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Experimental Study on the Mechanical Performance of Ordinary Portland Cement-Based Rubberized Concrete

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ABSTRACT

This study investigates the incorporation of crumb rubber (CR), derived from end-of-life tires as a partial replacement for OPC binder, fine aggregates, and coarse aggregates in OPC-based concrete. The effects on compressive strength, modulus of elasticity (EOM), and impact resistance were evaluated at CR replacement levels of 9.4%, 17.9%, 25.5%, and 32.5%, in accordance with ASTM C39, ASTM C469, and ACI 544 (1999). The results show that increasing CR content leads to a progressive reduction in both compressive strength and modulus of elasticity. For instance, the compressive strength decreased by up to 56.0% at a CR replacement level of 25.5% after 28 days. NaOH surface treatment mitigated the strength loss when CR replaced fine aggregates but exacerbated it when used as a replacement for coarse aggregates. CR significantly improved impact resistance, particularly at a 9.4% replacement level, where the impact energy increased by 93.37%. FTIR analysis confirmed significant chemical modifications on the CR surface after NaOH treatment, which enhanced the interfacial bonding with the cement matrix. The findings highlight the potential of CR as a sustainable alternative to conventional aggregates, where optimized surface treatment can improve both mechanical performance and sustainability in rubberized concrete.

INTRODUCTION

The rapid accumulation of end-of-life tires has emerged as a significant global environmental challenge, with more than 1.8 billion tires discarded annually worldwide (Kazemi *et al.,* 2023). Traditional disposal practices, such as landfilling and incineration, introduce substantial environmental risks, including soil contamination, fire hazards, and the emission of toxic pollutants (Jakhar *et al.,* 2023). According to the Rubber Manufacturers Association (RMA), over 233 million waste tires are produced each year, contributing significantly to environmental burden, over 40 million are landfilled, while more than 275 million tires accumulated from previous years remain stockpiled across the United States (Gomez *et al.,* 2025). These stockpiles represent significant environmental and public health threats, as they are highly susceptible to fire and serve as breeding grounds for disease-carrying insects, such as mosquitoes responsible for malaria and dengue (Abdullah *et al.,* 2024). The continuous reduction in available landfill capacity has further intensified the demand for sustainable waste tire management.

A promising approach involves converting waste tires into CR and incorporating it into concrete systems. This approach not only alleviates environmental issues associated with tire disposal but also reduces the reliance on natural aggregates and may lower overall material costs (Umar & Muthusamy, 2023). Concrete ranks among the most extensively utilized construction materials worldwide, second only to water in terms of global consumption, with an estimated 30 billion tons used annually (Nilimaa, 2023). In conventional concrete production, OPC serves as the primary binder (N. Su *et al.,* 2021). However, cement production is associated with considerable environmental impacts, particularly in terms of greenhouse gas emissions (Barbhuiya *et al.,* 2024). It has been reported that the production of one ton of clinker releases approximately 0.54 tons of carbon dioxide (CO_2) during the calcination process (Durastanti & Moretti, 2024). Moreover, the cement industry consumes approximately 12-15% of the total global industrial energy demand (Mohamad *et al.,* 2022). These environmental concerns have stimulated growing interest in sustainable and low-carbon construction materials (Shubbar *et al.,* 2019).

Beyond environmental considerations, conventional OPC-based concrete exhibits high compressive strength but relatively low toughness, rendering it inherently brittle and susceptible to impact loading (Aanu *et al.,* 2025) and (Behera *et al.,* 2025). Previous studies consistently demonstrate enhanced ductility and deformability in rubberized concrete systems. In particular, CR addition can enhance energy absorption capacity, reduce density, and improve crack resistance under dynamic loading conditions (Wang *et al.,* 2022). Several investigations have consistently reported increased ductility and deformability in rubberized concrete systems (J. Su *et al.,* 2023). Fattuhi and Clark (1996) further identified potential

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applications for rubberized concrete in structures requiring vibration damping, impact resistance, and non-structural components, such as foundations, pavements, walkways, playgrounds, and slope stabilization. To mitigate the strength reduction commonly associated with CR incorporation, surface treatment methods such as NaOH modification have been investigated (Li *et al.,* 2016). Treated CR particles have been reported to recover approximately 15-35% of the lost compressive strength (Tripathi *et al.,* 2025) and increase the elastic modulus by 10-25% (Xiao *et al.,* 2022).

Despite these advancements, several critical limitations still exist within the current body of research. Most existing studies have primarily focused on isolated aspects of rubberized concrete, such as compressive strength or durability, while comprehensive investigations addressing multiple influencing parameters simultaneously remain scarce. In particular, the combined influence of CR particle size, substitution type, and surface treatment on the mechanical performance of concrete has not been systematically evaluated. Furthermore, the impact resistance and energy absorption behavior of OPC based rubberized concrete, particularly under different substitution strategies, remain insufficiently explored.

Therefore, this study systematically evaluates the mechanical performance of OPC-based concrete modified with CR as a partial substitute for binder, fine aggregates, and coarse aggregates, with and without NaOH surface treatment. The mechanical performance of the developed composites is evaluated in terms of key properties, including compressive strength, modulus of elasticity, and impact resistance, in order to provide a comprehensive understanding of the performance of rubberized concrete and its potential application as a sustainable construction material. In addition, Fourier transform infrared (FTIR) spectroscopy was utilized to characterize the chemical alterations induced in the materials. Despite these advancements, a comprehensive understanding of the combined effects of CR substitution type, replacement level, and surface treatment on the mechanical performance of OPC-based concrete remains limited. Therefore, this study aims to systematically investigate these factors, and provides new insights into optimizing rubberized concrete for sustainable and impact-resistant applications.

