European Journal of Environmental and Civil Engineering

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tece20

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To cite this article: Hasan Mostafaei, Massih Kelishadi, Hadi Bahmani, Chengqing Wu & Bahman Ghiassi (2025) Development of sustainable HPC using rubber powder and waste wire: carbon footprint analysis, mechanical and microstructural properties, European Journal of Environmental and Civil Engineering, 29:2, 399-420, DOI: 10.1080/19648189.2024.2400485

To link to this article: https://doi.org/10.1080/19648189.2024.2400485

Published online: 10 Sep 2024.

EUROPEAN JOURNAL OF ENVIRONMENTAL AND CIVIL ENGINEERING
2025, VOL. 29, NO. 2, 399–420
https://doi.org/10.1080/19648189.2024.2400485

Development of sustainable HPC using rubber powder and waste wire: carbon footprint analysis, mechanical and microstructural properties

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ABSTRACT

This research advances the development of eco-friendly high-performance concrete (HPC) by integrating tire rubber powder and waste wire, focusing on both enhanced mechanical properties and reduced environmental impact. Substituting up to 40% of silica sand with rubber powder helps maintain the compressive strength necessary for high-strength concrete applications. The addition of waste wire is designed to improve ductility. A comprehensive evaluation includes mechanical and microstructural analyses, such as compressive, splitting tensile, and flexural strength assessments, in addition to Scanning Electron Microscopy (SEM) and Differential Thermal Analysis (DTA). Environmental implications are assessed by measuring the embodied carbon footprint. Findings indicate that the absence of rubber powder allows for a compressive strength peak of 95 MPa, while 50% rubber content leads to a decrease to 25 MPa, establishing a 40% rubber threshold for optimal strength. Conversely, 3% waste wire reinforcement enhances the strength to 106 MPa. Microstructural investigations reveal that increased rubber content adversely affects compressive strength by weakening the cement matrix, and reducing calcium-silicate-hydrate (C-S-H) formation. Significantly, the study reveals that replacing silica sand with rubber powder, along with waste wire reinforcement, substantially reduces the carbon footprint of the material, contributing to more sustainable construction methodologies.

ARTICLE HISTORY
Received 20 January 2024
Accepted 28 August 2024

KEYWORDS
Carbon footprint analysis; life cycle assessment; mechanical properties; microstructure; rubber powder; waste wire

1. Introduction

The development of high-strength concrete (HSC), specifically High-Performance Concrete (HPC), has revolutionized the construction industry by offering superior mechanical properties and durability (Bahmani et al., 2020b; Bahmani & Mostofinejad, 2022; Van Deventer et al., 2012; Van Jaarsveld et al., 1997). However, the significant environmental impact associated with the high cement content in HPC has raised concerns, prompting the exploration of sustainable alternatives. The use of waste materials such as

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tire rubber and steel fibers in concrete mixtures has emerged as a promising solution to mitigate these environmental effects (Bahmani et al., 2020a; 2022; Bahmani & Mostofinejad, 2023c; Shi & Day, 1996).

Life Cycle Assessments (LCAs) have been conducted to evaluate the environmental impacts of HPC, considering factors such as resource depletion, energy consumption, greenhouse gas emissions, water usage, and waste generation (Hossein et al., 2022; Mostafaei et al., 2023a; 2023b; 2023c). To mitigate these impacts, researchers have explored the substitution of cement with pozzolans and waste materials (Li et al., 2023; Xing et al., 2022). One promising approach is the utilization of waste rubber in concrete. Techniques such as compression casting encourage the use of waste rubber in concrete. This not only aids in waste management but also improves the tensile strength and ductility of the concrete (Aghamohammadi et al., 2024; Yadav, 2023; Yadav et al., 2022; Yadav & Tiwari, 2019).

In addition to waste rubber, materials like limestone powder and zeolite have been investigated as potential cement substitutes in UHPC (Bahmani et al., 2023; Bahmani & Mostofinejad, 2024). These findings offer promising avenues for reducing the environmental impact of HSC production.

The concept of reinforcing brittle mixtures with fibers to enhance their limited tensile strength has been traced back to ancient times (Afroughsabet et al., 2016; Meng & Khayat, 2017; Şanal et al., 2016). Despite its inherent fragility, concrete is one of the most extensively employed materials in the construction industry. Researchers have explored the implementation of industrial metal fibers, including recycled steel fiber waste derived from tires, to fortify concrete (Ali et al., 2020; Bahmani & Mostofinejad, 2023b; 2023c; Mostofinejad et al., 2023b; 2023c).

Recognizing the vast quantity of waste and its detrimental impact, researchers across various disciplines have explored the potential of utilizing recycled steel fiber waste derived from tires (Saikia & De Brito, 2012; Siddique et al., 2008; Yadav et al., 2008). Rubber concrete exhibits notable advantages such as exceptional wear resistance and high toughness, making it suitable for application in hydraulic structures, pavement, and bridge coverings.

Recent studies have demonstrated the potential of waste rubber powder as a partial replacement for traditional aggregates like silica sand. This substitution not only addresses waste management issues but also improves the tensile strength and ductility of concrete, making it a viable option for various structural applications. Additionally, the incorporation of waste steel fibers, specifically recycled tire wire, has shown to enhance the mechanical properties of concrete, offering a sustainable alternative to conventional reinforcement methods.

Despite the promising results, there is a need for a more comprehensive understanding of the effects of high-volume rubber powder and tire wire on the mechanical and microstructural properties of HPC. This study aims to bridge this gap by investigating the use of up to 50% rubber powder as a substitute for silica sand and varying percentages of waste tire wire as reinforcement in HPC. Through a series of mechanical tests, including compressive, tensile, and flexural strength assessments, along with microstructural analysis using Scanning Electron Microscopy (SEM) and Differential Thermal Analysis (DTA), this research seeks to evaluate the performance and sustainability of the developed HPC mixtures.

Moreover, the study conducts a carbon footprint analysis to assess the environmental impact of incorporating these waste materials into HPC, offering insights into the potential of these sustainable practices to reduce the carbon emissions associated with concrete production. By addressing both the mechanical and environmental aspects, this research contributes to the ongoing efforts to develop more sustainable construction materials.

2. Methodology

2.1. Raw materials

Type 1 cement, as specified in the ASTM-C150 standard, was carefully selected for this study due to its compliance with the desired properties outlined in Table 1. In line with previous research findings, silica sand with a particle size range of 50–150 μm was chosen as the aggregate for HPC with the desired properties outlined in Table 1. The micro-silica employed in the present study was sourced from the Iran Ferroalloy Company and conforms to the chemical characteristics described in Table 1. It is important to note that this micro-silica adheres to the ASTM C1240 standard (ASTM C1240-15,15, 2015), ensuring its quality and suitability for the research. To ensure that the mechanical properties of the HPC samples remained unaffected, rubber powder with a granulation size matching that of the silica sand was

Table 1. Chemical composition of the materials.

Chemical composition: % by weight	ASTM C 1240 (2015) limits	Silica fume	ASTM C 150 (2009) limits	Cement	Silica sand
Al_2O_3	–	0.6-1.2	–	0	0.4-1.7
SiO_2	≥85	90-95	–	22.0	97.0-99.0
Fe_2O_3	–	0.3-1.3	–	3.0	0.2-0.6
CaO	–	0.5-1.5	–	64.0	0.07-0.2
MgO	–	0.5-2.0	≤6.0	1.0	0
SO_3	–	–	≤3.5	1.0	–
LOI	≤6.0	0.4-3.0	≤3.0	0	–
Moisture content	≤3.0	0.01-0.4	–	0	–
K_2O	–	–	–	–	0.02-0.06
Na_2O	–	–	–	–	0-0.01
Cl	–	–	–	–	–
S_2	–	–	–	–	–
Mn_2O_3	–	–	–	–	–
TiO_2	–	–	–	–	–
I.R	–	–	–	–	–
P_2O_5	–	–	–	–	–
$MgCO_3$	–	–	–	–	–
$CaCO_3$	–	–	–	–	–

Table 2. Mixture proportions (kg/m^3).

