correlates with its higher compressive and durability performance.

In contrast, the inclusion of recycled rubber powder introduced noticeable changes in the interfacial transition zone (ITZ). The GGBSRRP mixes displayed the presence of rubber particles embedded within the cementitious matrix, often surrounded by weak bonding zones and microvoids. These voids are primarily due to the hydrophobic nature and smooth surface of rubber particles, which hinder proper adhesion with the cement paste. As the RRP content increased from 5% to 15%, the density of microvoids and discontinuities also increased, leading to a less compact microstructure.

However, at lower RRP content (GGBSRRP1), the matrix still maintained relatively good integrity due to the presence of GGBS, which compensated for the adverse effects of rubber by enhancing the formation of additional C–S–H gel. This resulted in a moderately dense microstructure with improved bonding compared to higher RRP mixes.

Overall, the SEM analysis confirms that GGBS enhances matrix densification and reduces porosity through secondary hydration, thereby improving mechanical and durability properties. Conversely, higher RRP content adversely affects the microstructure by increasing voids and weakening the ITZ. The optimum microstructural performance is observed in mixes with higher GGBS and limited RRP content, which aligns well with the experimental results obtained for strength and durability tests.

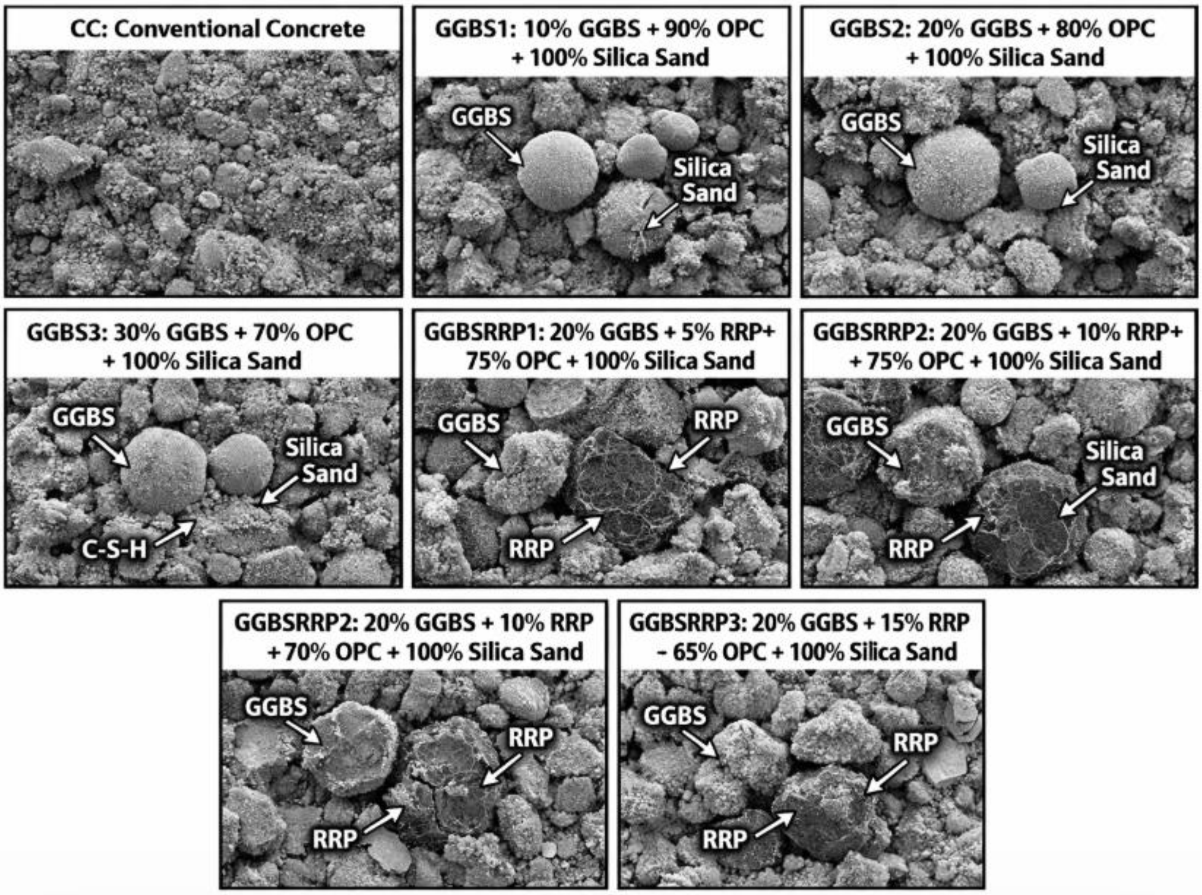

Figure 18. SEM images of all mix

5. CONCLUSION

This study evaluated the performance of high-performance concrete incorporating Granulated Blast Furnace Slag (GGBS) and recycled rubber powder (RRP) as partial replacements for cement and fine aggregate. The results indicate that the inclusion of GGBS improves workability due to its finer particles and smooth texture, whereas RRP reduces workability because of its hydrophobic nature. Nevertheless, all mixes maintained acceptable workability for M80 grade concrete.

In terms of mechanical properties, GGBS contributed to enhanced long-term compressive, split tensile, and flexural strengths, although early-age strength was slightly reduced. The mix with 30% GGBS achieved the highest 28-day strength. On the other hand, increasing RRP content led to a reduction in strength due to weak interfacial bonding and increased voids. Durability studies showed that GGBS significantly improved resistance to chloride penetration and sulphate attack by refining the pore structure, while higher RRP content slightly reduced durability performance.