MATERIALS AND METHODS

Raw Materials

In this study, OPC- based concrete with CR partial replacing cement, fine aggregate and coarse aggregate were prepared. The cement used is P·O 42.5 with a specific surface area of 378 m2/kg. The chemical composition of cement is presented in Table 1. Locally available crushed stone with a nominal maximum particle size of 19 mm was employed as the coarse aggregate. Its density and specific gravity were measured as 1800 kg/m3 and 2.75, respectively. The fine aggregate used was natural river sand (<4.75 mm) with a bulk density of 1600 kg/m3 and a specific gravity of 2.65. CR was incorporated as a partial replacement for cementitious material, as well as fine and coarse aggregates. An estimated average particle size approximately 10-15μm, 0.075 - 4.75 mm for fine aggregate, and 4.75 - 19 mm for coarse aggregate. The specific gravity and bulk density of CR were 1.13 and 640 kg/m3. Table 2. presents the chemical composition of CR.

Table 1: Chemical composition of binder materials (wt.%)

Composite	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	TiO_2	SO_3	Cl	Others
OPC	60-65	20-22	5-6	≤ 5	3-4	-	≤ 3	≤ 0.1	-

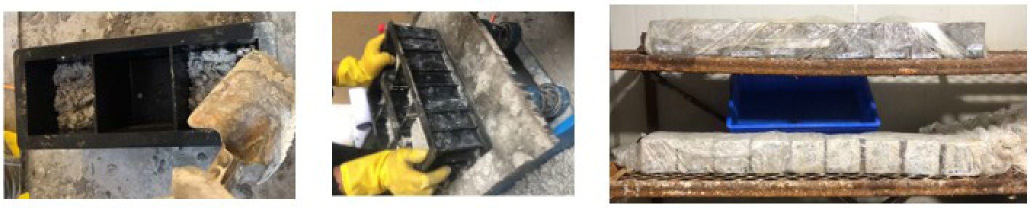
Table 2: Chemical composition of CR (wt.%)

Element	C	O	Na	Mg	Al	Si	K	Ca	Fe	Cu	Zn
CR	69.96	20.93	0.38	0.23	0.71	1.53	0.12	0.22	4.43	0.15	1.91

Preparation of OPC Concretes with CR

The mix proportions of OPC-based concrete are summarized in Table 3. CR was incorporated as a partial replacement for OPC, fine aggregates, and coarse aggregates at volumetric replacement levels of 9.4%, 17.9%, 25.5%, and 32.4%, corresponding to the respective constituent volumes. For comparative analysis, both without and with surface-treated CR were used in the concrete mixtures. For surface modification, CR particles were treated using a 1 M NaOH solution to improve interfacial bonding with the cement matrix. Specifically, CR was immersed in the NaOH solution for 24 h, followed by thorough washing with distilled water until the pH reached a neutral level. The treated CR was then air dried at ambient temperature prior to incorporation into the concrete mixtures. Concrete mixing was carried out in accordance with a standardized procedure. Initially, saturated surface dry (SSD) aggregates and CR were introduced into the mixer and dry mixed for 1 min to ensure uniform distribution. Subsequently, the binder (OPC) was added and mixed for an additional 1-2 min. Thereafter, mixing water was gradually introduced at a water-to-binder (w/b) ratio of 0.40, and the mixture was further mixed for 1-2 min to achieve a homogeneous consistency. The prepared concrete mixture was subsequently poured into pre-designed molds corresponding to different mechanical tests. For compressive strength, cubic specimens of 100 × 100 × 100 mm3 were prepared. For the static modulus of elasticity, prismatic specimens of 100 × 100 × 300 mm3 were cast. For impact resistance, cylindrical disc specimens with a diameter of 150 mm and a height of 63.5

mm were fabricated. All specimens were compacted using mechanical vibration to remove entrapped air and ensure proper densification. Following casting, the specimen surfaces were immediately covered with plastic film to minimize moisture loss and prevent contamination from external debris, as illustrated in Figure 1. The molds were labelled and stored in a controlled curing environment at 20 ± 2 °C. After 24 h, the specimens were demolded and subsequently cured under controlled conditions at 20 ± 2°C with a relative humidity exceeding 95%.



(a) Casting of specimens into molds.

(b) Compaction of the specimens using an electric vibrator.

(c) Immediate sealing of the specimen surfaces with plastic film to prevent moisture evaporation.

Figure 1: Preparation of specimens

Mix Design

A total of 42 concrete mix proportions were designed in this study to systematically evaluate the influence of CR incorporation on the mechanical performance of OPC-based concrete. The detailed mixture compositions are illustrated in Table 3. For compressive strength evaluation, 20 mix proportions were prepared, resulting in a total of 120 cubic specimens. Each mix consisted of six specimens, of which three were tested at 7 days and the remaining three at 28 days to assess early age and standard curing performance. CR was incorporated as a partial replacement for OPC, fine aggregates, and coarse aggregates, depending on the replacement strategy. The volumetric replacement levels of CR for OPC ranged from 0% to 25.5%, whereas for fine and coarse aggregates, the replacement levels varied from 9.4% to 32.4%. To investigate the influence of surface modification, both without treated and NaOH-treated CR were used in the mix design. For the static modulus of elasticity, 11 mix proportions were designed, producing a total of 66 prismatic specimens. In this case, CR was incorporated as a partial replacement for fine aggregates (9.4-25.5%) and coarse aggregates (9.4-32.4%), allowing evaluation of stiffness variation with different substitution levels. Similarly, for impact resistance testing, 11 mix proportions were prepared, yielding a total of 33 specimens. The same CR replacement ranges (9.4-25.5% for fine aggregates and 9.4-32.4% for coarse aggregates) were adopted to ensure consistency across mechanical performance comparisons.