Designation	Cement	Silica fume	Rubber	Silica sand	Water	SP	Waste wire
HPC	950	285	–	863	171	19	–
HPC (10% R)	990	285	27	767	171	22	–
HPC (20% R)	990	285	54	690	171	22	–
HPC (30% R)	990	285	81	604	171	26	–
HPC (40% R)	990	285	108	518	171	28	–
HPC (50% R)	990	285	135	432	171	30	–
HPC (1.5% WW)	990	285	27	767	171	22	118
HPC (2% WW)	990	285	27	767	171	22	157
HPC (2.5% WW)	990	285	27	767	171	22	196
HPC (3% WW)	990	285	27	767	171	22	235

carefully selected. This meticulous selection process aimed to mitigate any potential impact on the overall mechanical performance of the HPC. In order to achieve the necessary fluidity and workability of the concrete samples, a polycarboxylate-based superplasticizer was incorporated. Table 2 shows the mixture proportions used in this research.

2.2. Sample preparation

Per ACI 363 R (Russell et al., 1997), cylindrical specimens of 100 × 200 mm or 150 × 300 mm can be used for compressive strength testing. Considering the marginal variation in results obtained from these sample sizes, this research employed cylindrical specimens of 100 × 200 mm for the compressive strength test (three individual replications for each specific mix design). To execute the test, a robust 2000 kN hydraulic jack, as depicted in Figure 1a, was utilized. Testing was carried out at a loading speed between 0.2 and 0.4 MPa/s to ensure consistent and controlled force application.

Using the Brazilian tensile strength test, based on the ASTM C469 standard, 100 × 200 mm cylindrical samples were analyzed (three individual replications for each specific mix design). Figure 1b illustrates the implementation of a hydraulic jack to conduct the test on the cylindrical specimens, ensuring precise and accurate measurement of tensile strength (ASTM C496/c496m, 2004).

To assess the energy absorption capacity of the samples containing rubber powder and wire waste, a four-point bending test was conducted. This test, performed according to the ASTM C1018 standard (ASTM C 1018-97,97, 1998), employed a specialized device as depicted in Figure 1c. The samples were positioned between two cylindrical supports, maintaining a distance of 25 mm between the end of the sample and the support. The loading speed was meticulously determined to ensure that the first crack

Figure 1. Test setup (a) compressive strength, (b) splitting tensile strength, (c) flexural strength.

occurred between 30 and 60 s from the initiation of loading. This controlled loading speed facilitated the evaluation of the samples' energy absorption performance.

By employing these standardized testing methods and utilizing appropriate equipment, we aimed to obtain accurate and reliable data on the compressive strength, tensile strength, and energy absorption capacity of the concrete samples containing rubber powder and wire waste. These tests provide critical insights into the mechanical properties and structural behavior of the developed concrete, enabling a comprehensive assessment of its performance and suitability for practical applications.

2.3. Carbon footprint analysis

Carbon footprint analysis stands as a crucial tool, serving to evaluate and quantify the greenhouse gas emissions linked to specific activities, processes, products, or organizations (Ali et al., 2020; Garces et al., 2022; Nilimaa, 2023; Saffari et al., 2019; Taghikhah et al., 2022). It offers a holistic view of the environmental impact by quantifying the release of carbon dioxide equivalents (CO_2e) into the atmosphere. This analysis considers a range of factors, such as energy consumption, fuel usage, transportation, waste generation, and resource extraction, providing a thorough understanding of the overall impact on the environment (Shi et al., 2021; Xing et al., 2022). By measuring and scrutinizing these emissions, organizations and individuals gain the insight needed to pinpoint areas of high impact and implement strategies to curtail their carbon footprint (Chamasemani et al., 2023).

When it comes to High-Performance Concrete (HPC), the carbon footprint analysis delves into assessing and quantifying the greenhouse gas emissions entwined with the entire lifecycle of HPC. This encompasses raw material extraction, production, transportation, construction, and end-of-life disposal (Bajpai et al., 2020; Scherz et al., 2023). The analysis initiates by identifying the key components of HPC, notably cement, aggregates, water, and admixtures. The carbon footprint of cement, the most significant contributor to HPC emissions, is determined by considering the emissions generated during raw material extraction, fuel combustion in kilns, and the calcination process (Stengel & Schießl, 2008; 2014). Aggregates, which typically constitute a large portion of HPC, are evaluated for their transportation-related emissions and energy consumption during extraction and processing.

To calculate the carbon footprint, the emissions associated with each stage are quantified and converted into carbon dioxide equivalents (CO_2e) using emission factors. CO_2e accounts for the different global warming potentials of various greenhouse gases. The analysis may follow established guidelines and standards, such as ISO 14040 and ISO 14044 (ISO 14040:2006, 14040:2006, 2006), to ensure a systematic and consistent approach.

By conducting carbon footprint analysis of HPC, researchers can identify the major contributors to emissions and evaluate the environmental impact of HPC production and use. This information can guide the development and implementation of strategies to reduce the carbon footprint of HPC. These strategies may include optimizing the cement composition, incorporating alternative cementitious materials with lower emissions, improving energy efficiency during production, and promoting recycling or reuse of concrete waste (Du et al., 2022; Guo et al., 2023; Xia et al., 2023).

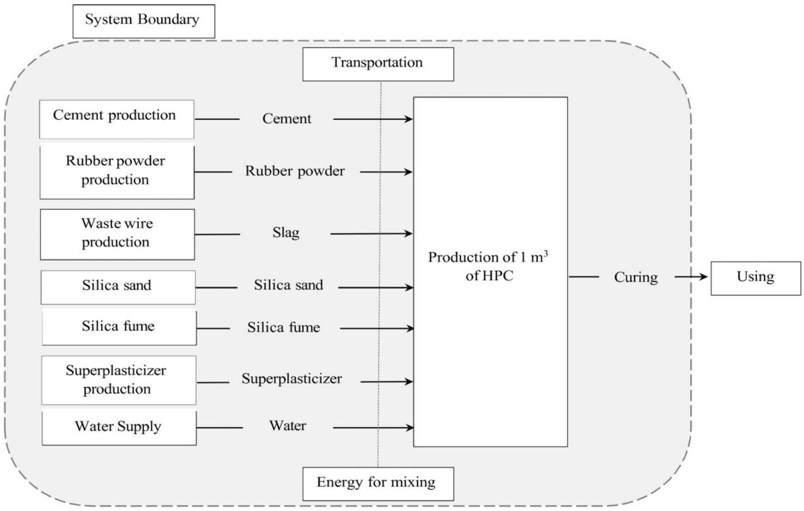

Figure 2. System boundary for producing 1 m^3 of different concrete types.

The aim of carbon footprint analysis in the context of HPC is to enhance the sustainability and environmental performance of concrete construction (Dong, 2018; Ji et al., 2022; Sameer et al., 2019). By identifying opportunities for emissions reduction and implementing best practices, the industry can minimize its carbon impact and contribute to global efforts to mitigate climate change. Moreover, carbon footprint analysis can assist in comparing different concrete formulations and construction techniques, enabling stakeholders to make more informed decisions based on environmental considerations.

