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Sustainable high-performance concrete: Using slag and recycled rubber

ABSTRACT

In this study, the mechanical and durability characteristics of M60 grade concrete using waste and industrial materials like rubber powder, silica sand, and GGBS were examined. Rubber powder is used as a substitute for fine aggregates, silica sand as a substitute for M sand, and GGBS as a substitute for cement. To evaluate the effects of the ingredients used in the study, sixteen different types of concrete mixes were prepared. The durability characteristics were evaluated using saturated water absorption, ultrasonic pulse velocity, and fast chloride penetration tests. The changes in the microstructure of the concrete mixtures were also examined using XRD analysis. Based on the results obtained during the testing, the addition of slag to the concrete mix greatly improved the durability characteristics. Based on the results obtained, the mix containing 40% slag addition had better durability characteristics than the others due to the lower absorption and penetration values and the higher ultrasonic pulse velocity values. This indicates the concrete mix is homogeneous and denser. The durability characteristics were also improved due to the addition of silica sand. However, the addition of rubber powder reduced the durability characteristics due to its hydrophobic and bonding properties.

Keywords: Slag, silica sand, rubber powder

1. INTRODUCTION

Sustainable high-performance concrete (HPC) is now often using industrial by-products and solid waste as a means of reducing its environmental impacts. The production of conventional concrete generates about 7-8% of global CO₂ emissions, mostly due to clinker production, which generates 0.8-0.9 t CO₂/ton cement, and the use of virgin aggregates [1]. The use of 40-70% GGBFS instead of Portland cement can result in a 30-60% reduction in embodied carbon, as well as the use of industrial by-products as a means of reducing waste disposal [2]. Similarly, the use of 5-30% recycled tire rubber or recycled concrete aggregate (RCA) instead of natural aggregates can result in the disposal of a significant amount of solid waste [3].

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GGBFS is utilized either as a SCM or as a primary binder in the form of an alkali-activated material [4]. In high-volume GGBFS recycled aggregate concrete, lime activation was found to increase the strength parameters by 9-20%, as well as reduce the production cost by 7-12% and environmental impacts by 32-67% compared to conventional concrete [6,7]. Slag-activated pavement composites containing 5-15% slag as a binder and up to 15% as a rubber component have been found to increase the unconfined compressive strength from 0.7 to 2.2 MPa, as well as the resilient modulus, and have negligible heavy metal leaching [8].

For the slag-based HPC systems, the range of 60-80 MPa is achieved for the compressive strength [9]. The lime-based HPC using industrial lime waste as the activator for the slag HPC has achieved a strength of 80 MPa, with low values of water absorption ranging from 2.0 to 2.5%, and a reduction in climate impact indices of 7-12% compared to conventional activators [10, 11]. For

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the crumb rubber-based HPC, a 20-50% reduction in compressive strength is observed for 10-30% fine aggregate replacement; however, the impact resistance increases by 80-85%, and the ductility also increases significantly. For structural-grade HPC, limiting the crumb rubber aggregate to $\leq 10\%$ ensures a compressive strength of 40-60 MPa [12].

Experimental research has revealed that the addition of 1-5% strips of secondary reinforcement in the concrete mix can result in a 3-30% loss in strength parameters, which can increase by 32% and 28%, respectively [13]. The density of concrete can also be reduced by 2-4% even when using recycled constituents, thus meeting the structural needs of the concrete mix [14]. The research on the optimization of concrete mix revealed that even when the concrete mix comprises 60% RCA and 10% secondary reinforcement, the concrete mix can still have a compressive strength of 40 MPa, thus meeting the conventional strength of M40 concrete [15]. Statistical models have also revealed that the optimum amount of slag in the concrete mix is 50-65%, whereas the optimum percentage of secondary reinforcement is below 20-25%, and the optimum value of the water-binder ratio is 0.30-0.38 [16].

Improvements in durability include reduced water absorption, often by 10-25% compared to OPC-based mixes, reduced chloride penetration, and improved density of the microstructures. [17,18] Although rubber increases porosity, matrices rich in slag help offset the negative effects of interfacial weaknesses, recovering up to $\approx 14\%$ compressive strength compared to untreated rubberized mixes. [19] Addition of rubber has a profound effect on fatigue life, sometimes increasing the number of cycles to half stiffness by up to 3-4 times, and impact energy absorption [20].

Research gaps and directions for this research, although much has been achieved in HPC with slag and recycled rubber, there is still much that needs to be addressed for sustainable HPC with slag and recycled rubber. Many studies have been carried out on individual variables replacing each other, but little is known about interactions between multiple variables including slag type and content, rubber size and pre-treatment, and supplementary nanopozzolans. Durability over long exposure for structural grade slag/recycled rubber-based HPC is less reported than short-term mechanical performance. Little has also been standardized in mix design philosophy for high performance concrete when slag and rubber are used together. More research is needed to establish design philosophies that incorporate short-term, long-term, and life cycle performance, as well as scaling up promising laboratory mixtures for field applications

in structures such as bridges, pavements, and pre-fabricated structures.

