

Enhancing Mechanical Properties of High-Performance Concrete Using Steel Waste

Ameer Ahmed Najji Al-JAMEL^{1,*}, Dr. Rafea Flaih HASSAN¹

¹ College of Engineering, University of Babylon, Hilla, Babil, Iraq.

* corresponding author: eng850.ameer.ahmed@student.uobabylon.edu.iq

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Abstract

In this study, steel waste is used as a sustainable replacement for quartz sand in high-performance concrete (HPC). Fifteen concrete mixes were prepared with 0%, 25%, 50%, 75%, and 100% as volume replacement of steel waste, with steel fibres added at 1%, 2%, and 3%. The experimental program included workability, compressive strength, splitting tensile strength, direct tensile strength, flexural strength, and density tests, in addition to microstructure analysis using scanning electron microscopy. The results showed that optimal performance was achieved when 50% of the steel waste was replaced with 3% steel fibres. The compressive strength of this mix was 118.6 MPa, the direct tensile strength was 16.62 MPa, the splitting tensile strength was 16.61 MPa, and the flexural strength was 20.16 MPa. Compared to the reference mix, compressive strength, direct tensile strength, and splitting tensile strength increased by 22.6%, 25.9%, and 36.7%, respectively. Higher replacement levels (75–100%) led to strength reductions due to weaker interfacial bonding and increased mix heterogeneity. In addition, steel waste increased concrete density, reaching heavyweight concrete at high replacement ratios. Overall, the findings indicate that a 50% replacement of quartz sand with steel waste provides the best balance between sustainability and mechanical performance in HPC.

Keywords

High-performance concrete (HPC); Steel waste; Steel fibre; Sustainability; Mechanical properties; Microstructure.

1. Introduction

High-performance concrete (HPC) has become evident as an advanced cementitious material capable of providing superior mechanical strength, durability, and long-term structural performance compared with conventional concrete. These characteristics are achieved through improved particle packing, low water-to-binder ratios, the use of supplementary cementitious materials, and the addition of steel fibres. As a result, HPC has been widely adopted in bridges, high-rise buildings, offshore structures, and other applications where high strength and durability are required.

Despite its engineering advantages, the production of HPC gives rise to environmental concerns. The extensive use of cement and natural aggregates contributes to significant carbon emissions and the depletion of natural resources.

Consequently, interest has increased in incorporating industrial by-products and recycled materials into HPC mixtures to improve sustainability while maintaining structural performance.

These properties produce a very fine and dense structure, contributing to high mechanical strength, enhanced durability, and a longer service life for concrete structures. High-performance concrete (HPC) is typically manufactured using a high cement content, silica fume, finely graded sand, quartz powder, steel fibres, and a low water-to-cement ratio. The elimination of coarse aggregate, along with improved particle packing and fine aggregate gradation, promotes exceptional homogeneity and enhanced rheological behaviour. As a result, HPC has become an important material for demanding structural applications, including long-span bridges, high-rise buildings, precast elements, transportation infrastructure, and other structures requiring high strength and durability (Yoo & Banthia, 2016; Abbas et al., 2016).

Previous studies have investigated the use of recycled fine aggregates, recycled sand, crushed glass, fly ash, ground granulated blast-furnace slag, and other waste materials as partial replacements for conventional constituents in HPC. Several researchers reported that moderate replacement levels can maintain or even improve mechanical properties, whereas excessive replacement often leads to strength reduction due to increased porosity and weaker interfacial transition zones. Likewise, the incorporation of steel fibres has been shown to enhance tensile strength, crack resistance, ductility, and overall mechanical performance of HPC.

Among the various industrial by-products, steel waste generated from machining and manufacturing operations represents a significant environmental challenge because of the large quantities produced annually and the costs of its disposal. Owing to its high density, rough surface texture, and metallic nature, steel waste has the potential to improve the mechanical performance of cementitious composites when appropriately incorporated into concrete mixtures. However, most existing studies have focused either on recycled aggregates or on the effect of steel fibres in HPC. Limited research has systematically investigated the combined effect of steel waste as a replacement for quartz sand together with different steel fibre contents on the full range of mechanical properties of HPC. Furthermore, the optimal replacement level of steel waste and its effect on concrete density and microstructural characteristics remain insufficiently understood.

High-performance concrete (HPC) achieves its exceptional mechanical properties and durability through a combination of optimized particle compaction, a low water-to-binding ratio, a high-density microstructure, improved mix homogeneity, and the addition of steel fibres. These properties collectively contribute to reduced porosity, enhanced interfacial zone (ITZ) strength, improved crack resistance, and a significant boost to the overall structural performance of the material (Shi, 2015). Although HPC offers high strength and durability, its widespread application is constrained by economic and environmental concerns. The high consumption of cement, silica fume, and fine aggregates increases both production costs and carbon emissions. In addition, the dense microstructure of HPC, while beneficial for mechanical performance and durability, may increase the risk of spalling when exposed to high temperatures, creating potential fire-safety concerns (Yoo & Yoon, 2016; Smarzewski, 2019).

Extensive research has been conducted to enhance the sustainability of HPC and UHPC through the incorporation of recycled and industrial by-products. Various studies have reported the successful use of supplementary cementitious materials and recycled constituents, such as fly ash, ground granulated blast-furnace slag, rice husk ash, recycled powder, crushed glass, and recycled aggregates, as partial replacements for conventional materials. These alternatives have been shown to reduce environmental impact by decreasing the demand for virgin raw materials and lowering overall energy consumption, while maintaining acceptable mechanical performance in cementitious systems (Zhang et al., 2018; Salahuddin et al., 2020; Chinzorigt et al., 2020; Jiang et al., 2019). In particular, it has been widely reported that recycled fine aggregate replacement levels of approximately 30–60% can achieve a balance between mechanical performance and durability, with up to 50% replacement often considered optimal in HPC systems without significant strength degradation.

Added of steel fibres has been extensively studied as a means of improving the tensile and flexural performance of cement-based composites. Experimental results have consistently demonstrated that increasing steel fibre content

enhances compressive strength, splitting tensile strength, and resistance to cracking, although excessive fibre dosages may lead to workability limitations (Salman & Hassan, 2023; Hanoon et al., 2025). Furthermore, recent studies have explored the structural advantages of HPC and UHPC in advanced applications, including beams with openings and torsional members (Ali et al., 2024; Al-Salim et al., 2024), where these materials significantly improve load-bearing capacity, stiffness, crack control, and overall structural efficiency compared with conventional concrete. Additional investigations on recycled aggregate-based HPC have also highlighted trade-offs between strength enhancement and volumetric stability, particularly in terms of shrinkage behaviour (Leng et al., 2023; Naidanjav et al., 2022).

Therefore, this study investigates the potential use of steel waste as a sustainable replacement for quartz sand in high-performance concrete. Fifteen mixes were produced using steel waste replacement ratios of 0%, 25%, 50%, 75%, and 100%, with steel fibre contents of 1%, 2%, and 3%. The experimental program included evaluating workability, compressive strength, splitting tensile strength, direct tensile strength, flexural strength, density, and microstructure properties using scanning electron microscopy (SEM).

The novelty of this research lies in the comprehensive assessment of the influence of steel waste replacement and steel fibre content on both the mechanical and microstructural performance of HPC. Unlike previous studies that primarily focused on recycled aggregates or fibre reinforcement, this work establishes the optimum steel waste replacement ratio for maximizing mechanical performance while promoting sustainable utilization of industrial waste. The results provide practical guidance for producing environmentally sustainable HPC with enhanced strength characteristics and reduced dependence on natural quartz sand.

The significance of this study extends beyond the evaluation of mechanical performance. The proposed approach contributes to sustainable construction by encouraging the reuse of steel industry waste as a substitute for natural quartz sand, thereby reducing the environmental burden associated with waste disposal and the excessive consumption of natural resources. Furthermore, determining the optimal amount of steel waste replacement provides practical guidance for producing HPC with enhanced strength properties while maintaining acceptable workability and microstructure integrity. The results of this research support the development of environmentally friendly HPC mixes and offer a practical solution for integrating industrial byproducts into modern building materials without effect on structural performance.

The primary objectives of this study are: (i) to evaluate the effect of steel waste replacement ratio and steel fiber content on the mechanical properties of HPC, (ii) to identify the optimum replacement level that maximizes performance, (iii) to investigate the corresponding microstructural characteristics by using SEM analysis, and (iv) To assess the effects of incorporating steel waste on concrete density and sustainability.

2. Materials and Methods

2.1. Cementing Materials

The study used CEM I SR 3.5–R42 5 (colours) - a special Type V cement fulfilling the requirements of PN-EN 197-1 (2012) and PN-B-19707 (2013). This cement was chosen because of its availability in the area and for it being appropriate for high-performance concrete (HPC) for chemically aggressive environments. It can be applicable for bridges, roads, airport constructions, hydrotechnical and industry constructions, ecological projects and precast invention engineering elements.

By using silica fume in production of concrete, ITZ between cement paste grain and aggregate grains can be densified for optimum characteristic. The particle size of silica fume is an ultrafine and it has a dimension of $\sim 0.1 \mu\text{m}$ which allows filling up to 99% voids, used as supplementary material in concrete leads to improved strength and durability in hardened concrete. In addition, the silica fume was characterized by a large specific surface area of $17,000 \text{ m}^2/\text{kg}$, which also contributed to microstructural refining.