The transportation phase involves assessing the emissions associated with the transportation of raw materials to the production facility, as well as the delivery of HPC to construction sites. The energy consumption during the production of concrete, including mixing, curing, and quality control, is also taken into account. Additionally, the carbon footprint analysis considers the emissions generated during the construction phase, such as equipment usage and waste generation. The system boundary for producing 1 m^3 of different concrete types is presented in Figure 2.

3. Data analysis and results

This section presents the mechanical properties of the samples, including compressive, flexural, splitting tensile strengths, and density. Moreover, SEM and TGA results of the optimized samples are scrutinized. Additionally, a detailed examination of the environmental impact linked to the mix design occurred through a comprehensive carbon footprint analysis.

3.1. Mechanical properties

3.1.1. Density

Figure 3 illustrates the results of the density of samples containing different percentages of rubber powder as a substitute for silica sand. The data reveals an interesting trend: as the replacement percentage of silica sand with rubber powder increases, the density of the samples decreases noticeably. For instance, in samples containing 30% rubber powder, the density decreases by approximately 500 kg/m^3. Based on this observation, the cement matrix becomes less compact as rubber powder is replaced with sand, resulting in increased porosity. There is less interlocking and cohesion between cementitious matrix constituents, causing this phenomenon.

Moreover, the density of samples incorporating various percentages of wire waste in conjunction with a constant 10% rubber powder content is presented in Figure 4.

Notably, the data highlights a direct correlation between the percentage of waste wire used and the density of the samples. As the proportion of wire waste increases, the density of the concrete samples

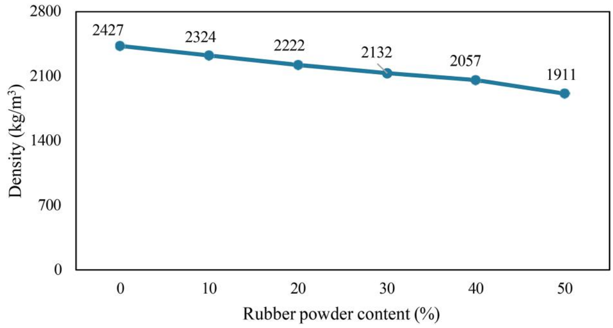

Figure 3. Density of samples containing different percentages of rubber powder.

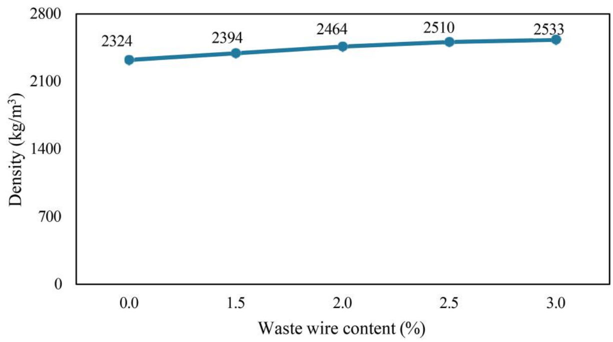

Figure 4. Density of samples incorporating various percentages of wire waste in conjunction with a constant 10% rubber powder content.

also rises. This outcome can be attributed to the relatively higher density of the wire waste as compared to the cement matrix. It becomes apparent that samples containing 3% waste wire exhibited the highest density, measuring approximately 2533 kg/m^3. Conversely, the lowest density was recorded in samples devoid of any wire waste, registering at 2324 kg/m^3.

3.1.2. Compressive strength

The stress-strain curve depicted in Figure 5 illustrates the behavior of samples containing varying proportions of rubber powder and wire waste.

As can be seen, the inclusion of rubber powder led to a noticeable reduction in compressive strength. This reduction is primarily attributed to the weak bonding capability of rubber powder with the cement paste, due to its non-polar and hydrophobic nature. The weakened bond results in a less cohesive interfacial transition zone (ITZ), which is critical to the overall strength of the concrete. Notably, the samples reinforced with wire scraps exhibit a more ductile fracture behavior compared to those without reinforcement. The incorporation of wire waste effectively mitigated crack development, leading to an increased capacity to endure compressive strain up to the point of rupture.

Furthermore, the stress curve for these samples demonstrates an almost parabolic trajectory up to the maximum load. Post-maximum load behavior varies depending on the percentage of wire utilized, with steeper slopes observed in samples containing lower percentages of wire waste. This reflects an increase in the inherent rigidity of the cement matrix due to higher wire waste content, subsequently elevating their compressive stress-bearing capacity.

Moreover, following the peak load, samples with a greater proportion of wire waste exhibit a gradual decline in stress, indicating enhanced ductility and toughness compared to those with lower wire waste content. The results also highlight that samples containing higher percentages of rubber powder exhibit lower maximum compressive stress. This phenomenon is likely attributed to the increased porosity of the cement matrix resulting from higher rubber powder content.

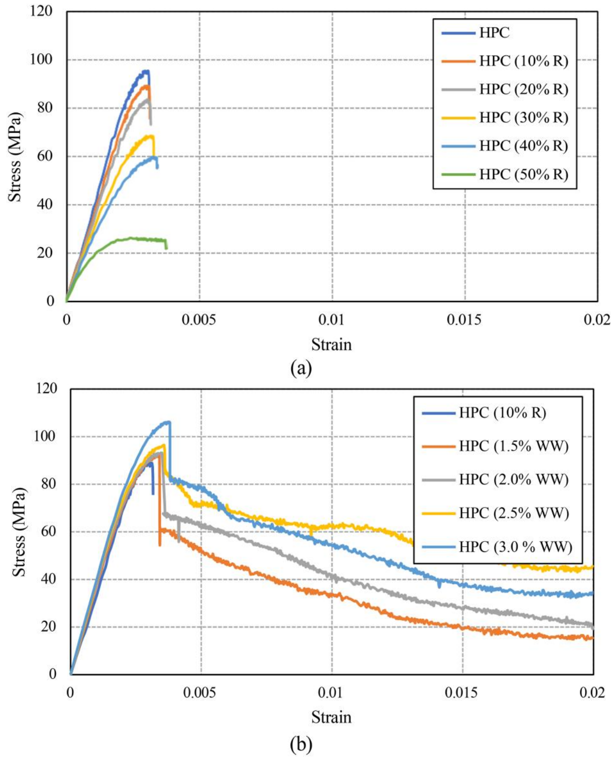

Figure 5. Stress-strain curve of samples (a) containing different percentages of rubber powder, (b) incorporating different percentages of rubber wire waste in conjunction with a constant 10% rubber powder content.

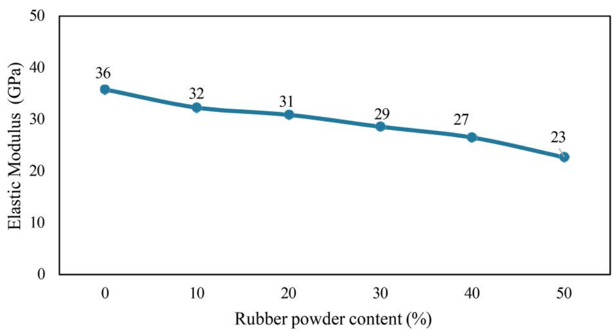

Figure 6. Elastic modulus of samples containing different percentages of rubber powder.