2. MATERIALS

The primary components chosen for this study to create HPC mixtures are OPC, GGBFS with a Blaine surface area of around 4800 cm²/g, silica sand, and recycled rubber powder [21]. In order to increase the concrete's flowability and lower its water content, a polycarboxylate-based super-plasticizer was added to the formulation. This increased the finished product's strength.

2.1. Cement

The main binder of the concrete mixture is OPC. Its availability and proven records of successful application in various building processes are the reasons why it was chosen. Its chemical composition allows for efficient hydration and strength gain, making it a reliable reference point for comparison in this study.

2.2. Slag

Pozzolanic properties of GGBFS, a by-product of the iron and steel manufacturing industry, enhance the mechanical properties of concrete. The Blaine fineness of the slag, used in the concrete mix, was 4800 cm²/g, ensuring the right surface area for reaction when the slag was used in the concrete mix. [22] The use of slag reduces the carbon footprint of the cement industry while enhancing its properties.

2.3. Silica sand

In this study, the fine aggregate used is silica sand. The workability, density, and mechanical strength of the concrete are increased when silica sand is used. This is because silica sand is known to be pure and consistent in its properties [23]. This makes the silica sand suitable to be used in combination with cement and slag in order to produce the best combination.

2.4. Recycled rubber powder (RRP)

Concrete's flexibility and impact resistance were increased by using recycled rubber powder made from shredded waste tires as a substitute aggregate. To assess its impact on the material's mechanical performance, varying amounts of this powder were added to the concrete mixture [24]. In addition to improving the material's capacity to absorb energy, the use of RRP in concrete offers an eco-friendly way to dispose of used tires. Figure 1 shows the particle size distribution of RRP and slag. The rubber powder showed a wider range of particle sizes than the slag particles, which were typically coarser. The physical and chemical

characteristics of the materials are summarized in Table 1.

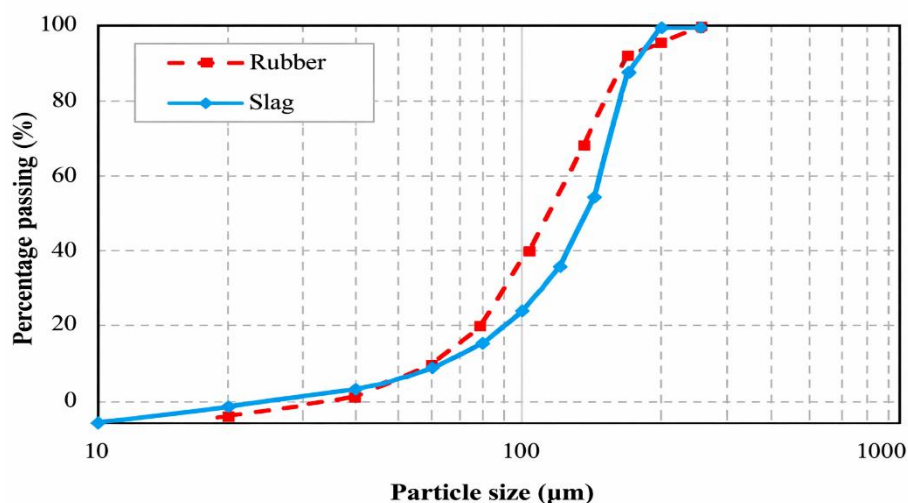


Figure 1. Particle size distribution of slag and recycled rubber powder

Table 1. Physical properties of materials

Property	OPC	GGBFS	Silica Sand	Recycled Rubber Powder	Polycarboxylate Superplasticizer
Physical state	Powder	Powder	Granular solid	Powder/crumb	Liquid
Color	Grey	Off-white to light grey	Light brown/white	Black	Light brown
Specific gravity	3.15	2.81	2.62	1.14	1.08
Blaine fineness (cm ² /g)	3321	4800	—	—	—
Mean particle size (μm)	<75	<75	600	900	—
Particle shape	Angular	Angular	Sub-rounded	Irregular	—
Bulk density (kg/m ³)	1215	1120	1590	595	1050
Water absorption (%)	—	—	0.75	1.0	—
Initial setting time (min)	62	—	—	—	—
Final setting time (min)	421	—	—	—	—
Standard consistency (%)	30.12	—	—	—	—
Soundness (mm)	1	1	—	—	—
Water reduction capacity (%)	—	—	—	—	30

Table 2. Chemical properties of materials

Material	CaO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	MgO (%)	SO ₃ (%)	Other Components
OPC	62.25	20.67	5.91	3.54	2.09	2.51	LOI ≤ 3%
GGBFS	40.62	35.75	12.09	1.23	7.96	<2	Glassy phase >85%
Silica Sand	0.62	98.15	<1	<1	—	—	High purity quartz
Recycled Rubber Powder	—	—	—	—	—	—	~40–50% carbon, 25–35% rubber hydrocarbons, 10–20% additives (ZnO, sulfur, fillers)
Polycarboxylate Superplasticizer	—	—	—	—	—	—	Organic polymer (C, H, O based)

3. EXPERIMENTAL METHODOLOGY

OPC, powdered GGBFS, silica sand, recycled

rubber powder, water, and superplasticizer based on polycarboxylate were mixed together for the concrete mixtures. To ensure the even distribution

of all the materials, all the dry materials were mixed together with the help of a pan mixer for approximately three minutes. Then, the water and the calculated amount of superplasticizer were mixed together and stirred well until a homogeneous mixture was formed. [25] Fresh concrete mixture was poured into the moulds in layers, and bubbles were removed using a vibrating table for compacting the concrete mixture. The concrete mixtures were withdrawn from the moulds and cured in potable water at $27 \pm 2^\circ\text{C}$ for the test age after one day.