For detailed reference:

Table 1 outlines the physical properties of the cement.

Table 2 provides the chemical compositions of both the cement and silica fume.

Table 1: Physical properties of cement

Material characteristics	Cement
Specific surface area [m^2/kg]	314
Water demand [%]	20
Start of setting [min]	110
End of setting [min]	160
Volume stability acc. to Le Chateliere [mm]	2
Compressive strength at 2 days [N/mm^2]	28
Compressive strength at 28 days [N/mm^2]	58
Tensile strength at 2 days [N/mm^2]	5.4
Tensile strength at 28 days [N/mm^2]	8.3

Table 2: Chemical composition of cement and silica fume in [%]

Compound	Cement	Silica Fume
SiO ₂	21.2	95
Al ₂ O ₃	3.6	1.32
Fe ₂ O ₃	4.41	0.85
CaO	63.66	0.55
MgO	1.22	0.70
SO ₃	3.06	NA
K ₂ O	0.37	1.25
Na ₂ O	0.23	0.40
Cl	0.08	NA
Loss on ignition	1.28	0.12
Insoluble matter	0.21	NA

2.2. Sand and Steel Waste

The HPC mixtures incorporated quartz sand as the natural fine aggregate, with its grain size distribution detailed in Table 3. To promote sustainability, steel waste specifically steel filings derived from machining car wheel flanges in industrial facilities was used as a partial replacement for natural sand. Different substitution ratios were tested to evaluate the effect of steel waste integration on the concrete's performance.

As shown in Figure 1, the steel waste used in this study were sieved through a table shaker of 600 μm mesh sieve to obtain a more uniform particle size distribution. In some locations, steel waste is considered a waste by-product and are discarded at the end of the working day, making them available free of charge. In other cases, they can be purchased at a relatively low cost, typically around 1 USD per 10 kg. With the continuous increase in the number of vehicles worldwide, substantial quantities of steel waste are generated during vehicle maintenance and repair operations. Consequently, this material has become widely available in large amounts and can be readily sourced from automotive service and maintenance workshops.

Steel waste has an approximate density of 6530 kg/m^3 and exhibit a high specific surface area due to their fine particle size and increased surface-to-volume ratio. They are free from oil contamination under standard conditions; however, the initially collected fraction should not be used in wheel balancing calibration due to possible contamination with lubricants or machining residues. Steel waste should be stored in a dry, low-humidity environment to minimize oxidation, as exposure to moisture and oxygen promotes the formation of iron oxides, thereby altering their physicochemical properties.

Table 3: Grading of fine aggregate

Sieve size	Passing [%]
10mm	100
4.75mm	92
2.36mm	81
1.18mm	73
600 μm	55
300 μm	24
150 μm	7

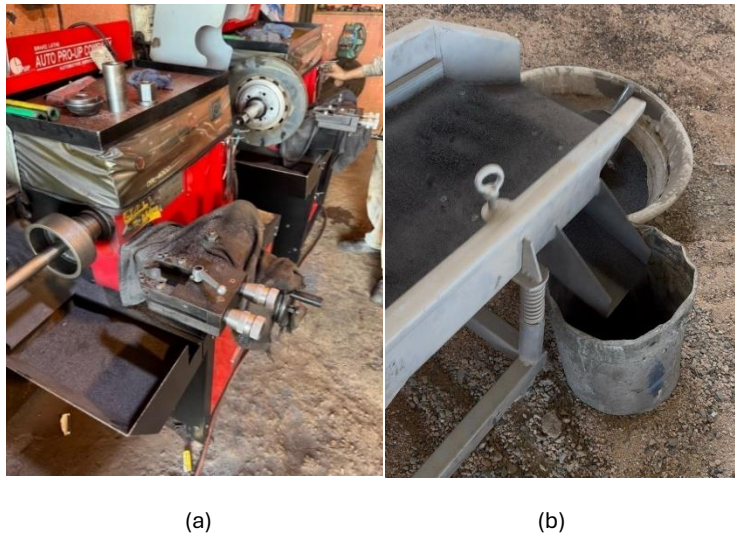


Figure 1: (a) Steel waste from industrial districts, (b) Sieving of steel waste

2.3. Steel Fibers

The microfibers have a density of approximately 7800 kg/m^3 as described in Table 4. Figure 2 shows these types of microfibers.

Table 4: Micro and hook fibres of steel characteristics

Product	Lengths, L [mm]	Diameters, D [mm]	Aspect proportion, L/D	Tensile strengths [MPa]
Micro steel fiber (WSF0213)	13	0.2	65	2860
Hooked fiber (KF 65/35)	35	0.55	64	2,200

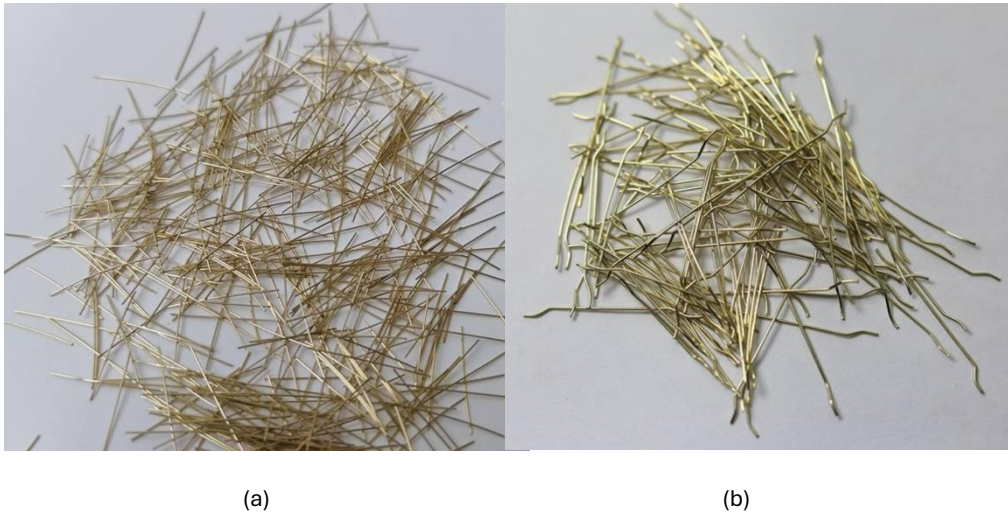


Figure 2: (a) Micro steel fibers, (b) Hooked steel fibers

2.4. Super-plasticizers

The study employed PC200 Hyperplastic, a third-generation polycarboxylate ether (PCE)-based superplasticizer, to enhance the workability and moisture efficiency of the HPC mixtures. This commercially available admixture consists of long-chain polymers and is chloride-free, ensuring compliance with ASTM C494 (2001), the industry standard for chemical admixtures in concrete.

3. Mixture Proportions

The mixture proportions for this HPC study were developed based on an extensive literature review, which identified that conventional HPC formulations typically employ high contents of cement, fine natural sand, and silica fume (Shaheen & Shrive, 2006; Wang et al., 2012).

The HPC mixture formulations in this study as shown in Table 5 contained fine quartz sand (1050 Kg/m³) passed through a sieve as listed in table3, sulphate resistance Portland cement (950 Kg/m³), superplasticizers (40 L/m³), silica fume (190 Kg/m³), and steel fibres with 1, 2, and 3% of the mix volume. The water-cementitious materials ratio (w/cm) of the mixtures was maintained at 0.22 to monitor the impact of the HPC properties. The utilized steel waste was passed through a sieve less than 2 mm. The quartz sand was substituted with steel waste in amounts of 0%, 25%, 50%, 75% and 100% of the sand volume. A light yellow polycarboxylate ethers-based, liquid superplasticizer was added to the HPC mixtures, equalling 4% of the volume of the cementitious materials, to achieve sufficient workability. The specific gravity of the material amounts to 1.07 at 20°C, contains alkali < 1.5% and chlorides < 0.1%, and does not give rise to air entrainment. The reference slump for the control mixture was 120 ± 20 mm.

Fifteen trial mixes were prepared and tested to determine the optimal mix proportions based on mechanical properties and workability requirements. The variables tested were the volume of the fibre, and steel waste proportion as replacement of sand, as shown in Table 5. Achieving a perfect mixture is crucial for High-Performance Concrete (HPC) to guarantee its proper placement in moulds by ensuring flowability and filling ability. It is important to prevent bleeding and agglomeration because they may negatively impact the HPC microstructure. Achieving a balance between these attributes optimizes the mechanical performance, including durability and strength.