Test Methods

Compressive Strength Test

Compressive strength tests were performed using a universal testing machine (UTM) in accordance with ASTM C39/C39M-25 (ASTM International, 2020). The tests were conducted at curing ages of 7 and 28 days to evaluate both early age and standard strength development. A constant loading rate of 0.25 MPa/s was applied throughout the test to ensure uniform stress application. The compressive strength for each group was calculated based on the average value of three specimens.

Table 3: Mix proportions and experimental of OPC based rubberized concrete mixtures

Mixture type	**Control**	**Binder replacement**			**Fine aggregate replacement**				**Coarse aggregate replacement**			
Specimen Label	C-B0	C-B10	C-B20	C-B30	C-FA10	C-FA20	C-FA30	C-FA40	C-CA10	C-CA20	C-CA30	C-CA40
Replacement level	0	9.4	17.9	25.5	9.4	17.9	25.5	32.4	9.4	17.9	25.5	32.4
Cement	1	0.96	0.93	0.89	1	1	1	1	1	1	1	1
Fine aggregate	1.32	1.32	1.32	1.32	1.26	1.2	1.15	1.09	1.32	1.32	1.32	1.32
Coarse aggregate	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.86	1.78	1.7	1.62
CR	0	0.04	0.07	0.11	0.06	0.11	0.17	0.22	0.08	0.16	0.24	0.32

CR Volume Fraction in Concrete	0	0.02	0.03	0.05	0.03	0.05	0.08	0.1	0.04	0.07	0.11	0.14
Compressive strength test	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d	7d 28d
Modulus of elasticity test	-	-	-	-	28d	28d	28d	28d	28d	28d	28d	28d
Drop-weight Impact test	-	-	-	-	28d	28d	28d	28d	28d	28d	28d	28d
Comparison samples of CR with surface treatment	x	x	x	x	√	√	√	√	√	√	√	√

Modulus of Elasticity Test

The static modulus of elasticity was determined using a universal testing machine (UTM) in accordance with ASTM C469/C469M-22 (ASTM International, 2022). All tests were conducted at a curing age of 28 days. Prismatic specimens were subjected to incremental loading, with stress levels applied up to 40% of the ultimate compressive strength. During testing, a longitudinal extensometer with a gauge length of 200 mm was mounted at the mid height of each specimen to measure axial deformation. Load and corresponding deformation readings were continuously recorded as the applied stress increased. The modulus of elasticity was calculated based on the stress strain relationship, using deformation measurements obtained from the extensometer. The strain readings were recorded with a precision of 1/1000 mm, ensuring high measurement accuracy. For each mix, the reported modulus of elasticity represents the average value of three specimens, thereby enhancing the reliability of the results.

Drop-Weight Impact Test

Several experimental methods have been developed to evaluate the impact resistance of cementitious materials, including the split Hopkinson pressure bar (SHPB) method, Charpy pendulum impact test, projectile impact test, and drop-weight impact test (Gdoutos & Konsta-Gdoutos, 2024). Among these, the drop-weight impact method is widely adopted due to its simplicity, cost-effectiveness, and ease of operation. In this study, the impact resistance of rubberized concrete specimens was evaluated using the drop-weight impact test in accordance with the procedure recommended by ACI 544 (1999; Badr & Ashour, 2005). The schematic of the experimental setup is illustrated in Figure 2. During testing, repeated impacts were applied to the specimen until visible cracking and ultimate failure occurred. The impact energy, defined as the total energy absorbed by the specimen prior to failure, was calculated using Eq. (1) (Vijay *et al.,* 2020):

$$W = m \cdot g \cdot h \cdot Ni \qquad (1)$$

Where W shows the impact energy (J), m indicates the mass of the hammer (4.45kg), g is the gravitational acceleration (9.81 m/s2), h is the drop height, ranging from 457 - 500 mm, with 457 mm considered for the test, and Ni is the number of blows at which the first crack is observed, typically on the top surface of the specimen during testing.

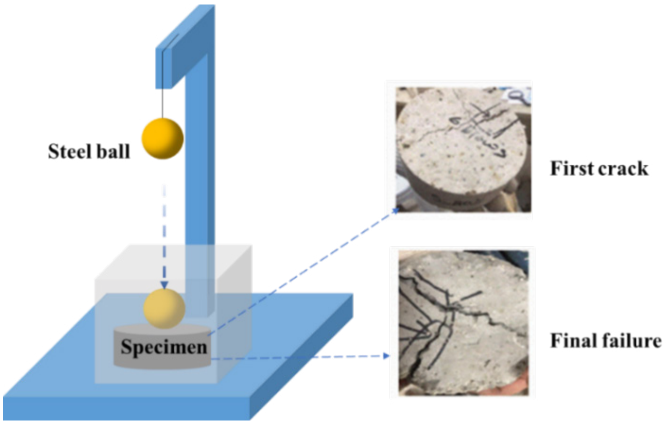


Figure 2: Drop-weight impact test instrument

Fourier transform infrared (FTIR) spectroscopy analysis

The chemical characteristics of CR, used as a coarse aggregate with and without surface treatment, were investigated using attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy. This analysis was performed to identify the functional groups, chemical structure, and interfacial bonding characteristics of CR, particularly to evaluate the effects of NaOH surface modification. FTIR spectra were acquired in the mid-infrared region (4000-500 cm-1) in transmittance mode, with a spectral resolution of 2 cm-1. To improve the signal-to-noise ratio, each spectrum was obtained by averaging 32 scans. The obtained spectra were used to analyze changes in surface functional groups and to assess the chemical modifications induced by the alkali treatment.