The compressive strength was checked by preparing concrete cubes of 150mm size. The cubes were subjected to compression testing at specified curing ages using a compression test machine. Before compression, the cubes were cleaned and aligned carefully for uniform stress distribution. The cubes were subjected to continuous loading without shock up to failure. [26] The maximum load was applied uniformly until failure occurred, and then it was divided by the area to get compressive strength. Three cubes were prepared for each mix, and their average was reported for each test age. The tensile strength of concrete was checked by carrying out a splitting tensile test on concrete cylindrical specimens of 150mm diameter and 300mm height [27]. The specimen was kept horizontally between two platens of the compression test machine, with small strips kept on both lines of contact for uniform stress distribution. A continuous load was applied until cracking occurred on the vertical diameter of the specimen. The split tensile strength was calculated from the load applied until failure occurred, using an analytical expression for split tensile strength. Three specimens were considered

for analysis. Flexural strength of the material was set on using a prism which measures 100 x 100 x 500 mm. The two-point loading method was used for the determination of the flexural strength. The sample was kept on two rollers of a given span length. The loading was continued up to the fracture point. The modulus of rupture was found from the load at the fracture point. The results were given for the average of three values.

Tests for absorption of water were carried out to rate the durability and structure. After the 28 days of curing, the specimens were dehumidifying at 105°C until a consistent bulk was achieved. The specimens were submerged in water for a day after the weights had been taken. The saturated surface-dry weights were measured and used to calculate the percentage absorption using the difference in weights. The quality and uniformity of the concrete were also checked using the ultrasonic pulse velocity method. The transducers were attached to opposite surfaces using a coupling gel. Transit time of the ultrasonic pulse was recorded, and pulse velocity was calculated by split the path length by the time of transit. The resistance to the ingress of chloride ions was assessed using 50 mm thick discs prepared from cylinders. The discs were subjected to a 60V potential difference for a period of six hours, and the total electrical charge was recorded in coulombs. Lower values of charge are indicative of resistance to the ingress of chloride ions. The phases were also identified by carrying out X-ray diffraction analysis on the powder sample prepared from crushed specimens. The scan was performed over a suitable 2θ range to identify the crystalline phases and products formed within the matrix. Table 3 indicates the mix description.

Table 3. Mix Description

Sl. No.	Mix ID	Cement %	Slag %	Silica Sand %	Rubber Powder %	M-sand %	Coarse Aggregate %
1	CC	100	-	-	-	100	100
2	CS1	90	10	-	-	100	100
3	CS2	80	20	-	-	100	100
4	CS3	70	30	-	-	100	100
5	CS4	60	40	-	-	100	100
6	CS5	50	50	-	-	100	100
7	CSS1	60	40	10	-	90	100
8	CSS2	60	40	20	-	80	100
9	CSS3	60	40	30	-	70	100
10	CSS4	60	40	40	-	60	100
11	CSS5	60	40	50	-	50	100
12	CSSR1	60	40	40	10	50	100
13	CSSR2	60	40	30	20	50	100
14	CSSR3	60	40	20	30	50	100
15	CSSR4	60	40	10	40	50	100

16	CSSR5	60	40	40	20	40	100
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4. RESULTS AND DISCUSSION

4.1. Compressive Strength

The results of the compressive strength test show that adding rubber powder, slag, and silica sand had a major impact on the concrete mixtures' mechanical behavior. After 7, 28, and 90 days of curing, the control mixture (CC) reached compressive strengths of 44.00 MPa, 68.41 MPa, and 71.15 MPa, respectively. The strength of the CS series increased steadily as the slag content increased, peaking at 40% slag replacement (CS4). At 7, 28, and 90 days, the compressive strengths at this level were 48.13 MPa, 74.83 MPa, and 77.82 MPa, respectively. The hydraulic and pozzolanic reactions of slag, which produce more calcium silicate hydrate (C–S–H) gel and result in a

denser concrete microstructure, are responsible for this improvement.

However, a minor drop in compressive strength was noted when the slag content reached 50% (CS5). The compressive strength in the CSS mixture series increased as the amount of silica sand increased, peaking at 50% replacement (CSS3). At 7, 28, and 90 days, this mixture's compressive strengths were 50.03 MPa, 77.77 MPa, and 80.89 MPa, respectively. On the other hand, because rubber powder was added, the CSSR mixtures' compressive strength decreased. Rubber particles' reduced stiffness, hydrophobicity, and weaker bonding with the cement matrix are the main causes of this decline. Figure 2 shows the overall compressive strength results.