Table 5: The Mixture proportions for HPC mixes

Symbol	C.[kg/m³]	S.[kg/m³]	S.F [kg/m³]	S.P [kg/m³]	W.[kg/m³]	Steel waste		Fiber	
						[%]	[kg/m³]	[%]	[kg/m³]
S01	950	1050	190	40	205	0	0	1	78.5
S02								2	157
S03								3	235.5
S251		787.5				25	777.6	1	78.5
S252								2	157
S253								3	235.5
S501		525				50	1555.2	1	78.5
S502								2	157
S503								3	235.5
S751		262.5				75	2332.8	1	78.5
S752								2	157
S753								3	235.5
S1001		0				100	3110.4	1	78.5
S1002								2	157
S1003								3	235.5

*C. cement, S. Sand, S.F. silica Fume, SP. super plasticizer, and W. Water

** water/binder ratio, or water/ cementitious materials = 0.22

4. Preparation and Casting of HPC Specimens

The quartz sand was prepared in a saturated surface dry condition prior to mixing. All mixture components were combined using a 100-liter laboratory mixer, with the mixing process lasting approximately 10 minutes for each batch. The procedure began by mixing the fine aggregates (with or without steel waste replacement) for the first 5 minutes, followed by the addition of half the required water. Subsequently, the cement, steel fibres, and silica fume were incorporated into the mixture.

After thorough mixing for an additional 5 minutes, the superplasticizer along with the remaining water was introduced to the mixer.

After mixing, the final workability of each mixture was evaluated with three slump tests, giving consistent values of 110–120 mm. The freshly prepared HPC was subsequently cast into moulds. The same mixing and compaction sequence was strictly followed for all mixtures. Identical curing regimes were used for all the specimens in order to minimize experimental variables.

The specimens were cured initially for 24 hours at room temperature ($20 \pm 2^\circ\text{C}$), and the demoulding was done thereafter. After demoulding, all the specimens were kept in a water bath at $20 \pm 2^\circ\text{C}$ until testing at 28 days. Full details of the HPC specimens (dimensional and compositional) are outlined in Table 6. This approach allowed mechanical properties across various mixture formulations to be reliably compared while keeping processing and curing variables well controlled. The specimens used in the study are shown in Figure 3.



(a)

(b)

Figure 3: HPC specimens (a) before casting, (b) after casting**Table 6:** Specimen's specifications

Test	Shape	Dimensions [mm]	Number
Compression	Cube	70×70	30
	Cylinder	100×200	15
Splitting tensile	Cylinder	100×200	15
Flexural	Beam	40×40×160	15
Direct tension	Bone	50×75×460	15

5. Results and Discussion

The fresh and hardened properties of the concrete mixtures are discussed in this section. As indicated in Table 7, the flowability and mechanical parameters, including the compressive, tensile, and flexural strengths, were measured for various mix designs. The following results and discussion investigate the impacts of different amounts of fibre and steel waste on these qualities, showing the behaviour and performance of each mix design.

5.1. Flowability (HPC)

The flowability of each HPC mixture was tested according to (ASTMC1856/C1856M-17, 2017; ASTM, C230/C230M-14, 2014; ASTM C1437-15, 2015). The mini-slump test was performed using the short cone with dimensions of 60, 70, and 100 mm for the height, top, and bottom diameters respectively. The mold was filled with fresh paste and then opened immediately to allow the paste to flow out. Fluidity was identified by taking the average of the two orthogonal diameters, as shown in Figure 4.

According to (ASTMC1856/C1856M-17, 2017), the HPC flow range is 200 to 250 mm and all the tested mixtures within these ranges. Figure 4 show the flowability test of the trial mixes of HPC. The incorporation of higher amounts of steel waste reduced the workability of the mixtures. Despite their inherent hydrophobicity, fibres and steel waste that were tested

still absorbed some water during the mixing process. As shown in Figure 5, water absorption by fibres and steel waste results in a decrease in fluidity compared to the reference non-steel waste mixture.

Table 7: Test results of mixtures

Symbol	Flowability (mini-slump test) [mm]	Compressive strength [MPa]			Tensile strength [MPa]			Hardened density [kg/m³]
		Cube [f _{cu}]		Cylinder [f' _c]	Direct tensile [f _t]	Indirect (splitting) [f _{sp}]	Flexural [f _r]	
		7days	28days	28days				
S01	242	70.19	97.84	82.77	8.41	10.26	13.86	2470
S02	240.5	74.37	110.9	89.09	8.88	10.94	16.48	2478
S03	239	77.42	112.23	96.76	13.2	12.15	20.56	2490
S251	234	79.72	107.26	96.61	12	7.72	14.56	2550
S252	233.5	84.62	122.59	102.83	11.44	12.06	18.67	2658
S253	232	85.4	123.37	103.56	11.56	12.94	19.5	2740
S501	225.5	92.37	108.71	96.7	9.92	11.65	15.22	2795
S502	224.5	94.87	111.51	112.75	13.72	14.44	19.45	2900
S503	223	96.38	140.25	118.6	16.62	16.61	20.16	3030
S751	210	80.24	112.31	97.47	8.4	10.13	15.56	3100
S752	207.5	84.56	119.7	107.31	8.8	14.81	19.89	3300
S753	206	86.88	128.8	108.08	16.52	18.13	20.56	3390
S1001	205.5	76.68	107.35	79.99	6.3	10.93	18.22	3650
S1002	202	76.85	118.26	89.03	13.28	15.07	20.22	3690
S1003	200.5	78.24	126.73	108.59	14.8	19.7	20.89	3740

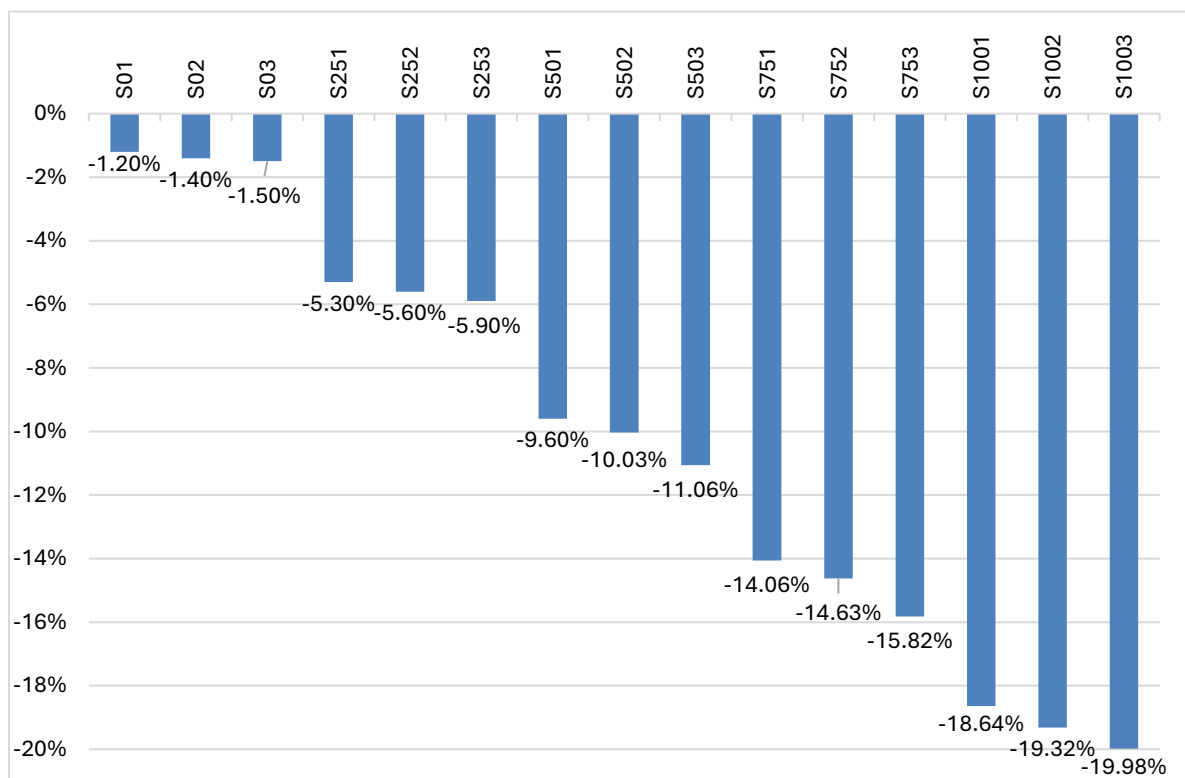


Figure 4: Percentage of decreasing flowability



Figure 5: Flowability test

5.2. Compressive Strength

At 28 days, the compressive strength of the HPC mixtures containing steel waste with steel fibre was determined. The impact of the steel waste and steel fibre content on the development of the compressive strength for cube specimens at 7, and 28 days and for cylinder specimens at 28 days can be seen in Figures 6 to 10.