Microstructural analysis confirmed that GGBS enhances matrix densification through the formation of additional C–S–H gel, whereas RRP introduces microvoids and weak transition zones. An optimum mix proportion of 20% GGBS and 5% RRP was identified, providing a balanced combination of strength, durability, and sustainability.

6. FUTURE SCOPE

Further research can focus on optimizing the percentage of recycled rubber powder using surface treatments or chemical modifications to improve its bonding with the cement matrix. The long-term durability performance under aggressive environmental conditions such as freeze–thaw cycles, carbonation, and marine exposure can be investigated. The use of hybrid supplementary cementitious materials along with GGBS may also be explored to enhance performance. Additionally, large-scale field applications and life cycle assessment studies can be conducted to evaluate the practical feasibility and environmental benefits of using GGBS and recycled rubber in sustainable concrete production.

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IZVOD

INTEGRACIJA RECIKLIRANE GUME I ZGURKE ZA ČVRSTOĆU I NISKOUGLJENIČNI OTISAK U ODRŽIVOM VISOKOUGLJENIČNOM BETONU

Ova studija istražuje razvoj održivog visokoperformansnog betona (HPC) uključivanjem granulisane zgure visoke peći (GGBS) i recikliranog gumenog praha (RRP) kao delimične zamene za cement i fini agregat. Cilj je poboljšanje mehaničkih i trajnih svojstava betona, uz istovremeno promovisanje ekološke održivosti. Različite betonske mešavine su pripremljene sa različitim procentima GGBS (10–30%) i RRP (5–15%). Obradljivost je procenjena pomoću testova sleganja, dok su čvrstoće na pritisak, zateznu čvrstoću cepanje i savijanje određene nakon 7, 14 i 28 dana. Performanse trajnosti su procenjene pomoću testa brzog prodiranja hlorida (RCPT) i testova otpornosti na sulfate, zajedno sa mikrostrukturnom analizom pomoću SEM-a. Rezultati su pokazali da GGBS poboljšava obradivost, dugoročnu čvrstoću i izdržljivost zbog prečišćavanja pora i dodatnog formiranja C–S–H. Nasuprot tome, RRP smanjuje čvrstoću i obradivost pri višim sadržajima zbog slabe međupovršinske veze. Međutim, umereno uključivanje RRP poboljšava održivost bez značajnog ugrožavanja performansi. Identifikovana je optimalna mešavina od 20% gumenog praha (GGBS) i 5% preporučene maloprodajne cene (RRP), koja pruža uravnoteženu kombinaciju čvrstoće, izdržljivosti i ekološke prihvatljivosti.

Ključne reči*: Gumeni prah, GGBS, cement, silikatni pesak, visokoperformansni beton*

Naučni rad
Rad primljen: 02.05.2026.
Rad prihvaćen: 07.06.2026.

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