In Figure 6, you can see the outcomes regarding the elastic modulus of specimens where various proportions of rubber powder have been used instead of silica sand. The findings consistently show a clear pattern: when the percentage of rubber powder replacement rises, there is a corresponding decrease in the elastic modulus of the specimens. The specimens that do not contain any rubber powder exhibit the highest elastic modulus, measuring at 35.8 GPa. Conversely, the specimens with 50% rubber powder replacement demonstrate the lowest elastic modulus, measuring at 22.7 GPa.

Figure 7 provides a visualization of the results concerning the elastic modulus from samples incorporating different proportions of waste wire derived from rubber. A noticeable pattern emerges, indicating that as the percentage of waste wire in the samples increases, the elastic modulus also rises. This striking effect can be attributed to the waste wire's ability to deter brittle failure within the samples. It's worth noting that samples containing 3% waste wire exhibit the highest elastic modulus, measuring an

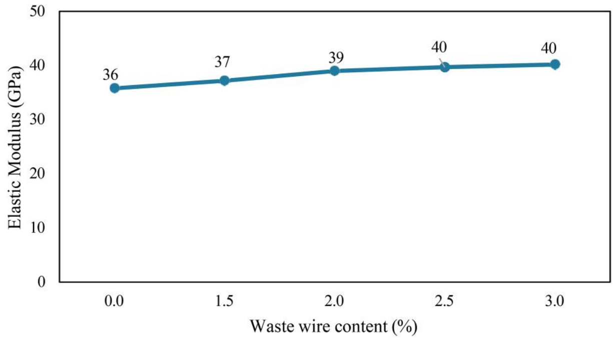

Figure 7. Elastic modulus of samples incorporating various percentages of wire waste in conjunction with a constant 10% rubber powder content.

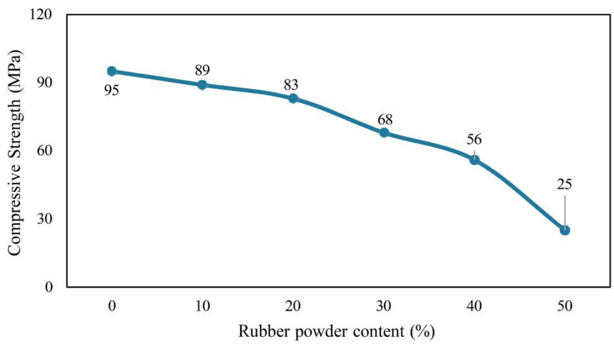

Figure 8. Compressive strength of samples containing different percentages of rubber powder.

impressive 40.2 GPa. In contrast, samples devoid of waste wire display a comparatively lower elastic modulus of 35.8 GPa.

Figure 8 presents the results of the compressive strength of samples containing different percentages of rubber powder as a replacement for silica sand. The data reveals a notable trend: as the percentage of rubber powder substitution increases, the compressive strength of the samples decreases. The samples without any rubber powder exhibited the highest compressive strength, reaching 96 MPa. In contrast, samples containing 50% rubber powder displayed the lowest compressive strength of 25 MPa. This decline in compressive strength can be attributed to the weakening of the bond between the cement matrix and aggregates as the replacement percentage of rubber powder increases.

Based on the findings in Figure 8, it can be concluded that samples containing 50% rubber powder as a substitute for silica sand do not meet the required compressive strength standards for high-strength concrete applications. The excessive decrease in compressive strength observed when replacing more than 40% of silica sand with rubber powder indicates that using percentages higher than 40% of rubber powder is not recommended.

Furthermore, Figure 9 illustrates the compressive strength results obtained from samples incorporating different percentages of rubber wire waste. A discernible trend can be observed, indicating that the compressive strength of the samples increases as the percentage of waste wire used increases. As a result of the waste wire's ability to prevent brittle failure within the samples, this noteworthy effect occurs. Waste wire reinforces concrete and enhances its load-bearing capacity. In samples with a high percentage of waste wire, rigid elements improve compressive strength as their presence increases. It can be noted that samples containing 3% waste wire exhibit the highest compressive strength, measuring an impressive 106 MPa. In contrast, samples without any waste wire display a comparatively lower compressive strength of 89 MPa. These findings highlight the significant influence of waste wire on the compressive strength of the concrete samples.

The reduction in compressive strength due to the higher proportion of rubber powder is influenced by several factors. The poor bonding between rubber particles and cement paste, as previously

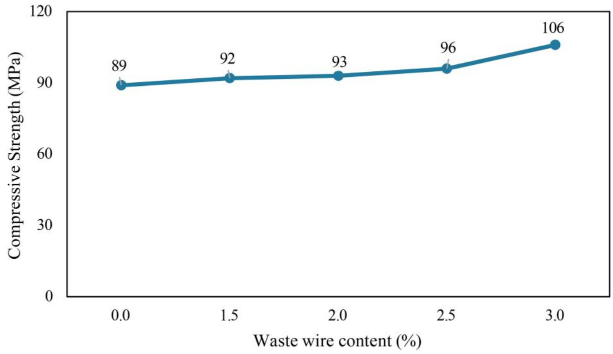

Figure 9. Compressive strength of samples incorporating different percentages of rubber wire waste in conjunction with a constant 10% rubber powder content.

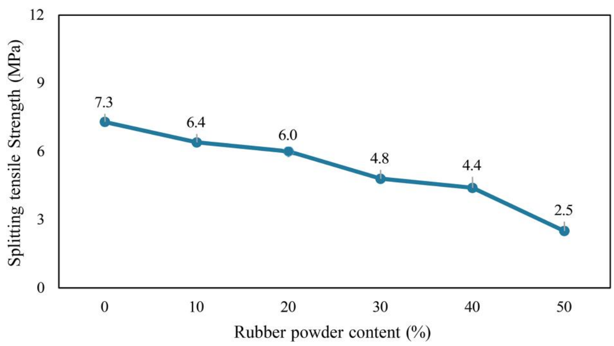

Figure 10. Splitting tensile strength of samples containing different percentages of rubber powder.

mentioned, leads to a weak ITZ, initiating and propagating cracks under load. Additionally, the lower modulus of elasticity of rubber particles compared to traditional aggregates reduces the overall stiffness of the concrete, further diminishing its compressive strength. The differential deformation between rubber particles and the surrounding matrix creates micro-cracks that coalesce under continued loading, resulting in a significant loss of strength.

To address these issues, potential solutions include surface modification techniques to improve the compatibility of rubber particles with the cement paste. By enhancing the bonding between these materials, the adverse effects on compressive strength can be mitigated. Additionally, optimizing mix proportions by balancing the rubber content with other aggregates or admixtures could maintain the benefits of using rubber powder while retaining the necessary compressive strength for HPC applications.

3.1.3. Splitting tensile strength

Figure 10 displays the results of the splitting tensile strength tests conducted on samples with various percentages of rubber powder as a replacement for silica sand. As the percentage of rubber powder increased in place of silica sand, a notable decrease in splitting tensile strength was observed. The base sample exhibited the highest splitting tensile strength, measuring at 7.3 MPa. Conversely, samples containing 50% rubber powder displayed the lowest splitting tensile strength, measuring at 2.5 MPa. This decline in splitting tensile strength can be attributed to the weakening of the bond between the cement matrix and the aggregates, which occurs with an increasing proportion of rubber powder replacing silica sand.