Figure 6: Compressive strength test of (a) cube specimen, (b) cylindrical specimen

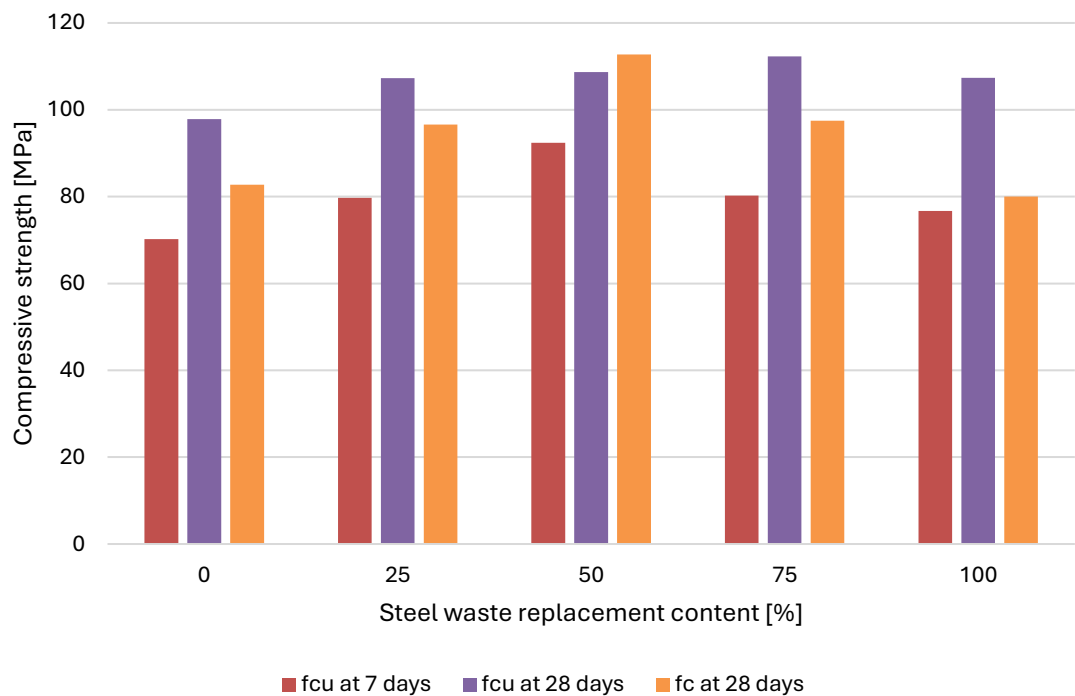


Figure 7: Compressive strength results with 1% steel fibre

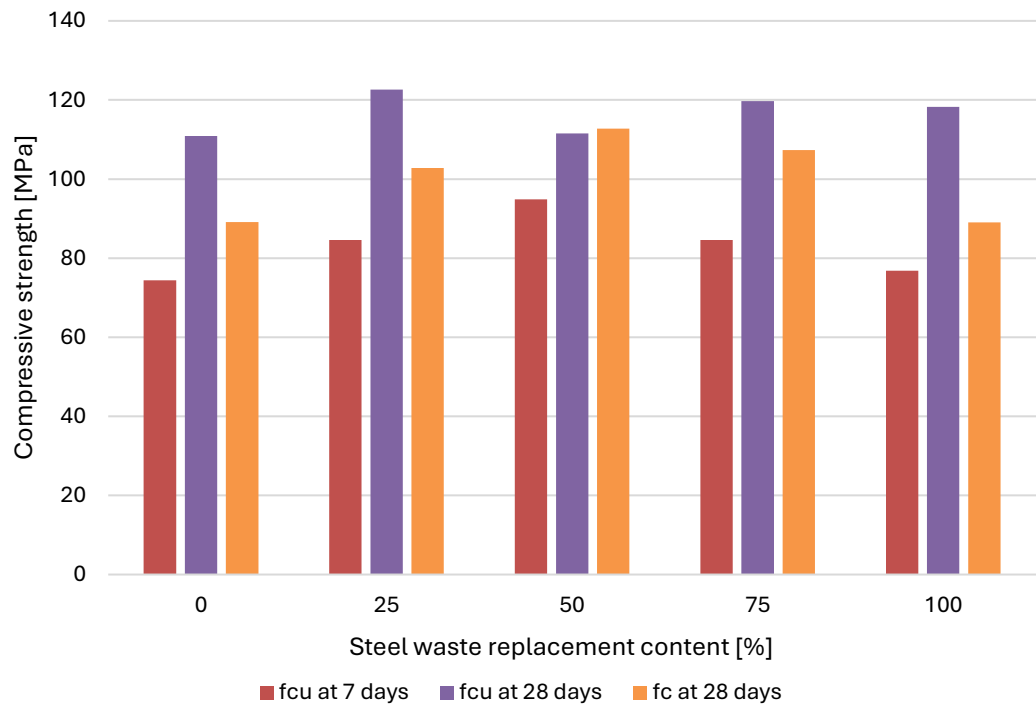


Figure 8: Compressive strength results with 2% steel fibre

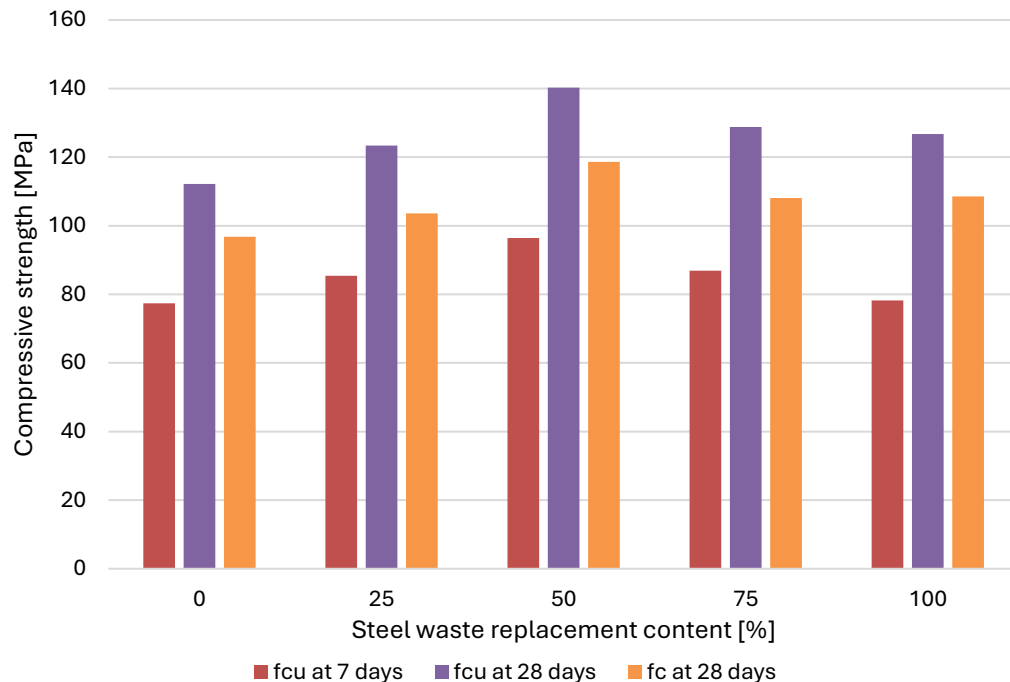


Figure 9: Compressive strength results with 3% steel fibre

The average compressive strengths for the HPC cylinder specimens at 28 days without steel waste with 1, 2, and 3% steel fibre were 82.77, 89.09, and 96.76MPa, respectively, and these results show that 1% increment in steel fibre gave 7.64 and 8.61% increment in compressive strength. Replacing steel waste with sand by 25% in volume obtained an average compressive strength of 96.61, 102.83, and 103.56Mpa for 1, 2, and 3% steel fibre respectively, and these mean 1% increment in steel fibre gave 6.44 and 0.71% increment in compressive strength. These results show that steel fibre effect reduce with increase steel waste replacement percent. Increasing replacement of steel waste to 25% made increasing in compressive strength by 16.72, 15.42, and 7.03% for 1, 2, and 3% steel fibre, respectively.

Increasing replacement of steel waste to 50% gave average compressive strength of 96.7, 112.75, and 118.6MPa for 1, 2, and 3% steel fibre, and these results mean increasing in compressive strength by 16.6 and 5.2%. Increasing replacing percent of steel waste from 25% to 50% made increasing in compressive strength by 0.01, 9.65 and 14.52% for 1, 2, and 3% steel fibre, respectively. Here, steel waste with steel fibre shows an important increasing in compressive strength.

Replacing steel waste with sand by 75% in volume obtained an average compressive strength of 97.47, 107.31, and 108.08Mpa for 1, 2, and 3% steel fibre respectively, and these mean 1% increment in steel fibre gave 10.10 and 0.72% increment in compressive strength. These results show that steel fibre effect reduce with increase steel waste replacement percent. Increasing replacement of steel waste from 50% to 75% made increasing in compressive strength by 0.80 for 1% steel fibre and decreasing by 4.82, and 8.87% for 2, and 3% steel fibre, respectively.

Full replacement of steel waste with sand and different ratio of steel fibre 1, 2, and 3%, The 28-day cylinders attained a mean compressive strength with an average value of 79.99, 89.03, and 108.59MPa respectively, and thus the increments in compressive strength were 11.30, and 21.97% for each 1% increase in steel fibre, and this increment is about twice for each 1% increase in steel fibre. Increasing replacement of steel waste from 75% to 100%, decreasing compressive strength by 17.93, and 17.03% for 1, and 2% steel fibre, respectively, and increasing by 0.47% for 3% steel fibre.