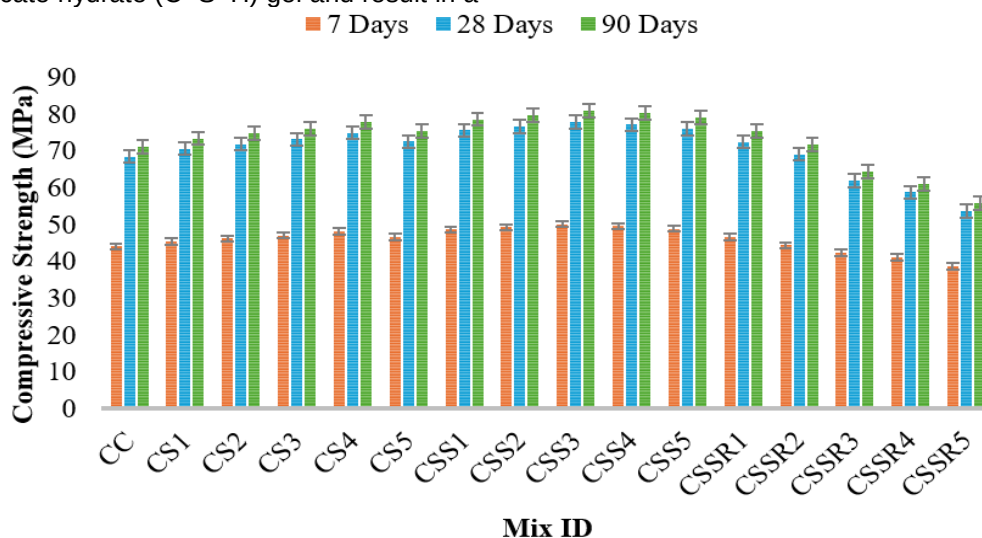


Figure 2. Compressive strength results

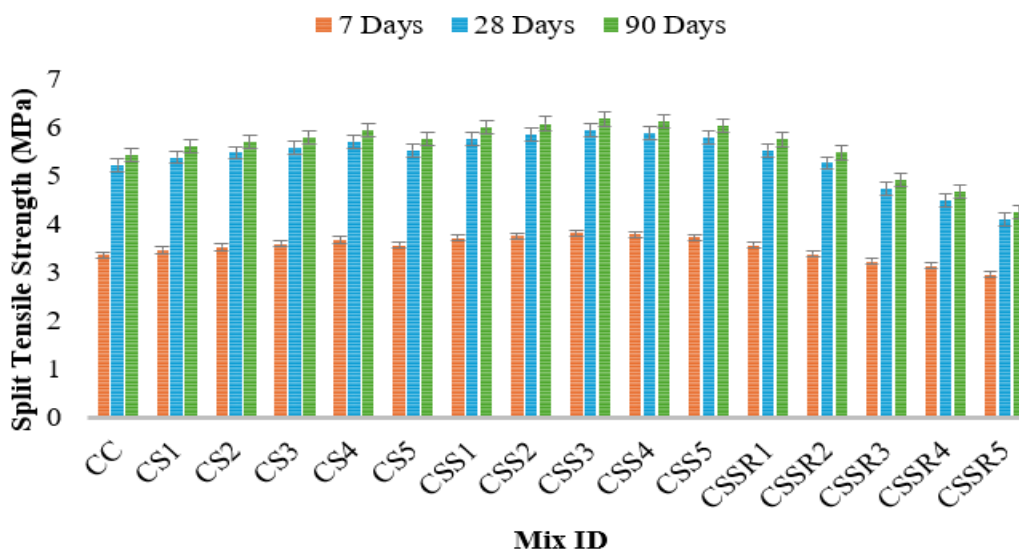


Figure 3. Split tensile strength results,
Top of Form, Bottom of Form

4.2. Split tensile strength

The split tensile strength results showed a similar trend to the compressive strength results, suggesting that rubber powder, silica sand, and slag affected the concrete's tensile behavior. At 7, 28, and 90 days, the split tensile strengths of the control mix (CC) were 3.37 MPa, 5.23 MPa, and 5.44 MPa, respectively. Tensile strength in the CS series was enhanced by partially substituting slag for cement up to 40% replacement (CS4), reaching 3.68 MPa, 5.72 MPa, and 5.95 MPa at the corresponding curing times. The pozzolanic reaction of slag, which creates more C–S–H gel and enhances the concrete microstructure, is responsible for this improvement.

However, because of the lower cement content, a minor drop in strength was noted at 50% slag replacement (CS5). Tensile strength was further increased in the CSS series by substituting silica sand for M-sand, with CSS3 exhibiting the highest values (3.83 MPa, 5.95 MPa, and 6.19 MPa). In contrast, the CSSR series exhibited decreased strength as a result of the rubber particles' weaker bonding and decreased stiffness. The split tensile strength results are shown in Figure 3.