The results indicate that samples with 10%, 20%, 30%, 40%, and 50% rubber powder exhibited decreases in splitting tensile strength by approximately 11%, 16%, 33%, 39%, and 65%, respectively, as compared to the base sample. Moreover, Figure 11 presents the results of the splitting tensile strength tests conducted on samples incorporating different percentages of waste wire. It can be seen that as the

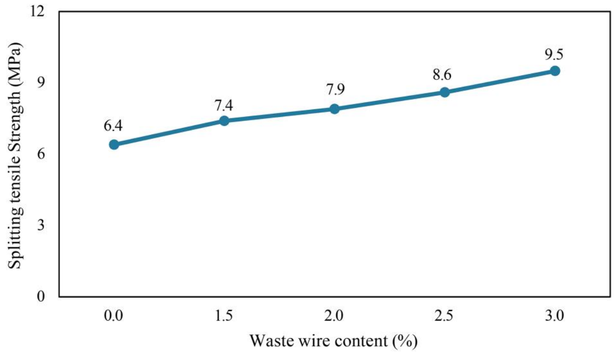

Figure 11. Splitting tensile strength of samples incorporating different percentages of rubber wire waste in conjunction with a constant 10% rubber powder content.

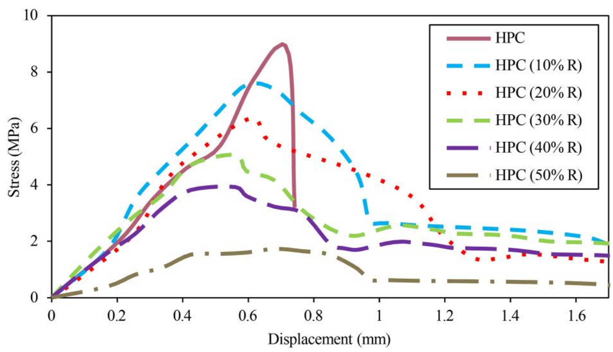

Figure 12. Stress-displacement curves of samples containing different percentages of rubber powder.

percentage of wire used increased, the splitting tensile strength of the samples also increased. Notably, the samples containing 3% waste wire exhibited the highest splitting tensile strength, reaching 9.6 MPa. On the other hand, the samples without waste wire (with 10% rubber powder as a substitute for silica sand) displayed the lowest splitting tensile strength, measuring at 6.4 MPa. This observation can be attributed to the positive impact of waste wire reinforcement on the mechanical properties of HPC.

Employing wire waste as reinforcement for High-Performance Concrete (HPC) at fractions of 1.5%, 2%, 2.5%, and 3% resulted in a visible increase in tensile strength. Specifically, the tensile strength improved by 15%, 24%, 35%, and 50%, respectively, in contrast with the base sample. One key advantage is the ability of waste wire to facilitate the closure of both macro and micro cracks, thereby delaying crack propagation. By incorporating a higher percentage of waste wire, the samples exhibited enhanced crack resistance and improved load-bearing capacity, resulting in higher splitting tensile strength. The presence of waste wire effectively bridges the cracks within the concrete matrix, offering increased structural integrity and overall strength. Hence, the progressive increase in splitting tensile strength with a higher proportion of waste wire emphasizes its role as a reinforcement material in enhancing the mechanical performance of HPC.

To optimize the mechanical properties of HPC containing rubber powder and waste wire, the following strategies are proposed. Surface modification of rubber particles could enhance their bonding with the cement paste, potentially improving both tensile and flexural strengths. Techniques such as chemical treatments or the use of coupling agents could increase the polarity of rubber particles, making them more compatible with the hydrophilic nature of cement.

Moreover, optimizing the mix proportions by carefully balancing the amount of rubber powder and waste wire can lead to a more favorable outcome. For instance, using a combination of rubber powder with other high-strength aggregates or fibers could counteract the reduction in strength, while still achieving the environmental benefits associated with rubber utilization. Future research could focus on refining these strategies to maximize the performance of sustainable HPC formulations.

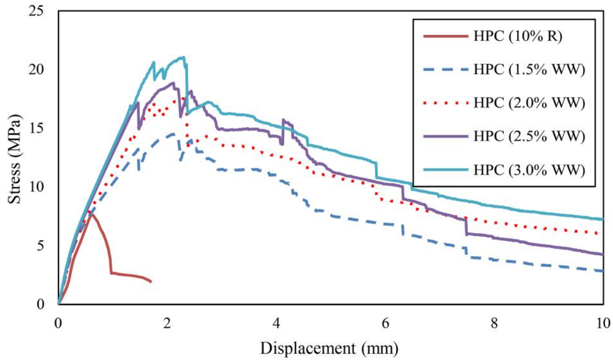

Figure 13. Stress-displacement curves of samples incorporating different percentages of rubber wire waste in conjunction with a constant 10% rubber powder content.

3.1.4. Flexural test

3.1.4.1. Stress-displacement curves. Figure 12 presents the stress-displacement curves of samples with various percentages of rubber powder. The impact of including rubber powder is evident in the displacement stress curves, revealing three clear stages: the pre-cracking phase, the hardening stage (from cracking loads to maximum load), and the softening stage (from maximum loads to ultimate load). Furthermore, a noticeable trend is the decrease in the maximum load corresponding to an increase in the percentage of rubber powder. This trend notes that the highest load-carrying capacity was achieved in HPC samples without the addition of rubber, indicating the development of a more densely compacted cement matrix in those samples.

Besides, the results reveal that as the percentage of rubber powder increased from 10% to 50% in the HPC samples, the area under the stress-displacement diagram decreased. Although it was possible to achieve similar displacements across all replacement percentages, the load corresponding to the maximum load diminished with higher replacement percentages. Consequently, this reduction in the load resulted in a decrease in the overall area covered by the stress-displacement diagram.

The stress-displacement curves for samples incorporating various percentages of used waste wire are illustrated in Figure 13. The results reveal that as the percentage of waste wire used increased, the surface area under the load-displacement diagram after the maximum load also increased. This observation suggests that samples with higher proportions of wire fragments exhibited a more gradual and softer fracture behavior, as evidenced by the larger softening area on the stress-displacement diagram. Furthermore, it can be observed that as the percentage of wire used increased, the maximum load in the load-displacement curves also increased. This indicates that the incorporation of waste wire as reinforcement in the HPC samples effectively delays the initiation and propagation of cracks, ultimately leading to an increase in the maximum load experienced by the concrete. The presence of waste wire reinforcement contributes to the enhanced load-bearing capacity of the HPC specimens.

3.1.4.2. Flexural strength. Figure 14 displays the flexural strength of samples with various percentages of rubber powder. The results reveal that the highest bending strength was observed in samples without any rubber powder, measuring at 8.75 MPa. Conversely, the samples containing 50% rubber powder showed the lowest bending strength (1.7 MPa). This discovery is in harmony with prior academic studies, as reported in the literature (Ali et al., 2020; Bahmani & Mostofinejad, 2023b; Mostofinejad et al., 2023b; Saikia & De Brito, 2012; Shi & Day, 1996; Siddique et al., 2008; Yadav et al., 2008).

The flexural strength results of samples reinforced with different percentages of waste wire are presented in Figure 15. With waste wire reinforcement of 1.5%, 2%, 2.5%, and 3%, HPC flexural strength increased significantly. As the percentage of waste wire increased, the flexural strength improved by approximately 89%, 128%, 146%, and 175%, respectively, compared to samples without any wire reinforcement.

Moreover, the samples reinforced with 3% waste wire exhibited the highest bending strength of 21 MPa, which is approximately three times higher than the samples without any wire reinforcement. On

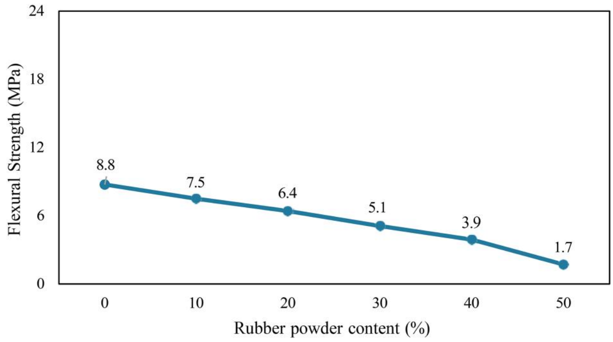

Figure 14. Flexural strength of samples containing different percentages of rubber powder.