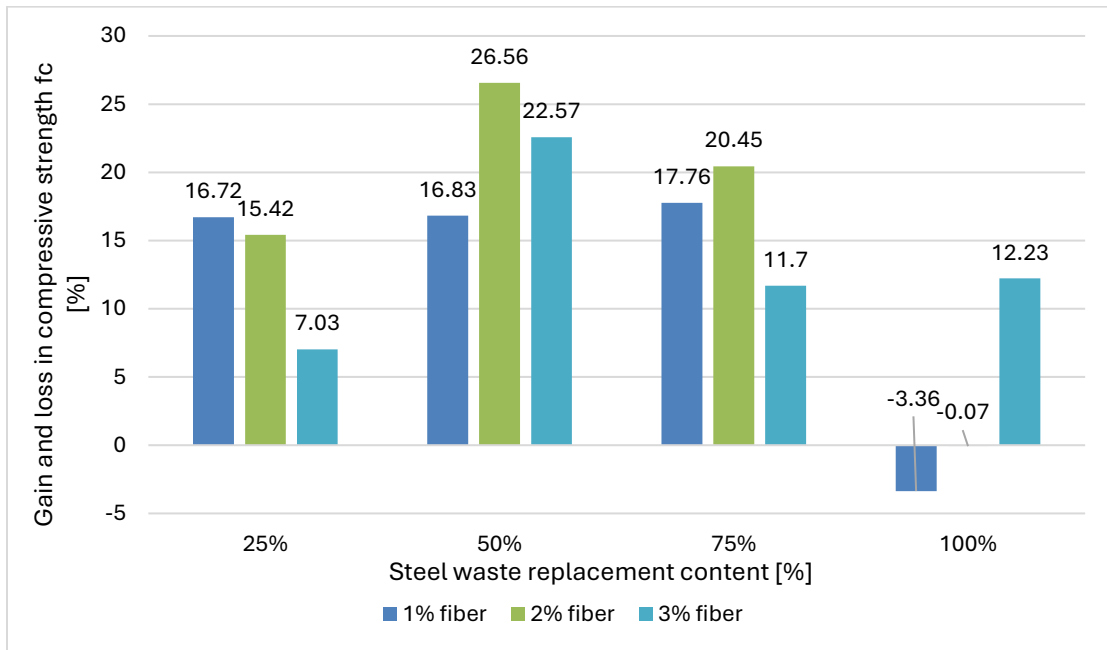


Figure 10: Percentage of changes in compressive strength of HPC mixtures

At 0% steel waste, increasing content of the steel fibre from 1% to 3% increased the 28-day cylinder compressive strength from 82.77 MPa to 96.76 MPa, corresponding to an increase of 16.9%. Similar trends were observed for all steel waste replacement levels, confirming the positive contribution of steel fibres to crack reducing and confinement.

For concrete containing 3% steel fibres, increasing the steel waste from 0% to 50% increased the compressive strength from 96.76 MPa to 118.6 MPa, representing an increase of 22.6%. Beyond 50% steel waste replacement, the strength gradually decreased, indicating that excessive steel waste adversely affected the concrete mix.

Steel waste replacement increased compressive strength up to an optimum replacement level of approximately 50%. Beyond this level, the strength decreased, excessive steel waste disrupt particle packing and weaken the bond between the cement mix and aggregate phase.

5.3. Splitting Tensile and Flexural Strength

Splitting tensile strength tests were carried out at 28 days as shown in Figure 11. Figures 12 and 13 show the differences in the splitting tensile strength of HPC with the various steel waste contents.



Figure 11: Specimen of splitting tensile strength test

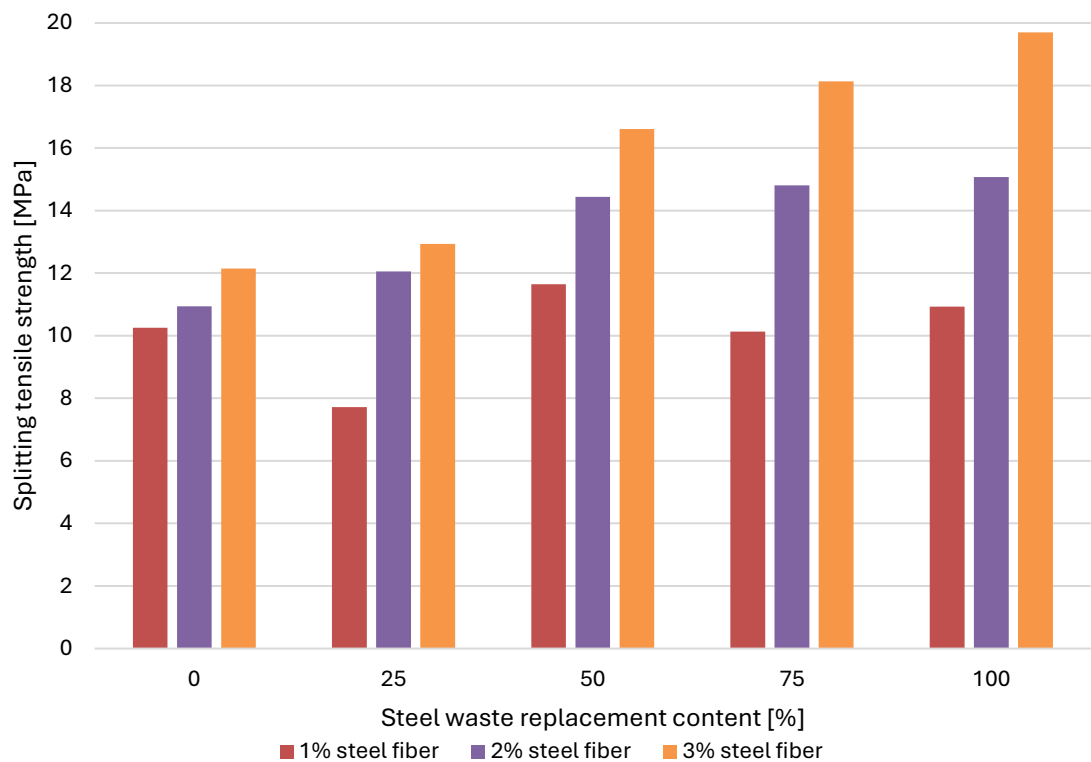


Figure 12: Splitting tensile strength results with different ratio of steel fibre and steel waste

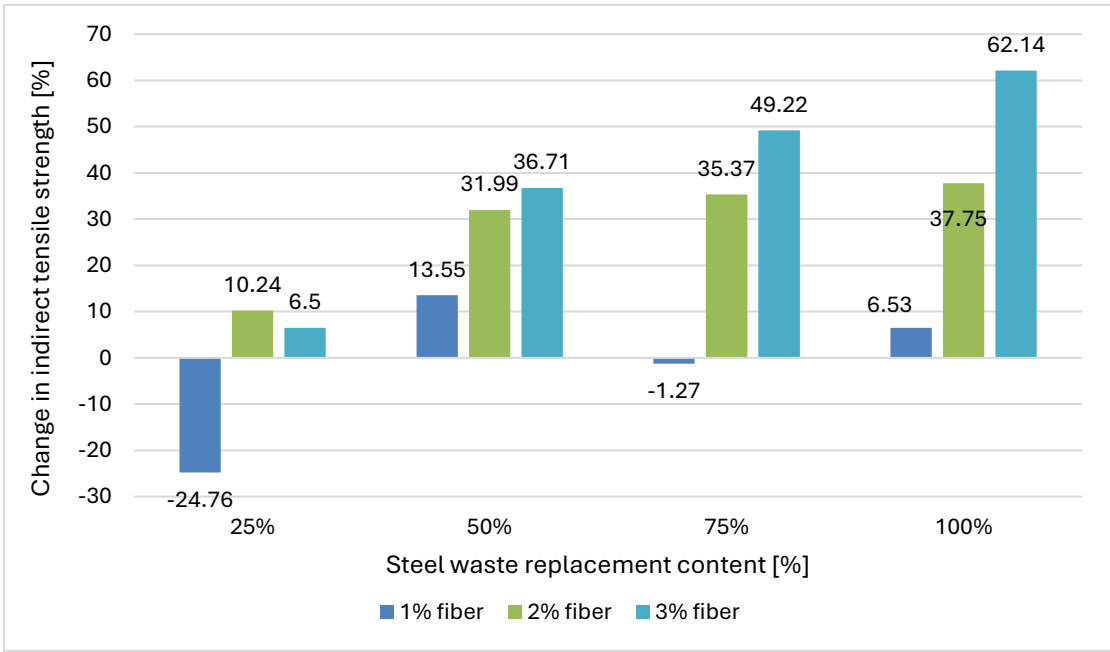


Figure 13: Percentage of change in indirect tensile strength of HPC mixes

This variation with any amounts of steel waste was quite alike to that seen as regards the compressive strength. A trend of a rise in splitting tensile strength with an increase in steel waste replacement was noticed clearly at 3% steel fibre, while splitting tensile strength became approximately equal at up to 50% of steel waste replacement with 2% steel fibre. Random results of splitting tensile strength with maximum value at 50% of steel waste when decreasing steel fibre to 1%.

At 1% steel fibre, splitting tensile strength decreased by 24.76% at 25% steel waste, then gave maximum value at 50% steel waste replacement by 13.55% increment. After that, splitting tensile strength decreased and increased by -1.27, and +6.53% at 75% and 100% steel waste replacement, respectively.

Increasing steel fibre to 2%, splitting tensile strength increased by 10.23 and 32% at steel waste 25 and 50%, respectively. Slight increases are achieved at 75 and 100% by 35.37 and 37.75%, respectively.

Uniform increasing of splitting tensile strength occurred at 3% steel fibre, these increases were 6.5, 36.71, 49.22, and 62.14% at 25, 50, 75, 100% steel waste replacement.