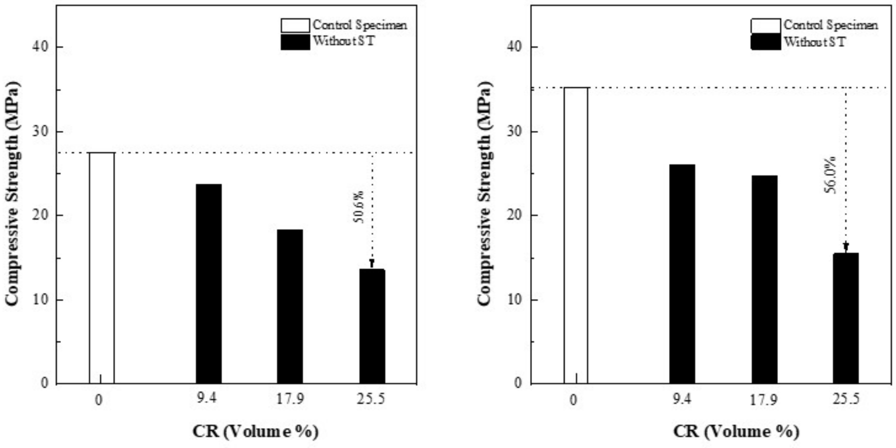
RESULS AND DISCUSSION

This section presents and analyses the results obtained from the experimental setup described in Section 2.

Influence of Partial Replacement of Cement with Crumb Rubber on the Compressive Strength of Concrete

The effect of partially replacing the OPC binder with CR on the compressive strength of concrete at 7 and 28 days is presented in Figures 3A and 3B. The results clearly indicate that increasing CR content leads to a progressive reduction in compressive strength compared to the control mix (0% CR). This behavior aligns with previously reported findings on rubberized concrete systems, which report similar reductions in compressive strength with increasing CR content (Eissa *et al.,* 2024; (Kevin *et al.,* 2025)).

The strength reduction strength is primarily attributed to the poor interfacial bonding between the CR particles and the cementitious matrix, the increased porosity of the mixture, and the lower stiffness of CR particles compared to conventional aggregates and binders. These factors collectively hinder effective stress transfer within the cementitious matrix. At 7 days, the control specimen showed a compressive strength of 27.5 MPa. Concrete mixes with 9.4%, 17.9%, and 25.5% CR replacement by volume showed strength reductions of 13.8%, 33.0%, and 50.6%, respectively. A similar trend was observed at 28 days, where the control mix reached 35.2 MPa, with corresponding reductions of 26.0%, 29.8%, and 56.0%. These findings differ from some previous reports (Kang *et al.,* 2018), which may be attributed to variations in CR particle size, surface treatment, and mix design parameters.



(A) 7 days

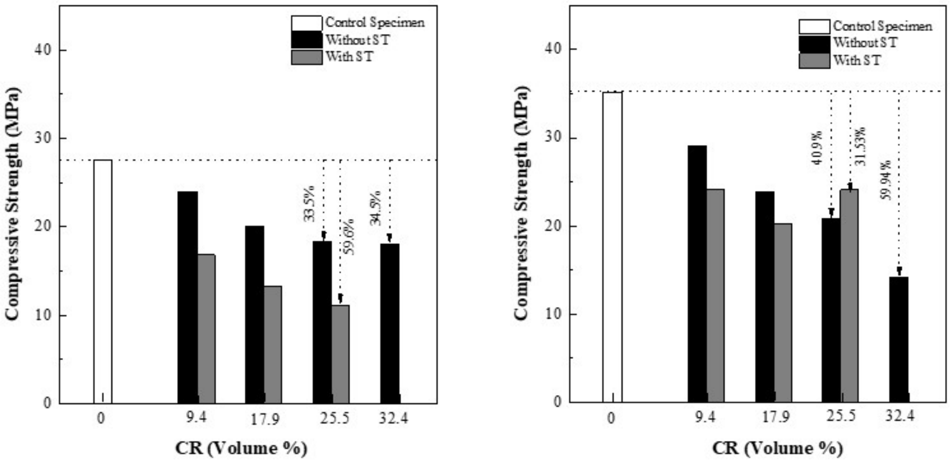
(B) 28 days.

Figure 3: Compressive strength of OPC concrete with cement partially replaced by CR

Influence of Partial Replacement of Fine and Coarse Aggregates with Crumb Rubber on the Compressive Strength of Concrete