4.3. Flexural Strength

The flexural strength results show that the addition of rubber powder, silica sand, and slag affected the concrete mixtures' ability to withstand bending. At 7, 28, and 90 days of curing, the flexural strengths of the control mix (CC) were 4.77 MPa, 7.67 MPa, and 7.71 MPa, respectively. The flexural strength in the CS series increased when 20%, 30%, and 40% slag was substituted for cement, reaching 5.21 MPa, 8.39 MPa, and 8.43 MPa at the corresponding curing ages. The hydraulic and pozzolanic properties of slag, which increase the amount of C–S–H gel and strengthen the concrete's resistance to bending, are primarily responsible for this improvement. However, when the slag content rose to 50% (CS5), a minor decrease in strength was noted.

In the CSS series, the addition of silica sand to mixtures containing 30% slag further enhanced the flexural strength, with CSS3 recording the highest values of 5.42 MPa, 8.72 MPa, and 8.76 MPa at 7, 28, and 90 days. Conversely, the CSSR series showed a gradual decrease in flexural strength as the rubber powder content increased. The flexural strength results are presented in Figure 4.

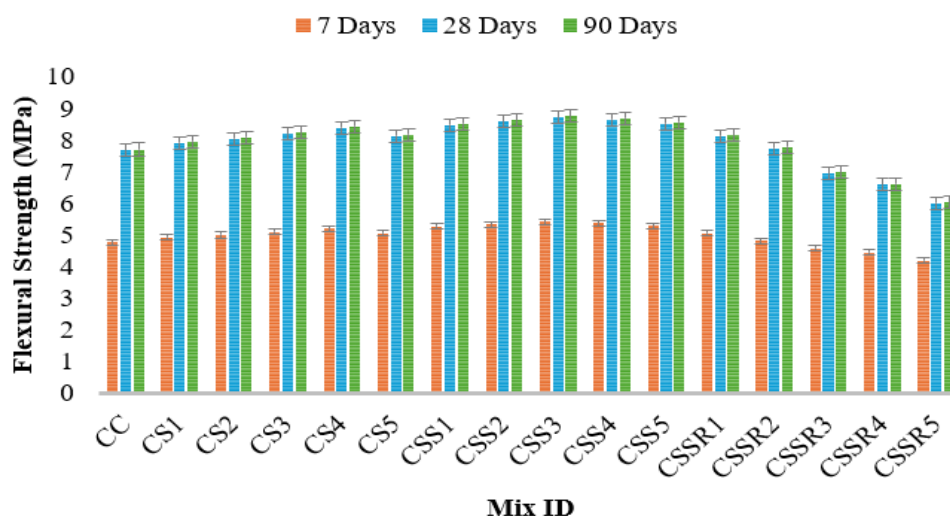


Figure 4. Flexural strength results

4.4. Saturated Water Absorption (SWA)

The SWA test was employed to rate the durability of concrete by determining the water absorption capacity. The results exhibit that the control mix CC had water absorption values of 2.32% at 28 days and 2.21% at 90 days. In the CS series, it is observed that the addition of slag significantly reduces the water absorption. The lowest values were recorded by CS4, which had

40% slag. It recorded water absorption values of 2.11% and 1.99% at 28 and 90 days, respectively. This is because the slag particles react with Ca(OH)_2 to produce additional C–S–H gel. However, there is a slight increase in water absorption in the CS5 mix, which had 50% slag. In the CSS series, it is observed that the addition of silica sand reduces the water absorption. CSS3 recorded the lowest values of water absorption,

i.e., 2.02% and 1.89% at 28 and 90 days, respectively. However, in the CSSR series, it is seen that the water absorption values are

increased with the addition of rubber powder. Figure 5 shows the results of SWA.