Flexural strength examinations were carried out at 28 days. Figures 14 and 15 plots the flexural strength against the steel waste replacement level.

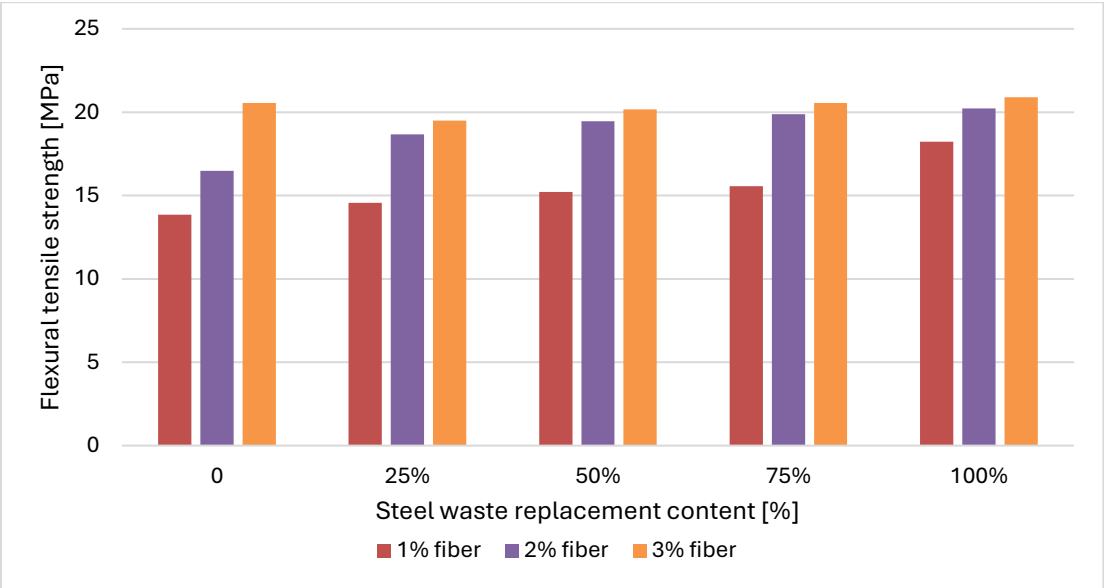


Figure 14: Flexural strength results with different ratios of steel fibre and steel waste

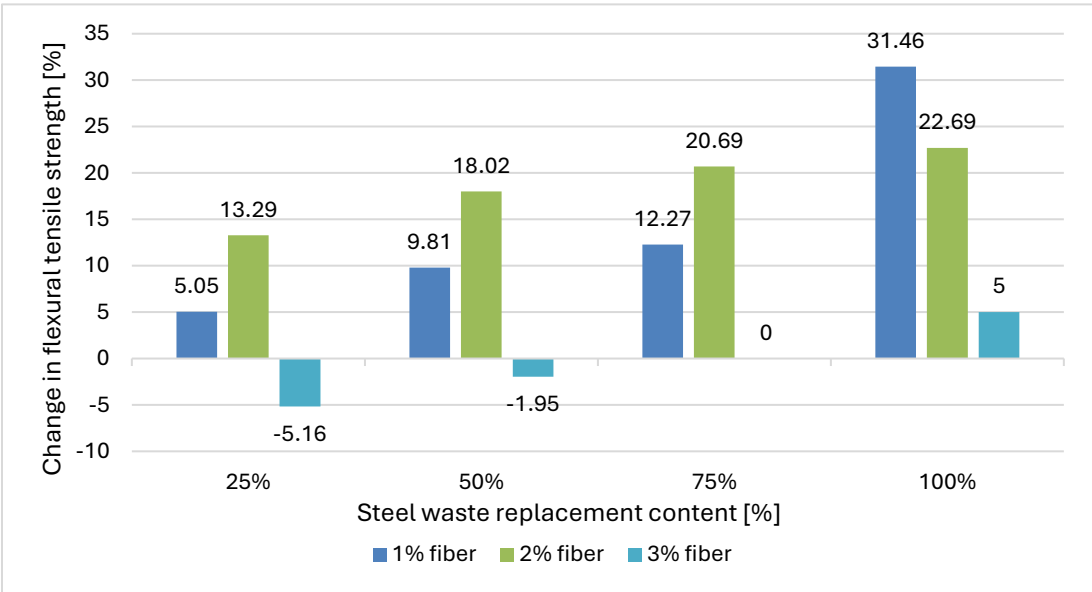


Figure 15: Percentage of change in flexural tensile strength of HPC mixes

The results displayed in Figure 14 illustrate that maximum value of flexural strength with 1% steel fibre was 35.7Mpa at 25% steel waste, while with 2 and 3% steel fibre maximum value was 41.5 and 50.7Mpa at 50% steel waste.

5.4. Direct Tensile Strength

Direct tensile strength tests were carried out at 28 days as shown in Figure 16. Figures 17 and 18 shows the differences in the direct tensile strength of HPC with the various steel waste contents. The direct tensile strength was calculated using the following formula:

$$f_d = \frac{P}{A} \quad (1)$$

Where:

f_d - direct tensile strength in MPa,

P - failure load in Newtons,

A - cross-section area (in mm^2 (50 mm x 50 mm)).

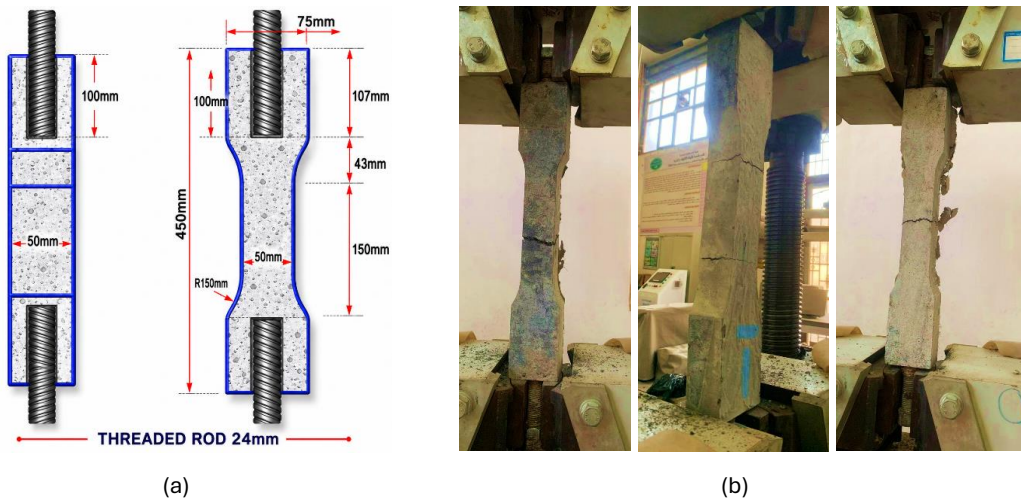


Figure 16: Direct tensile strength specimen. a) dog bone detail b) Direct tensile strength test

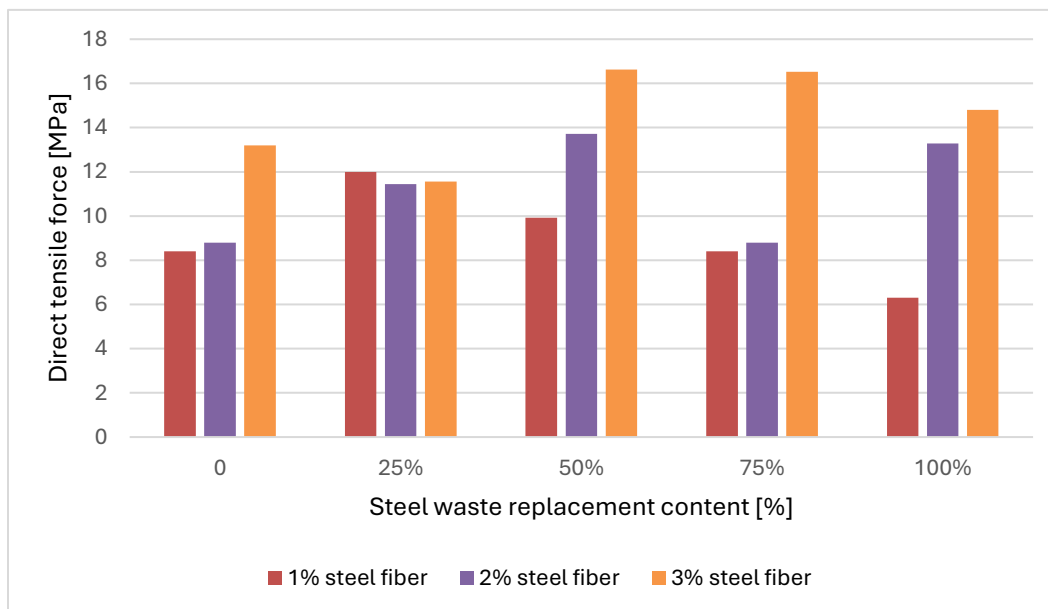


Figure 17: Direct tensile strength results with different ratio of steel fibre and steel waste