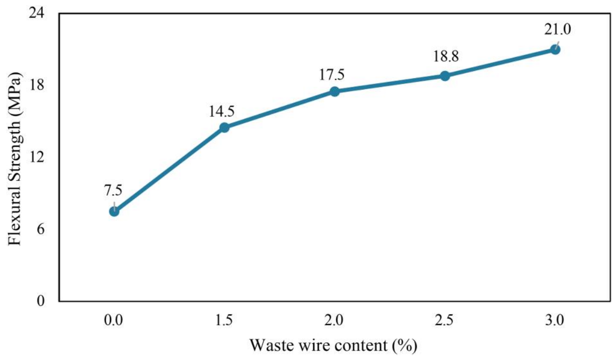

Figure 15. Flexural strength of samples incorporating different percentages of rubber wire waste in conjunction with a constant 10% rubber powder content.

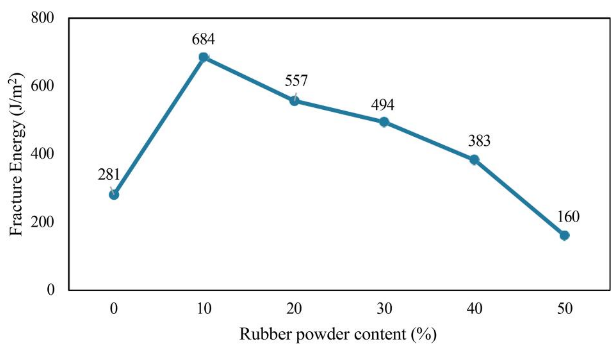

Figure 16. Fracture energy of samples containing different percentages of rubber powder.

the other hand, the samples devoid of any wire reinforcement, specifically those containing 10% rubber powder, demonstrated the lowest bending strength, measuring at 7.65 MPa.

3.1.4.3. Fracture energy. Bazant (Bazant, 2003) formulated the equations for concrete fracture energy, expressed as Equations (1) and (2).

$$P_0 = {}^{4M_0}\!/_{S} \quad (1)$$

$$W_F = W_0 + 2P_0\mu_0 \quad (2)$$

where S denotes the distance between the two bottom supports, μ_0 represents the maximum displacement at the midpoint of the span. The presence of the specimen's self-weight induces the moment M_0,

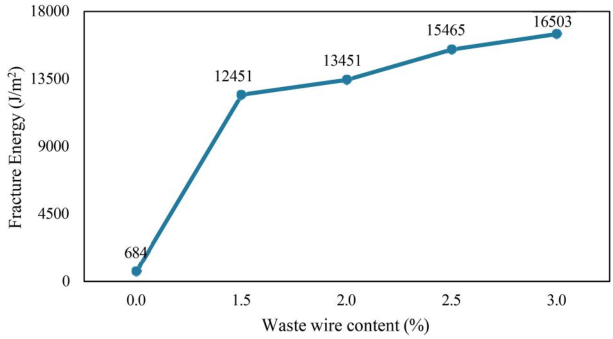

Figure 17. Fracture energy of samples incorporating different percentages of rubber wire waste in conjunction with a constant 10% rubber powder content.

and W_0 corresponds to the area under the load-displacement curve. The fracture energy can be calculated using Equation (3).

$$G_F = {}^{W_F}\!/_{A} \tag{3}$$

By employing Equation (8), the fracture energy of the concrete specimen can be computed. This parameter serves as a valuable metric in assessing the material's resistance to crack propagation and its ability to absorb and dissipate energy under loading conditions.

Figure 16 depicts the fracture energy results of HPC samples incorporating different percentages of rubber powder. The results highlight that among the different replacement percentages of rubber powder with aggregates, the utilization of 10% rubber powder yields the highest fracture energy, measuring at 684.4 J/m^2. Moreover, it can be observed that an increase in the replacement percentage of rubber powder from 10% to 50% leads to a significant decrease in fracture energy, amounting to approximately 75%. This finding aligns with previous scholarly investigations (Alsheyab et al., 2023; Li et al., 2024; Moolchandani et al., 2024; Mostofinejad et al., 2023a).

The results of fracture energy for samples incorporating different percentages of waste wire as reinforcement are presented in Figure 17. The results demonstrate a notable increase in the fracture energy of the samples as the percentage of waste wire used for reinforcement rises. When wire waste was used as reinforcement for High-Performance Concrete (HPC) at dosages of 1.5%, 2%, 2.5%, and 3%, there was a significant enhancement in the fracture energy. Specifically, it increased by factors of 17, 19, 21, and 23 times, respectively, as compared to the base sample. This enhancement in fracture energy is attributed to the role of waste wire reinforcement in retarding crack propagation within the cement matrix. As a result, the area beneath the load-displacement diagram after the cracking point expands, leading to an increase in the fracture energy exhibited by the samples.

3.2. Microstructure of HPC

Figure 18 illustrates the results of SEM results of samples of HPC, wherein rubber powder was used as a substitute for silica sand at different percentages: 0%, 10%, and 50%. The chosen percentages were based on the observation that the samples without any rubber powder (0% content) exhibited the highest compressive strength. Conversely, the samples containing 50% rubber powder demonstrated the lowest compressive strength. Notably, among the different ratios tested, the samples with 10% rubber powder displayed the most favorable compressive strength outcomes as compared to the base samples. Consequently, these samples were selected for further investigation into the bonding characteristics between aggregates and the cement matrix.

The weakening of the bond between aggregates and the cement matrix is primarily attributed to the higher proportion of rubber powder. This study delves deeper into the microstructural changes induced by this modification, with a focus on the implications for calcium-silicate-hydrate (C-S-H) bonds. Scanning Electron Microscopy (SEM) images reveal that increasing the replacement percentage of rubber powder relative to silica sand leads to a more pronounced presence of the CH hydration product. Concurrently, there is a discernible reduction in the C-S-H hydration product, which is critical for the development of

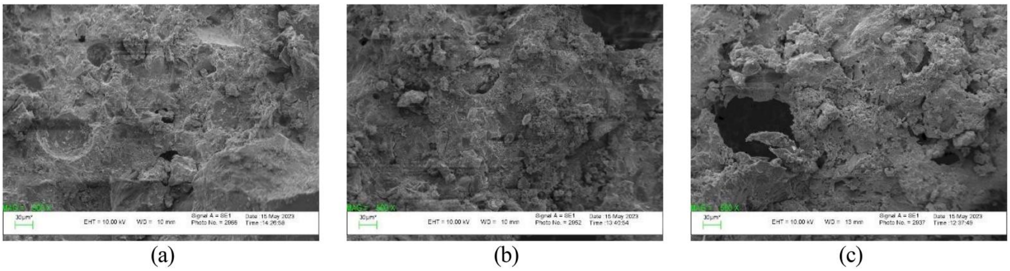

Figure 18. SEM test results for HPC (a) without rubber, (b) with 10% rubber powder, (c) with 50% rubber powder.