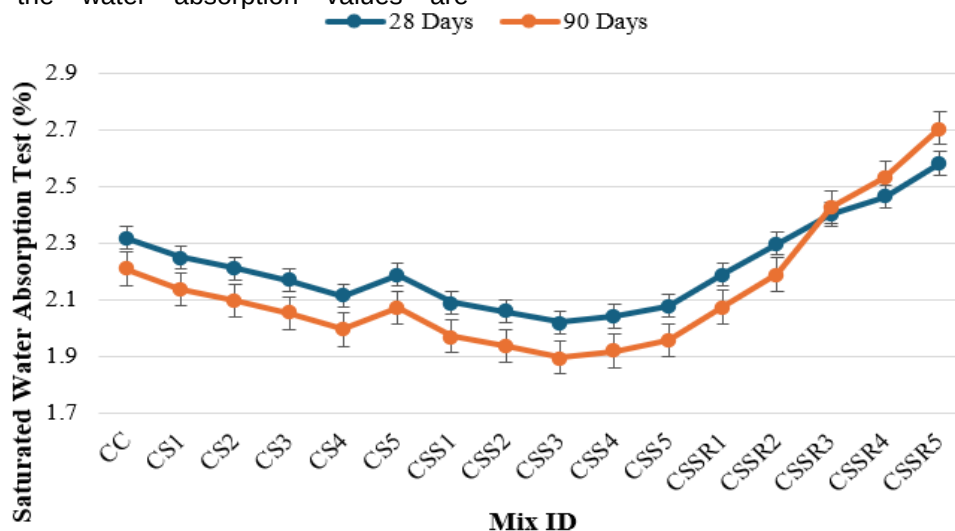


Figure 5. SWA results

4.5. Ultrasonic Pulse Velocity (UPV)

An UPV test was carried out to assess the quality and homogeneity of concrete mixes. A higher UPV indicates a denser concrete matrix with fewer internal voids and microcracks. The control mix, CC, had UPV values of 4.17 km/s at 28 days and 4.41 km/s at 90 days, signifying good quality concrete. In the case of mixes in series CS, with increasing percentages of slag, UPV values increased up to 40% replacement, as indicated by mix CS4, which had UPV values of 4.56 km/s and 4.82 km/s at 28 and 90 days, respectively. These

results can be attributed to pozzolanic and hydraulic reactions of slag, resulting in additional C-S-H gel formation, thus improving concrete microstructure. However, a slight decrease was observed in UPV values for mix CS5 with 50% replacement of slag. In series CSS, with increasing percentages of silica sand, UPV values increased, with the highest values observed for mix CSS3. Conversely, UPV values decreased with increasing percentages of rubber powder in mixes in series CSSR. Figure 6 shows the UPV results.

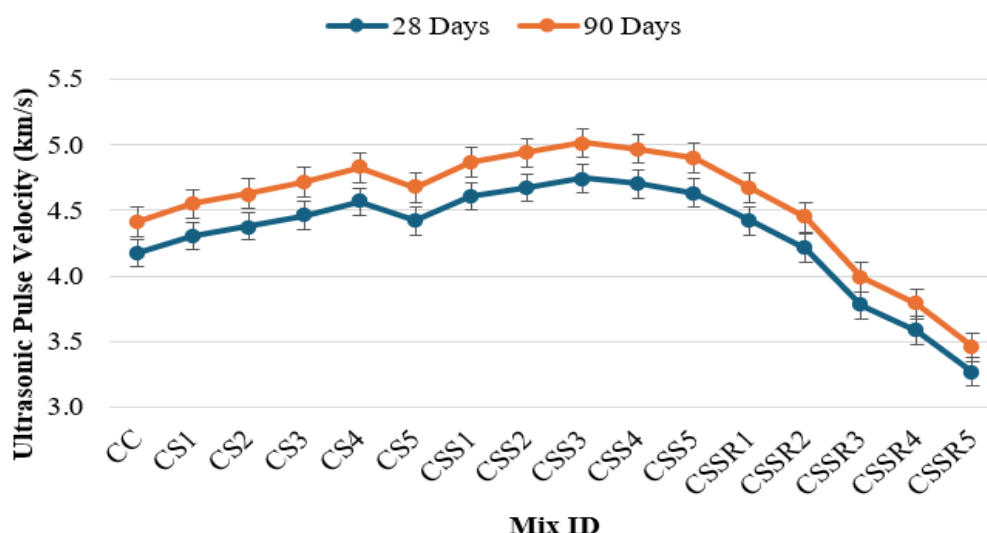


Figure 6. UPV results
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4.6. Rapid Chloride Penetration Test (RCPT)

The RCPT was executed to measure the

resistance of the concrete mixes to the ingress of chloride ions. This is an vital parameter for the long-term durability of reinforced concrete structures. The lower the RCPT values, the higher the resistance to the ingress of chloride ions. The control mix CC recorded 917.41 coulombs at 28 days and 834.10 coulombs at 90 days. The RCPT values for the concrete mixes of the CS series gradually decreased up to 40% replacement of slag (CS4), which recorded 839.34 coulombs at 28 days and 752.92 coulombs at 90 days. This is due to the

pozzolanic and hydraulic reactions of slag, which generate additional C–S–H gel. The RCPT values for the concrete mixes of the CSS series recorded lower values compared to the concrete mixes of the CS series. The lowest values were recorded for the concrete mixes of the CSS3 series. The RCPT values for the concrete mixes of the CSSR series recorded increasing values compared to the concrete mixes of the CS series. Figure 7 RCPT Results.