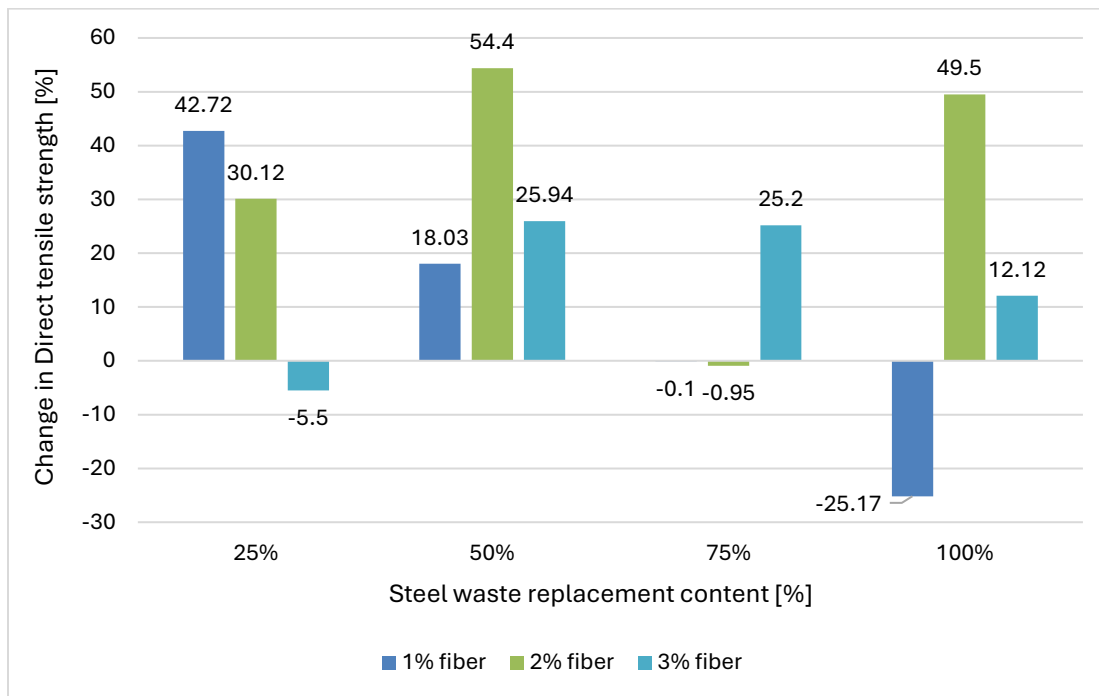


Figure 18: Percentage of changes in direct tensile strength of HPC mixes

Maximum value of direct tensile strength was at 25% steel waste for 1% steel fibre with value of 12MPa and at 50% steel waste for 2 and 3% steel fibre with values of 13.72 and 16.62MPa, respectively.

At 1% steel fibre, the increase in direct tensile strength was 42.72%, and 18.03% at 25% and 50% steel waste and decreased by 0.1% and 25.17% at 75% and 100% steel waste. At 2% steel fibre, direct tensile strength increased by 30.12%, 54.43%, and 49.48% at 25%, 50%, and 100 steel waste and decreased by 0.95% at 75% steel waste. At 3% steel fibre, direct tensile strength decreased by 5.45% at 25% steel waste and increased by 25.94%, 25.15%, and 12.12% at 50%, 75%, and 100% steel waste.

5.5. Microstructure

The microstructural characteristics of the HPC mixtures were examined using scanning electron microscopy (SEM) to identify compound formation and micro-crack development. Figure 8 presents comparative micrographs of the reference mixture (0% steel waste) and the mixture containing 50% steel waste replacement.

Visual examination of the SEM micrographs shows dense microstructures in mixtures. The mixture containing 50% steel waste exhibited a more compact appearance and a more uniform distribution of hydration products compared with the other mixtures. Furthermore, fewer visible voids and discontinuities were observed within the mix, due to improved particle packing and a denser microstructural arrangement.

The enhanced mechanical performance for the 50% steel waste mixture may be associated with the improved packing of the steel waste particles, which promoted a more homogeneous mix and more interaction between the cementitious paste and the surrounding constituents.

Although mixtures containing higher steel waste replacement levels (75% and 100%) exhibited similar surface features, but mechanical properties were reduced. This reduction may be attributed to the excessive amount of steel waste, which could adversely affect particle distribution, workability, and mix homogeneity, thereby limiting the beneficial packing effect observed at moderate replacement ratios.

It should be noted that the SEM observations presented in this study are qualitative in nature. Therefore, interpretations regarding porosity reduction, and interfacial transition zone (ITZ) characteristics are based on visual observations only. More comprehensive characterization using complementary techniques such as energy-dispersive spectroscopy (EDS), X-ray diffraction (XRD), and quantitative porosity analysis would provide further verification of these microstructural features and is recommended for future investigations.

The presence of visible voids in mixtures may be due to entrapped air and the high dosage of superplasticizer used in the HPC mixtures, which could influence compaction efficiency and air-void distribution within the concrete mix.

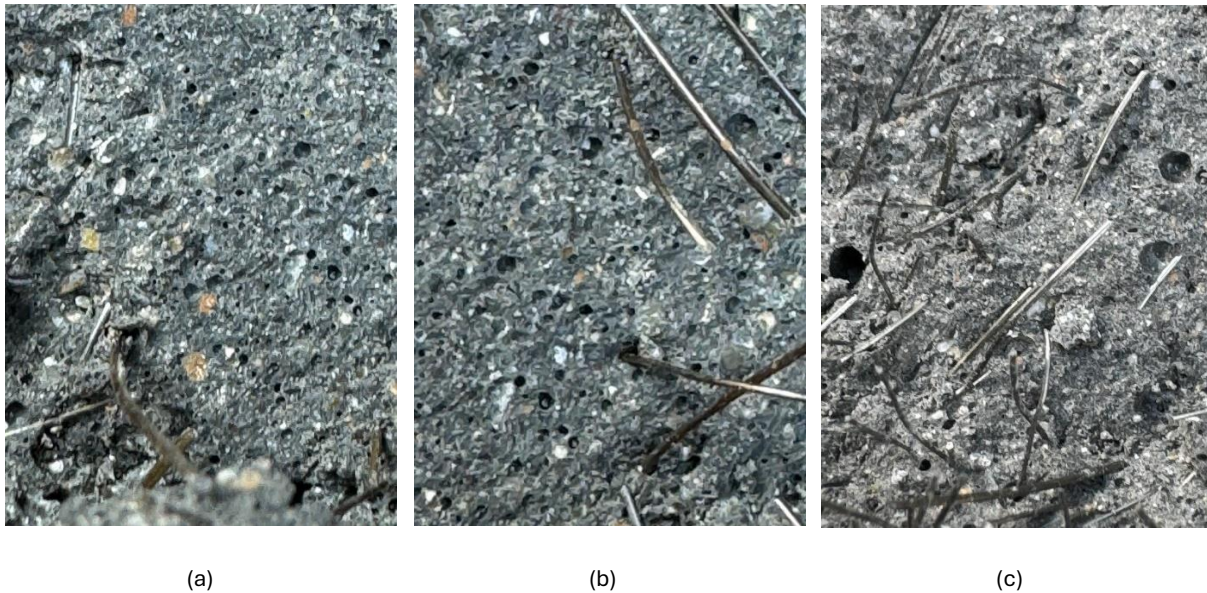


Figure 19: SEM micrographs of HPC specimens. (a) 25% replacement of steel waste; (b) 50% replacement of steel waste; (c) 75% replacement of steel waste

5.6. Hardened Concrete Density

The incorporation of steel waste as a volumetric replacement for natural sand is expected to significantly increase the density of hardened concrete due to the substantially higher density of steel particles compared with conventional fine aggregates. As the replacement level increases from 0% to 100%, a progressive increase in the unit weight of concrete is anticipated. This increase can be attributed to the high specific gravity of steel waste, which is approximately three times greater than that of natural sand.

The density of hardened concrete particularly high-strength concrete (HSC) is a fundamental physical property that reflects the material's mass per unit volume after curing. It is commonly used in quality control, structural design, durability assessment, and mix optimization.

$$\rho = \frac{M}{V} \quad (2)$$

Where:

ρ - density of hardened concrete in kg/m^3 ,

M - mass of the concrete specimen in kg,

V - volume of the specimen in m^3 .

Based on the mixture proportions adopted in the present study, as shown in Table 7, the density of hardened concrete increased gradually with increasing steel waste content. The control mixture exhibits a density within the normal-weight concrete range, whereas mixtures containing high replacement levels of steel waste approach the characteristics of

heavyweight concrete. Mixtures incorporating 75% and 100% steel waste demonstrate substantially greater densities than the reference mixture.

The addition of steel fibres at volume fractions of 1%, 2%, and 3% contributes to a further increase in hardened concrete density. Although the effect of fibres is less pronounced than that of steel waste replacement, their high density and uniform distribution within the mix slightly increase the overall unit weight of the composite material.

The increase in concrete density resulting from the incorporation of steel waste provide several engineering advantages, including improved radiation shielding capacity, enhanced impact resistance, and increased abrasion resistance. However, the higher self-weight associated with elevated steel waste contents should be considered during structural design, particularly for mixtures containing replacement levels greater than 50%.

Based on the constituent materials and replacement levels employed in this study, the hardened density of the concrete mixtures is ranged from approximately 2400–2500 kg/m³ for the control mixture to approximately 3700–3800 kg/m³ for mixtures containing 100% volumetric replacement of sand with steel waste.