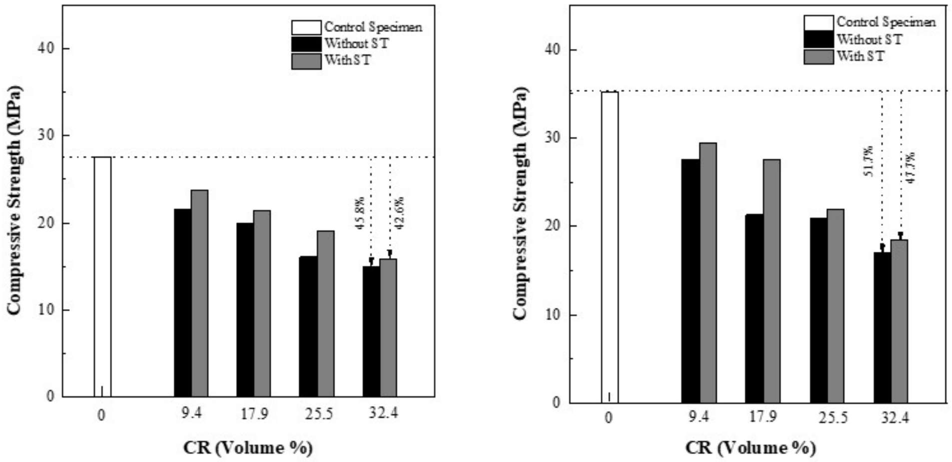
The impact of partial replacement of fine and coarse aggregates with CR, both with and without surface treatment (ST), on the compressive strength of OPC-based rubberized concrete at 7 and 28 days is illustrated in Figures 4 and 5. Consistent with extensive research on rubberized concrete. The compressive strength systematically decreases with increasing CR content for both fine and coarse aggregate replacements, regardless of surface treatment. This decline is primarily attributed to the lower stiffness of CR particles, increased void content, and weakened interfacial transition zones between CR and the cementitious matrix, as reported in previous studies (Lương *et al.,* 2021; Mutar *et al.,* 2018).

As illustrated in Figures 4A and B, at 7 days, the mix with 25.5% CR replacing fine aggregate without surface treatment (ST) showed a 55.1% reduction in compressive strength compared to the control specimen. When CR was surface treated (ST), the strength reduction at the same replacement level decreased to 38.2%. At 28 days, the compressive strength reductions were 46.3% for without treated and 40.4% for surface treated CR at 25.5% fine aggregate replacement. These findings indicate that surface treatment partially mitigates strength loss when CR is used as a fine aggregate replacement. For CR as a partial replacement for coarse aggregate, as illustrated in Figures 5A and B, similar trends of strength reduction were observed. However, in contrast to CR replacing fine aggregate, surface treated CR slightly increased the compressive strength of concrete compared to without treated CR at equivalent replacement levels. This observation is consistent with the mechanical response reported in previous studies, which suggests that replacing conventional aggregates with CR particles weakens the concrete's load-bearing capacity due to the inherent elasticity and lower modulus of CR compared to conventional aggregates (J. Dong *et al.,* 2024). This study further explores the potential of CR beyond conventional aggregate replacement, suggesting its possible contribution as a supplementary material in OPC systems. Unlike previous studies where CR incorporation severely compromised compressive strength, our findings show that even at higher replacement levels (17.9% and 25.5%), CR retains comparable mechanical performance to the control mixes, challenging the conventional view of its limitations (Liu *et al.,* 2023; H. Zhang *et al.,* 2022). Furthermore, this study reveals that NaOH surface treatment of CR diminishes interfacial bonding between CR particles and the matrix, thereby reducing compressive strength for both fine and coarse aggregate replacements. This finding differentiates the current work from existing literature (R. Zhang *et al.,* 2022). Notably, the research also uncovers a complex interaction between surface treatment and CR's role as fine aggregate, where surface treatment leads to greater strength loss compared to without treated CR, a phenomenon that has not been widely reported in prior studies (Grinys *et al.,* 2020). These results provide deeper insight into the role of CR in sustainable concrete applications and highlight the importance of optimizing both replacement level and surface treatment. Offering valuable insights into optimizing CR content and surface modification techniques to improve mechanical performance while enhancing sustainability.



(A) 7 days (B) 28 days

Figure 4: Compressive strength of OPC concrete with fine aggregate partially replaced by CR



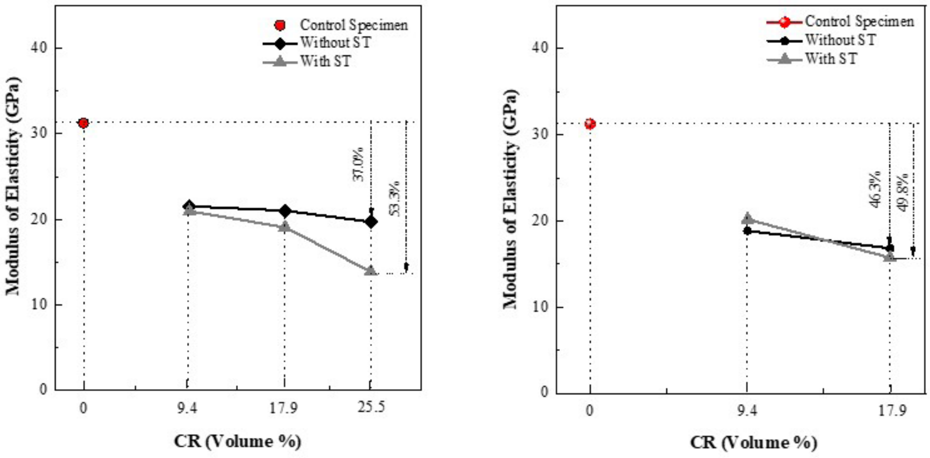
(A) 7 days (B) 28 days

Figure 5: Compressive strength of OPC concrete with coarse aggregate partially replaced by CR

Influence of Partial Replacement of Fine and Coarse Aggregates on the Static Modulus of Elasticity of Concrete