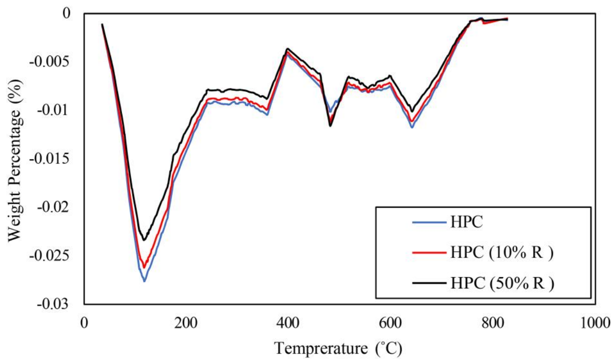

Figure 19. DTA results of samples with different percentage of rubber powder.

strength in the cement matrix. The SEM analysis also shows that the samples containing 50% rubber powder exhibit a weakened bond between aggregates and the cement matrix. This observation is consistent with the mechanical testing results, where these samples demonstrated a notable decline in compressive strength.

To elucidate the underlying mechanisms, we refer to recent studies that have explored the dynamic mechanical properties of C-S-H and its response to changes in composition and environmental conditions (Bahmani & Mostofinejad, 2023a; 2023d; 2024; Hajiaghamemar et al., 2022; Mostofinejad et al., 2023c). These studies suggest that the interlayer water in C-S-H plays a pivotal role in its mechanical properties, with the removal of water molecules leading to a significant reduction in volume and modulus of elasticity (Bahmani & Mostofinejad, 2023a; 2023d; 2024; Hajiaghamemar et al., 2022; Mostofinejad et al., 2023c). Furthermore, the interaction of calcium ions within the interlayer region of C-S-H is crucial for its structural integrity. It is plausible that the incorporation of rubber powder alters the hydration dynamics, potentially affecting the distribution and state of interlayer water in C-S-H, thereby impacting its mechanical properties.

The control samples, devoid of rubber powder, displayed the densest microstructure, as evidenced by SEM. This denser microstructure is likely responsible for the superior compressive strength observed in these samples. The contrast between the control samples and those with rubber powder substitution underscores the influence of rubber powder on the microstructure and, consequently, the mechanical properties of the cement matrix. Future work will aim to quantify these effects using advanced characterization techniques and to explore the potential of modifying the rubber powder to mitigate its adverse impact on the C-S-H bonds.

3.3. Thermal properties

To investigate the factors contributing to the highest compressive strength in samples without rubber powder and the lowest compressive strength in samples containing 50% rubber powder, DTA was conducted. Figure 19 illustrates the DTA results which allow for a closer examination of the thermal properties and weight changes in the samples.

Previous research has indicated that the weight loss observed before 200 °C in TGA data corresponds to the interlayer water content within cementitious binders, particularly the C-S-H phase (Abdulkareem et al., 2018). Furthermore, the weight loss occurring between 300-600 °C is attributed to the decomposition of portlandite ($Ca(OH)_2$). The results indicate that the samples without rubber powder exhibited the highest amount of C-S-H hydration products. Conversely, the samples containing 50% rubber powder displayed the lowest quantity of C-S-H. These findings align with the results obtained from the SEM analysis, thus corroborating the influence of C-S-H hydration on the compressive strength trends observed in the samples without rubber powder.

The DTA analysis provides further insight into the interplay between the composition of the samples and their compressive strength characteristics. The higher amount of C-S-H hydration products in the samples without rubber powder signifies the presence of a more substantial binder phase, facilitating enhanced bonding and resulting in the highest compressive strength. On the other hand, the reduced quantity of C-S-H in the samples containing 50% rubber powder substantiates the weakened bond between the aggregates and the cement matrix, contributing to the lowest compressive strength observed in those samples.

3.4. Environmental impacts

Figure 20 illustrates the embodied carbon footprint for the HPC samples containing different percentages of rubber powder. Concrete production can be mitigated by adding rubber powder and waste wire (Li et al., 2021; Long et al., 2018; Shao et al., 2023; Shi et al., 2021) to concrete mixtures. Rubber powder can be used as a replacement for silica sand in this study, which confirms this notion.

The results indicate that carbon footprint values decrease as the percentage of rubber powder increases in the samples. This indicates that incorporating more rubber powder into the HPC mix reduces its carbon footprint. The highest carbon footprint is observed in the sample with 0% rubber powder, while the lowest carbon footprint is in the sample with 50% rubber powder. Moreover, by substituting silica sand with rubber powder, the demand for finite natural resources is decreased. Furthermore, this substitution also helps curtail the release of toxic chemicals into the atmosphere, promoting a cleaner and healthier environment.

The strength per environmental impact for the HPC samples containing different percentages of rubber powder is presented in Figure 21. It is observed that as the proportion of rubber powder increases in the HPC mixtures, there is a decline in compressive strength. However, this reduction in compressive strength can be counterbalanced by the corresponding decrease in embodied carbon emissions. Remarkably, the sample containing 20% rubber powder exhibits the highest impact resistance among all the samples. The strength per environmental impact values shows a trend as the percentage of rubber powder changes. Initially, as the percentage of rubber powder increases up to 20%, there is a noticeable improvement in the strength per impact. This suggests that incorporating rubber powder in the HPC mixture enhances its ability to withstand impact forces. However, beyond the 20% threshold, a significant decline in the strength per environmental impact is observed. In fact, when the rubber powder content surpasses 30%, the reduction in strength per environmental impact becomes even more pronounced.

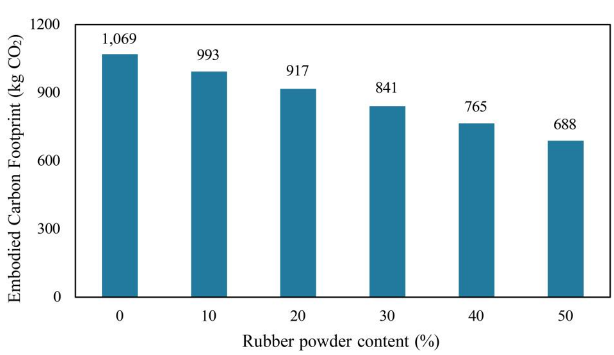

Figure 20. Embodied carbon footprint of HPC samples containing different percentages of rubber powder.

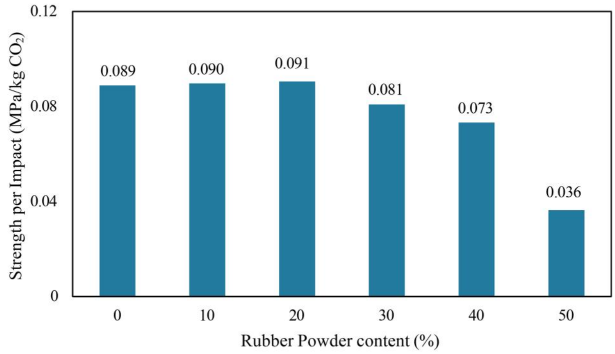

Figure 21. Strength per environmental impact for the HPC samples containing different percentages of rubber powder.

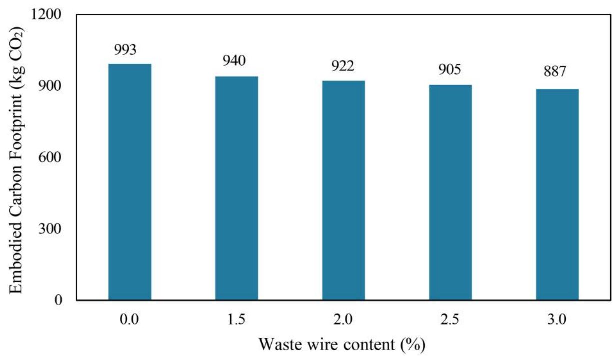

Figure 22. Embodied carbon footprint of HPC samples containing different percentages of waste wire.