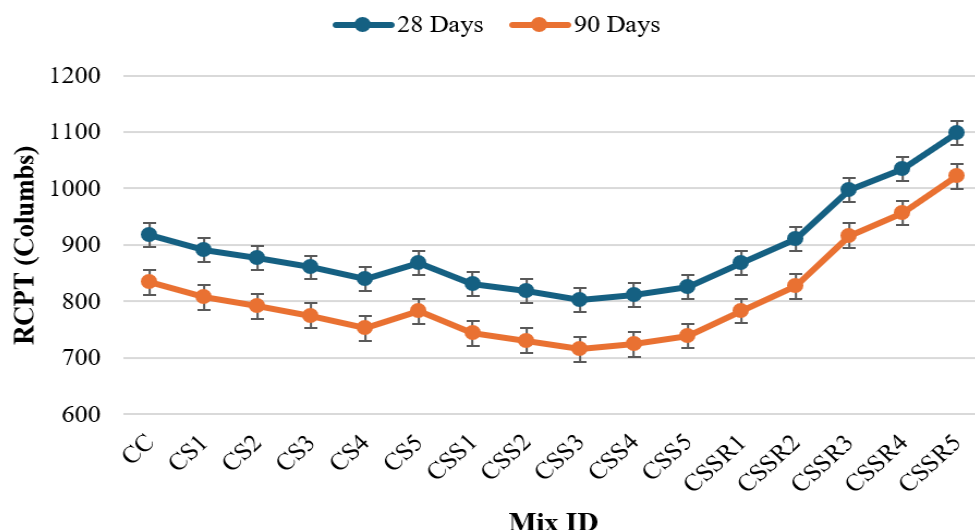


Figure 7. RCPT results

4.7. X-Ray diffraction (XRD)

An XRD analysis was carried out to identify the mineralogical phases and hydration products of mixes CC, CS4, CSS3, and CSSR1. From this analysis, the effect of slag, silica sand, and rubber powder addition on concrete microstructure can be determined. In the XRD of control mix CC, peaks corresponding to calcium hydroxide, calcium silicate hydrate, quartz, and ettringite are observed, which are hydration products of ordinary Portland cement. In the case of mix CS4, containing 40% slag, the intensity of calcium hydroxide peaks was lower compared to control mix CC. This indicates

that, due to pozzolanic reactions of slag, calcium hydroxide reacts with silica present in slag to form more C–S–H, resulting in a denser microstructure. In mix CSS3, higher peaks of silica and more C–S–H formation are observed due to higher silica content in silica sand, resulting in higher strength properties. In mix CSSR1, lower intensities of peaks are observed compared to mix CSS3 due to the addition of rubber powder, which results in lower compactness of concrete microstructure. Figure 8 to 11 shows the XRD images of CC, CS4, CSS3 and CSSR1 mix.