The effects of CR as a partial replacement for fine and coarse aggregates on the modulus of elasticity (EOM) in OPC concrete are illustrated in Figure 6. The results reveal a systematic decrease in modulus of elasticity with increasing CR content for both fine and coarse aggregate replacements, regardless of the surface treatment (ST). As illustrated in Figure 6A, when CR replaced fine aggregate, the modulus of elasticity exhibits a progressive decrease progressively, with reductions of 31.2%, 32.9%, and 37.0% for the without treated CR group and 33.0%, 39.0%, and 55.3% for the surface-treated (ST) CR group at the respective replacement levels. Notably, surface treatment exacerbated the deterioration of EOM, resulting in more significant reductions than those observed in the without treated CR group. This trend further supports earlier findings on stiffness reduction in rubberized systems, which suggest that surface treatment of CR may adversely affect the modulus of elasticity due to increased porosity and weakened interfacial bonding, potentially due to the increased porosity and weakened interfacial bonding between the treated CR particles and the cement matrix (W. Dong *et al.,* 2020). For the case of CR replacing coarse aggregate, as illustrated in Figure 6B, the modulus of elasticity exhibited similar behavior for both the treated and without treated CR groups. The ST group showed a reduction almost identical to that of the without treated CR group, suggesting that surface treatment has little effect on the EOM when CR replaces coarse aggregates. This behavior contrasts with the fine aggregate replacement case, where surface treatment significantly exacerbated the modulus reduction. These findings align with the work of (Wu *et al.,* 2024), who noted that the effect of surface treatment on CR's properties in concrete may be significantly influenced by the type of aggregate replaced (fine vs. coarse). This study underscores the complex role of surface treatment in modifying the mechanical properties of OPC concrete with CR replacement. While surface treatment improves the interfacial bonding of CR with the cement matrix in some cases, its impact appears to be more favorable when CR is used as a coarse aggregate replacement compared to fine aggregates. Previous research has similarly demonstrated that CR used as coarse aggregate may exhibit less deterioration in mechanical properties than when used as fine aggregate, likely due to differences in particle shape and size (P. Zhang *et al.,* 2025).

The results indicate that for fine aggregate replacement, surface treatment of CR does not provide the expected mechanical benefits and may, in fact, lead to further weakening of the concrete. This is likely due to the increased surface area of the treated CR particles and the altered interactions between the matrix and the CR particles, which can result in weaker bonding and reduced stiffness. These findings contribute to the growing body of knowledge on the use of CR in concrete, emphasizing the need to carefully consider both the type of aggregate replaced and the surface modification techniques when designing rubberized concrete for practical applications.



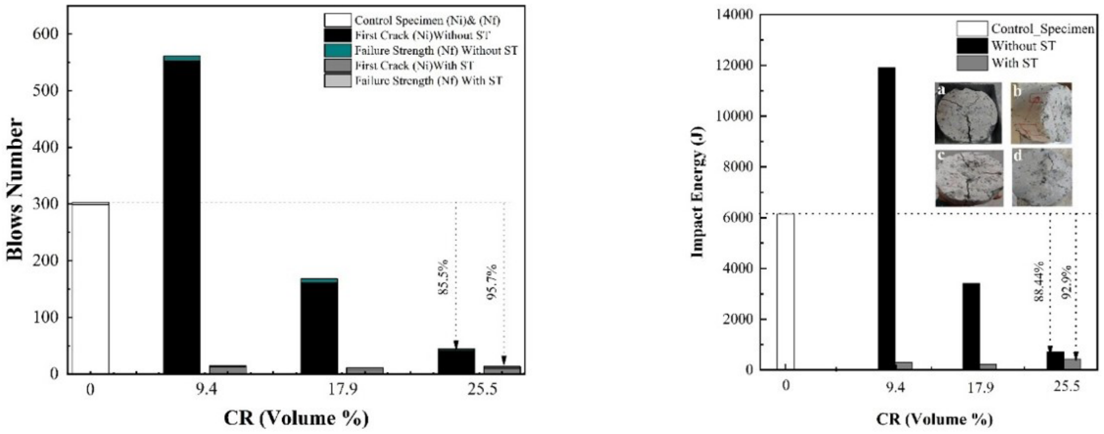
(A) Fine aggregate partially replaced by CR

(B) Coarse aggregate partially replaced by CR

Figure 6: Elasticity of OPC concrete incorporating varying levels of CR to replace fine or coarse aggregate

Influence of Partial Replacement of Fine and Coarse Aggregates on the Impact Properties of Concrete

Figures 7 and 8 present the impact resistance properties of OPC concrete incorporating CR as a partial replacement for fine and coarse aggregates, with and without surface treatment (ST). Impact resistance was quantified by the number of blows to first crack (Ni), the number of blows to failure (Nf), and the corresponding impact energy. These parameters were measured for all concrete mixes. In the impact test, the center of the specimen is the location where the load concentration occurs due to the sudden and repetitive nature of the impact load. Given the short duration of the impact load, the failure mode of the specimen differs significantly from that observed under compressive load. Concrete failure under impact loading is characterized by the initiation of a critical crack from the stress concentration point within a short time, rapidly propagating until the specimen is divided into multiple pieces, as illustrated in Figures 7B and 8B. For mixes in which fine aggregates were partially replaced by CR, the results indicate that CR without surface treatment significantly enhances the impact resistance at low replacement levels (Figure 7A). The increase in Ni and Nf demonstrates an enhanced capacity of the concrete matrix to resist crack initiation and propagation. This enhancement is primarily governed by the viscoelastic nature of CR particles, which facilitates energy dissipation and stress redistribution under impact loading, effectively dissipating stress concentration within the cementitious matrix. Comparable behavior has been documented in previous investigations, where the inclusion of CR particles improved the toughness and impact resistance of concrete due to their crack bridging and energy dissipation mechanisms (Siddique & Naik, 2004; Zaland *et al.,* 2024). The impact energy results shown in Figure 7B further confirm this trend. Without surface treatment, the impact energy increased with CR content. At a 9.4% CR replacement level, the impact energy reached its maximum value of 11898.4 J, representing a 93.37% increase compared to the control concrete (6153.21 J). This significant enhancement indicates that moderate CR replacement can significantly improve the impact energy absorption capacity of concrete. However, when the CR content increased to 17.9% and 25.5%, the impact energy decreased to 3415.44 J and 711.56 J, respectively. This reduction at higher replacement levels is likely due to a weaker interfacial transition zone (ITZ) between CR particles and the cement matrix, as well as increased porosity and reduced stiffness of the composite material (Thomas *et al.,* 2016). Excessive CR content compromises the load transfer mechanism within the matrix, leading to a reduction in impact resistance. In contrast, for the fine aggregate partial replacement with CR subjected to ST, a different mechanical response was observed. The impact energy remained relatively stable, ranging from 304.95 J to 437.1 J across the studied replacement levels (9.4-25.5%), which is notably lower than the corresponding mixtures without ST. This suggests that the surface treatment may have altered the deformation characteristics of the CR particles or affected the interfacial bonding with the cement matrix. In some cases, surface treatment can increase the stiffness or reduce the inherent elasticity of CR particles, thereby limiting their ability to absorb and dissipate impact energy effectively (Q. Dong *et al.,* 2013).