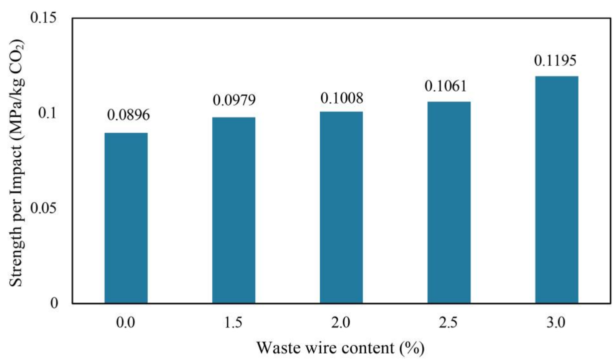

Figure 23. Strength per environmental impact for the HPC samples containing different percentages of waste wire.

Figure 22 displays the embodied carbon footprint of HPC samples containing different percentages of waste wire. The sample incorporating 3% waste wire exhibits the lowest carbon footprint, whereas the sample without any waste wire registers the highest carbon footprint. This implies that incorporating waste wire as reinforcement in HPC can be an effective way to mitigate the environmental impact linked with concrete production. This highlights the potential of waste wire as an effective strategy for mitigating the environmental impact associated with concrete production. HPC samples demonstrate a significant reduction in carbon footprint by using waste wire for reinforcement.

Furthermore, Figure 23 presents the strength per impact for the HPC samples containing different percentages of waste wire. Notably, the inclusion of waste wire in HPC concrete not only enhances impact resistance but also helps in minimizing its environmental footprint. The highest strength per impact is observed in the sample with 3% waste wire, while the lowest value is seen in the sample with 0% waste wire. This suggests that the inclusion of waste wire in the HPC mixture enhances its ability to withstand impact and improves its overall durability.

3.5. Real-world applications and limitations

The integration of waste materials, such as rubber powder and waste wire, into High-Performance Concrete (HPC) offers promising avenues for sustainable construction practices. The enhanced mechanical properties, including improved tensile strength, ductility, and fracture energy, make these materials suitable for a range of structural applications, from residential buildings to complex infrastructure projects like bridges and highways. The use of rubber powder and waste wire not only contributes to waste management by recycling industrial by-products but also aligns with global efforts to reduce the carbon footprint of construction activities.

However, the application of these materials in HPC is not without limitations. The study revealed that while rubber powder can reduce the density and carbon footprint of concrete, its higher proportions lead to a significant reduction in compressive strength, making it unsuitable for certain high-strength applications. Additionally, the long-term durability and performance of HPC containing these waste materials require further investigation, particularly in diverse environmental conditions. The potential variability in the quality and properties of waste materials also poses challenges for consistent performance in real-world applications.

Future research should focus on addressing these limitations by optimizing mix designs, improving the compatibility of waste materials with cementitious matrices, and conducting long-term durability studies. Despite these challenges, the use of waste rubber and wire in HPC holds considerable potential for advancing sustainable construction practices, provided that these materials are used judiciously and with a thorough understanding of their effects on concrete properties.

3.6. Comparative analysis with existing literature

This section provides a contextual analysis that underscores the novelty and significance of our research on sustainable high-performance concrete (HPC) using tire rubber powder and waste wire.

Our approach to enhancing the mechanical properties and sustainability of HPC by substituting silica sand with rubber powder and reinforcing with waste wire is consistent with recent advancements in the field. For instance, a study published in MDPI's Buildings journal explored the use of crumb rubber and mineral additions as partial substitutes for natural fine aggregates and cement in concrete (Moolchandani et al., 2024). They found that specific mix proportions could achieve comparable compressive and split tensile strength to the control mix, with an improvement in flexural strength due to the pozzolanic action of silica fume and the filler effects of marble slurry powder and fly ash. This aligns with our findings where the optimal use of waste wire significantly enhanced various mechanical parameters.

Another study in the same journal investigated the effect of waste crumb rubber aggregate proportions on tensile and flexural properties of ultra-high-performance alkali-activated concrete (Li et al., 2024). They concluded that a crumb rubber replacement ratio exceeding 35% led to a reduction in both tensile and flexural strengths, which is consistent with our observation that exceeding a 40% rubber powder substitution level resulted in a substantial decline in compressive strength.

Furthermore, findings on the environmental benefits of using rubber powder resonate with the literature that highlights the potential of using waste materials to reduce the carbon footprint of concrete. The reduction in the embodied carbon footprint with the incorporation of rubber powder and waste wire as reinforcement is a significant contribution to the field, offering a sustainable alternative to traditional concrete formulations.

The microstructural analysis conducted in our study, which indicated a weakening of the aggregate-cement bond and a reduction in C-S-H gel with increased rubber content, is a novel aspect that adds to the understanding of the material's behavior. While other studies have examined the durability and elastic properties of fiber-supported concrete with waste rubber aggregates (Alsheyab et al., 2023), our detailed SEM and DTA analysis provides a deeper insight into the microstructural changes occurring within the concrete matrix.

In summary, this research contributes to the growing body of knowledge on sustainable concrete by providing a comprehensive assessment of mechanical and microstructural properties, as well as environmental impacts. The comparative analysis with existing literature establishes the novelty of the approach in optimizing the use of waste materials for sustainable construction, highlighting the delicate balance required for optimized concrete performance and environmental conservation.

4. Conclusion

This research focuses on the development of sustainable HPC by incorporating rubber powder and waste wire. To assess the mechanical and microstructural properties of the concrete, comprehensive tests were conducted, including compressive, splitting tensile and flexural strength as well as SEM and TGA tests. Moreover, the environmental impacts of the developed concrete were assessed through a carbon footprint analysis. The findings of the research are outlined as follows:

1. Higher rubber powder content in HPC reduced density, while adding waste wire increased it; for example, 3% waste wire resulted in a density of 2533 kg/m^3, compared to 2324 kg/m^3 with no waste wire.
2. Compressive strength in HPC peaked at 95 MPa without rubber powder but dropped to 25 MPa at 50% rubber content, suggesting a limit of 40% rubber for optimal strength. Conversely, 3% waste wire reinforcement increased strength to 106 MPa.
3. The sample containing 3% waste wire demonstrated the highest splitting tensile strength, at 9.5 MPa. In contrast, the samples with 50% rubber powder as a substitute for silica sand exhibited the lowest splitting tensile strength, at only 2.5 MPa. It is worth mentioning that the sample without any rubber powder had a splitting tensile strength of 7.3 MPa.
4. Flexural strength in HPC was highest at 21 MPa with 3% waste wire and the lowest at 1.7 MPa with 50% rubber powder, indicating that waste wire enhanced while rubber powder diminished flexural strength.
5. The utilization of higher percentages of waste wire in HPC resulted in a noticeable increase in the area under the load-displacement diagram after reaching the maximum load. This observation indicated that samples containing a greater proportion of wire exhibited a ductile failure mode. The incorporation of an optimal percentage of scrap wire as reinforcement in HPC led to a remarkable enhancement in rupture energy, with an average increase of 23 times.
6. SEM and DTA analyses indicated that increasing rubber powder in HPC weakened the aggregate-cement bond and reduced C-S-H gel, leading to diminished mechanical properties.
7. Substituting silica sand with rubber powder in HPC remarkably lowered the carbon footprint, with 20% rubber offering the best balance of impact strength and sustainability. Additionally, increasing waste wire content further reduced the carbon footprint, with 3% waste wire yielding the lowest values and highest impact strength.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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