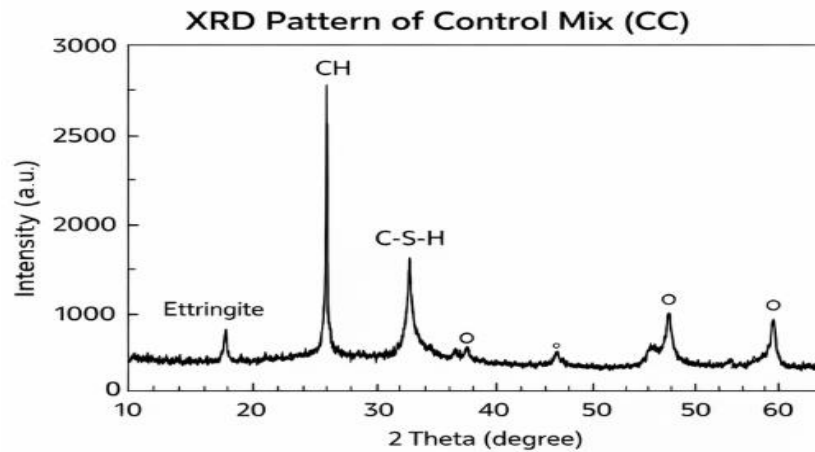


Figure 8. XRD for CC mix

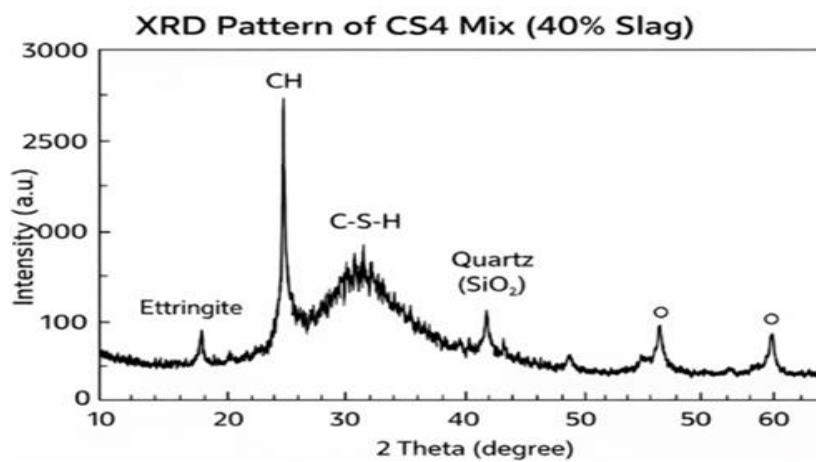


Figure 9. XRD for CS4 mix

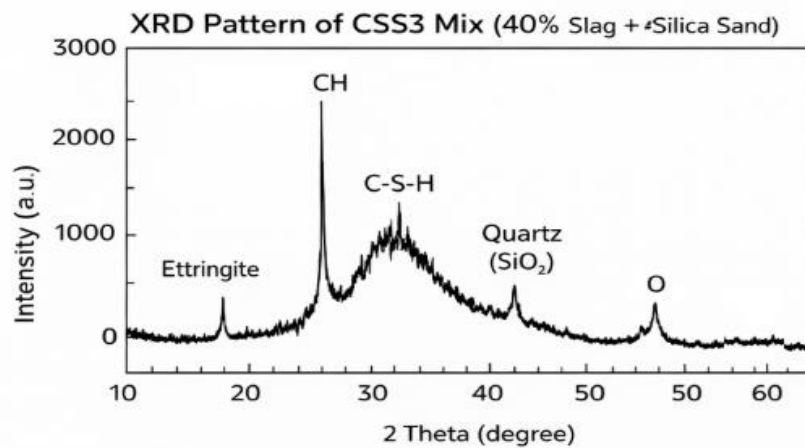


Figure 10. XRD for CSS3 mix

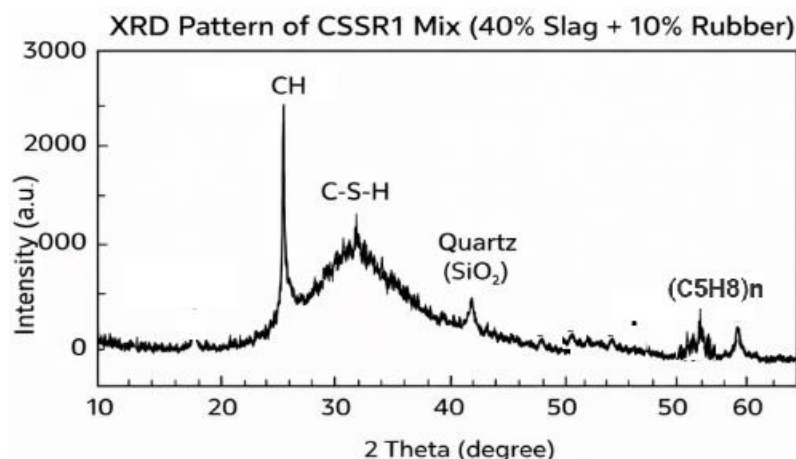


Figure 11. XRD for CSSR1 mix

5. CONCLUSION

This study aims to evaluate the mechanical and durability characteristics of concrete made with M60 grade concrete that has been supplemented with recycled rubber powder, silica sand, and GGBFS. Cement was partially replaced with GGBFS, M sand was partially replaced with silica sand, and fine aggregate was partially replaced with RRB. Using the techniques of SWA, UPV, RCPT, and XRD, sixteen concrete mix designs were created and tested in order to evaluate the concrete's qualities. According to the testing findings, adding GGBS to the concrete mixture greatly enhanced the material's durability. In the CS series, increasing the quantity of blast furnace slag as a partial substitute for cement up to 40% (CS4) decreased the absorption value, raised the UPV values, and decreased the RCPT charge passing values.

Moreover, further improvement in the properties was also found in the CSS series, where the replacement of M sand with silica sand resulted in better particle packing and reduced internal voids. Of all the mixes, the CSS3 mix showed the best properties, indicating the lowest values in water absorption and RCPT and the highest values in UPV. However, the CSSR series also showed a gradual decrease in durability due to the addition of rubber powder, which is hydrophobic in nature and has a lower bonding ability. XRD analysis also showed the reduced amount of calcium hydroxide and increased amounts of C-S-H.

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IZVOD

ODRŽIVI VISOKOPERFORMANSNI BETON: KORIŠĆENJEM ZGURE I RECIKLIRANE GUME

U ovoj studiji ispitane su mehaničke karakteristike i karakteristike trajnosti betona klase M60, uz upotrebu otpadnih i industrijskih materijala kao što su gumeni prah, kvarcni pesak i granulisana zgura visoke peći (GGBS). Gumeni prah je korišćen kao zamena za sitni agregat, kvarcni pesak

kao zamena za veštački pesak (M-pesak), a GGBS kao zamena za cement. Radi procene uticaja korišćenih sastojaka, pripremljeno je šesnaest različitih vrsta betonskih mešavina. Karakteristike trajnost i procenjene su putem ispitivanja apsorpcije vode u zasićenom stanju, brzine ultrazvučnog impulsa i brzine prodiranja hlorida. Takođe su ispitane promene u mikrostrukтури betonskih mešavina primenom XRD analize. Na osnovu dobijenih rezultata ispitivanja, utvrđeno je da dodatak zgure značajno poboljšava karakteristike trajnosti betona. Mešavina sa dodatkom 40% zgure pokazala je bolje karakteristike trajnosti u odnosu na ostale, usled manjih vrednosti apsorpcije i prodiranja, kao i veće brzine ultrazvučnog impulsa. Ovo ukazuje na to da je betonska mešavina homogena i gušća. Karakteristike trajnosti su takođe poboljšane dodatkom kvarcnog peska. Međutim, dodatak gumenog praha je umanjio karakteristike trajnosti, usled njegovih hidrofobnih svojstava i karakteristika vezivanja.

Ključnereči: zgura, kvarcni pesak, gumeni prah

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