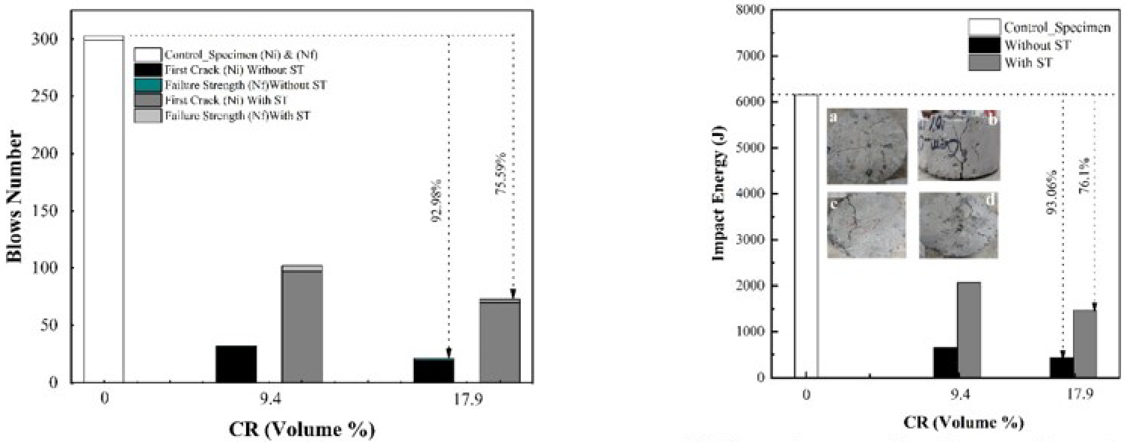


(A) Blows number N_i and Nf.

(B) Impact energy W (The specimen sections a-b are without ST and c-d with ST).

Figure 7: Impact resistance properties of OPC concrete incorporating CR with and without ST as a partial replacement for fine aggregates

For mixtures in which coarse aggregates were partially replaced by CR, as illustrated in Figure 8, the impact resistance generally decreased regardless of whether surface treatment was applied. For the without treated CR group, the impact energy showed noticeable variation with increasing CR content; however, the values remained significantly lower than those of the control concrete at all replacement levels. This behaviour can be attributed to the substantial difference in stiffness between CR particles and natural coarse aggregates, which weakens the structural skeleton of the concrete and reduces its ability to resist impact loads (Liyungu *et al.,* n.d.). The replacement of coarse aggregates with CR particles reduces the overall load bearing capacity of the concrete matrix, resulting in lower resistance to crack propagation. Interestingly, for the coarse aggregate replacement with ST, the impact energy at all studied replacement levels (9.4-17.9%) was noticeably higher than that of the corresponding mixes without ST. This suggests that surface treatment improved the interfacial bonding between CR particles and the surrounding cement matrix, partially mitigating the negative effects of CR incorporation. Improved bonding enhances stress transfer efficiency and reduces premature debonding under impact loading (Najim & Hall, 2012). However, the impact resistance of these mixtures still remained lower than that of the control concrete, indicating that replacing coarse aggregates with CR particles should be carefully optimized. Additionally, the findings from this study suggest that the optimum improvement in impact resistance occurs when CR is used as a partial replacement for fine aggregates at moderate replacement levels without surface treatment. In contrast, the replacement of coarse aggregates generally results in a reduction in impact performance. These results highlight that the mechanical performance of rubberized concrete is governed not only by CR content but also by the interaction between surface treatment and aggregate type, which significantly influences interfacial bonding and stress transfer mechanisms.



(A) Blows number N_i and N_f.

(B) Impact energy (Specimen sections a-b are without ST and c- d with ST).

Figure 8: Impact resistance properties of OPC concrete incorporating CR with and without ST as a partial replacement for coarse aggregates

FTIR Analysis of Crumb Rubber with and without NaOH Surface Treatment

To investigate the effect of NaOH surface treatment (ST) on CR, FTIR spectroscopy was performed to identify functional groups and assess chemical changes induced by the treatment. Figure 9 presents the FTIR spectra of CR with and without surface treatment (ST). The without ST of CR exhibits typical spectral characteristics of hydrocarbon-based elastomers, as shown by C-H stretching vibrations in the range of 2846-2915 cm-1, which correspond to aliphatic hydrocarbon chains. A prominent peak at 1535 cm-1 is associated with C=C stretching, indicating the presence of double bonds within the polymer backbone. Additionally, the bands observed between 800-1100 cm-1 represent C-H bending and C-C skeletal vibrations, which are typical for unmodified styrene-butadiene CR. These spectral features confirm that without treated CR maintains a predominantly hydrophobic hydrocarbon surface. Such a surface, devoid of polar functional groups, leads to the formation of a weak interfacial transition zone (ITZ) when in contact with cementitious matrices, as the lack of polar groups prevents effective chemical interaction (Yin *et al.,* 2025). Furthermore, the presence of sulfur or nitrogen-containing additives, along with other inert impurities in untreated CR, may exacerbate the weak bonding characteristics. In contrast, NaOH-treated CR exhibits significant chemical modification of the CR surface. Notably, a strong O-H stretching band at 3689 cm-1 appears, indicating the formation of hydroxyl groups (-OH). Additionally, enhanced peaks in the 950-1000 cm-1, 1400 cm^{-1}, and 1700-1750 cm-1 ranges correspond to carbonyl (C=O) groups, marking the presence of oxidative cleavage and subsequent formation of aldehydes and carboxyl groups during NaOH treatment. These changes are consistent with the results of previous studies (Huang *et al.,* 2013; Aly *et al.,* 2019). The notable reduction in the 1535 cm-1 C=C stretching peak further confirms the transformation of C=C bonds into carboxyl groups during the NaOH pre-treatment. Distorted peaks in the 750-900 cm-1 region correspond to S=O stretching vibrations, indicating the oxidation of sulfur-containing components in the CR polymer network (Kilani *et al.,* 2025). These modifications suggest extensive surface oxidation during NaOH treatment, which increases the polarity and surface energy of CR. As a result, the surface energy of CR is significantly enhanced, making the material more hydrophilic and improving its compatibility with cementitious binders (Xiao *et al.,* 2022). The NaOH treatment serves a dual purpose: it cleans the CR particles by removing additives and contaminants and also physically alters the surface by introducing voids, which increase surface roughness and porosity (Aown *et al.,* 2025). This transformation of the CR surface results in improved adhesion between the CR particles and the surrounding cement matrix, as the rough and porous surface promotes better interfacial bonding. Moreover, due to the inherent low stiffness of CR compared to natural aggregates (Aly *et al.,* 2019), the surface treatment improves the stiffness of CR, leading to better retention of compressive strength in most of the tested mixes in this study.

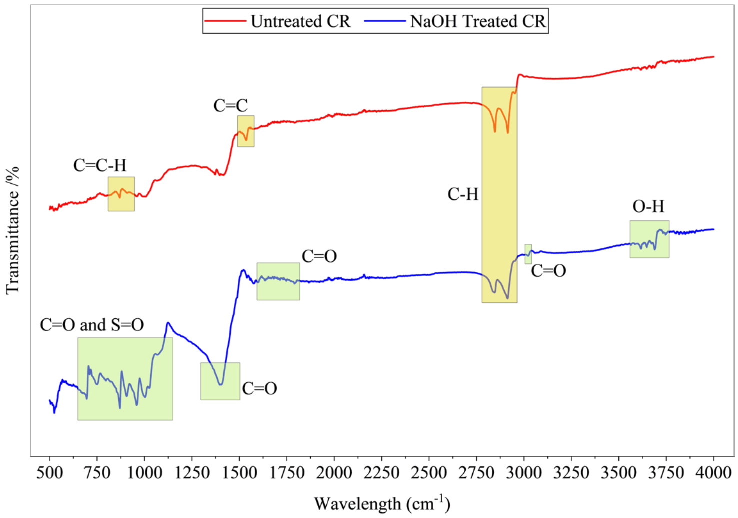


Figure 9: FTIR Spectroscopy image of Untreated CR and NaOH treated CR

CONCLUSION

Based on a systematic experimental investigation of OPC concrete incorporating CR as partial replacements for the binder, fine aggregates, and coarse aggregates, the following conclusions are drawn:

1) The incorporation of CR leads to a notable reduction in compressive strength across all replacement strategies, primarily due to weak interfacial transition zones (ITZ) and the low stiffness of rubber particles, with a maximum strength reduction of 56.0% observed at higher replacement levels.

2) A consistent decrease in modulus of elasticity is observed with increasing CR content, reflecting reduced stiffness and enhanced deformability of the rubberized concrete.

3) CR incorporation significantly enhances impact resistance at moderate replacement levels due to its viscoelastic behaviour, which promotes energy absorption and crack bridging mechanisms, particularly at moderate replacement levels. The maximum enhancement was observed at 9.4% fine aggregate replacement, where impact energy increased by approximately 93.37% compared to the control sample. However, surface treatment reduces impact energy absorption, likely due to increased stiffness and reduced deformability of CR particles.

4) FTIR analysis confirms significant surface modification of CR following NaOH treatment, characterized by the formation of hydroxyl and carbonyl functional groups that enhance surface polarity and interfacial interaction.

5) Overall, CR incorporation introduces a trade-off between reduced mechanical strength and enhanced impact resistance, highlighting the importance of optimizing both replacement level and surface treatment conditions.

This study provides a comprehensive evaluation of CR incorporation in OPC-based concrete by simultaneously investigating the effects of replacement type, replacement level, and surface treatment. Unlike previous studies focusing on single parameters, this work reveals the critical interaction between surface treatment and aggregate type, demonstrating that NaOH treatment may adversely affect fine aggregate mixtures while partially improving coarse aggregate performance. These findings offer new insights into the design and optimization of rubberized concrete for sustainable and impact-resistant structural applications

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