5.7. Expected Durability and Corrosion Behaviour of HPC

The incorporation of steel waste as a partial or full replacement of sand, together with steel fibre, significantly modifies both the mechanical performance and durability characteristics of high-strength concrete. However, these modifications are not always linear or purely beneficial, particularly at high replacement ratios (50–100%).

At moderate replacement levels (25–50%), steel waste particles can improve the microstructure of concrete due to improved particle packing density, reduced void content, enhanced interfacial transition zone (ITZ) bonding, and increased compressive and tensile strength.

However, at higher replacement levels (75–100%), durability will tend to become more complex and often deteriorate due to increased porosity resulting from irregular particle shape and poor classification of steel waste, increased water absorption variation, and consequently, the interfacial transition area will be weakened due to the non-homogeneous distribution of materials, and the likelihood of internal micro-cracks due to the difference in hardness between the cement slurry and the steel particles.

The incorporation of steel waste and its fibres introduce a significant amount of embedded metallic phases into the concrete mix, directly impacting its corrosion behaviour. In mixes with high steel waste content, the risk of corrosion increases due to the formation of micro-galvanic cells between the steel particles and the surrounding cement paste. Furthermore, the presence of steel waste can contribute to the formation of more tightly bound micro-space structures, facilitating the entry of oxidizing agents such as chloride ions and moisture, thus accelerating the removal of the protective layer. Once corrosion begins, its spread will be further amplified by the increased total surface area of the steel provided by both the fibres and the steel waste particles. The expansive nature of the corrosion products, which occupy a much larger volume than the original steel, generates internal tensile stresses within the concrete, leading to micro-cracking, increased permeability, and a gradual deterioration of the protective capacity of the cement mix.

6. Conclusions

Through the evaluation of mechanical properties, this study systematically explored the feasibility of employing steel waste as a sustainable replacement for quartz sand in high-performance concrete (HPC). The HPC specimens were tested experimentally at different levels of steel waste replacement (by volume) of 0%, 25%, 50%, 75% and 100% in terms of flowability, compressive strength, flexural strength, splitting tensile strength, direct tensile strength, and hardened concrete density. The key findings demonstrate that:

1. The highest average values across all strength parameters (compressive flexural splitting tensile and direct tensile strengths) were observed at 50% steel waste substitution where the optimum mechanical performance was presented. At this replacement level, the most significant generation of calcium-silica-hydrate (C-S-H) gel was manifested in SEM images resulting in improved microstructural properties that directly correlated with performance enhancement.
2. The results show that the concrete mixture with 50% steel waste as a volumetric replacement of fine aggregate (sand) and 3% steel fibres, exhibited the highest mechanical performance among all investigated mixtures. The corresponding cylindrical compressive strength, direct tensile strength, splitting tensile strength, and flexural strength were 118.6 MPa, 16.62 MPa, 16.61 MPa, and 20.16 MPa, respectively. Increasing steel waste to 50% with maintain steel fibre at 3%, these values represent improvements of 22.6%, 25.9%, and 36.7% in compressive, direct tensile, and splitting tensile strengths, respectively, while the flexural strength showed a slight decrease of 1.95%. These results indicate that increasing the steel waste content to 50% significantly enhanced most of the mechanical properties of the concrete, although a marginal reduction in flexural performance was observed.
3. The enhancement observed at 50% steel waste replacement can be attributed to the improved particle packing and filler effect of steel waste, which reduced internal voids and increased mix densification. Furthermore, the presence of steel fibres reduces the progressive of crack and stress redistribution, leading to higher mechanical performance.
4. At higher replacement levels (75–100%), steel waste may cause particle segregation and increased interfacial transition zones, resulting in reduced stress transfer efficiency and lower mechanical performance.
5. At a 50% replacement of sand with steel waste and a steel fibre content of 3%, the concrete mixture exhibited a slump flow diameter of 223 mm, which remained within the acceptable limits specified by the ASTM standards. This result indicates that the mixture maintained adequate workability despite the incorporation of a relatively high volume of steel waste and steel fibres.
6. The density of hardened concrete containing 50% steel waste ranged from 2800 to 3050 kg/m³, classifying it as a moderately dense concrete. As the proportion of steel waste increased, the concrete density increased correspondingly due to the higher specific gravity of steel compared with natural sand. At full replacement and a steel fibre content of 3%, the density reached approximately 3740 kg/m³, indicating the production of a heavyweight concrete. These results demonstrate the significant influence of steel waste incorporation on the density characteristics of concrete.
7. The presence of steel waste and steel fibres within concrete increases its susceptibility to corrosion due to the additional metallic phases and the increased surface area of exposed steel. The spread of corrosion can lead to the formation of expanding corrosion products, resulting in internal tensile stresses, micro-cracking, increased permeability, and a gradual decrease in concrete durability.
8. On microstructural analysis, the mixture with 50% replacement was found to have maximum densification with efficient and uniform dispersal of C-S-H gel surrounded by significantly less void content. On the other hand, increasing replacement levels (75-100%) were found to be ineffective since excess fines led to a weaker interfacial zone, while fine particles interfered with the cementitious mix.
9. The mechanical and microstructural findings provide conclusive evidence that 50% volume of steel waste is the optimal replacement value for quartz sand used in HPC production. This validation of the technical feasibility of steel waste usage and its associated ability to pinpoint the specific limit at which environmental benefits can be reached without jeopardizing any of the phenomenal structural performance properties intrinsic to HPC gives this finding a dual contribution. The outcomes contribute to the sustainable formulation of HPC addressing industry waste management issues.

10. Although steel waste and steel fibres can enhance the mechanical performance of high-strength concrete, their high-volume incorporation introduces durability concerns. The main governing factor is the increase in internal heterogeneity and permeability, which accelerates chloride ingress and corrosion initiation.
11. Steel waste significantly increases the density of concrete, transforming it from ordinary concrete to heavyweight concrete at high steel waste replacement ratios. Steel fibres also slightly increased density. While this improves protection and strength properties, the increased self-weight must be considered during design, especially when the replacement ratio exceeds 50%.

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Author Contributions

A. A. N. A.-J. Conceptualization, methodology, literature review, data collection, formal analysis, investigation, visualization, writing – original draft preparation. **R. F. H.** Supervision, validation, writing – review and editing, project administration.

All authors have read and approved the final version of the manuscript.

References

- Yoo, D., & Banthia, N. (2016). Mechanical properties of high-performance fiber-reinforced concrete: A review. *Cement and Concrete Composites*, 73, 267–280. <https://doi.org/10.1016/j.cemconcomp.2016.07.001>.
- Abbas, S., Nehdi, M. L., & Saleem, M. A. (2016). High performance concrete: Mechanical performance, durability, sustainability and implementation challenges. *International Journal of Concrete Structures and Materials*, 10(3), 271–295. <https://doi.org/10.1007/s40069-016-0145-7>.
- Shi, C., Wu, Z., Xiao, J., Wang, D., Huang, Z., & Fang, Z. (2015). A review on high performance concrete: Part I. Raw materials and mixture design. *Construction and Building Materials*, 101, 741–751. <https://doi.org/10.1016/j.conbuildmat.2015.10.034>.
- Yoo, D. Y., & Yoon, Y. S. (2016). A review on structural behavior, design, and application of high-performance fiber-reinforced concrete. *International Journal of Concrete Structures and Materials*, 10(2), 125–142. <https://doi.org/10.1007/s40069-016-0125-y>.
- Smarzewski, P. (2019). Study of toughness and macro/micro-crack development of fibre-reinforced high performance concrete after exposure to elevated temperature. *Materials*, 12(8), Article 1210. <https://doi.org/10.3390/ma12081210>
- Zhang, H., Ji, T., Zeng, X., Yang, Z., Lin, X., & Liang, Y. (2018). Mechanical behavior of high performance concrete (HPC) using recycled fine aggregate cured under different conditions and the mechanism based on integrated microstructural parameters. *Construction and Building Materials*, 192, 489–507. <https://doi.org/10.1016/j.conbuildmat.2018.10.140>.
- Salahuddin, H., Qureshi, L. A., Nawaz, A., & Raza, S. S. (2020). Effect of recycled fine aggregates on performance of reactive powder concrete. *Construction and Building Materials*, 243, Article 118223. <https://doi.org/10.1016/j.conbuildmat.2020.118223>.
- Chinzorigt, G., Lim, M. K., Yu, M., Lee, H., Enkhbold, O., & Choi, D. (2020). Strength, shrinkage, creep, and durability aspects of concrete including CO₂-treated recycled fine aggregate. *Cement and Concrete Research*, 136, Article 106062. <https://doi.org/10.1016/j.cemconres.2020.106062>.
- Jiang, J., Zhou, W., Gao, Y., Wang, L., Wang, F., Chu, H., Xu, G., Vandevyvere, B., Sierens, Z., & Li, J. (2019). Feasibility of manufacturing high performance cement-based composites (HPCCs) with recycled sand: A preliminary study. *Waste Management*, 83, 104–112. <https://doi.org/10.1016/j.wasman.2018.12.022>.
- Salman, B. A., & Hassan, R. F. (2023). Experimental investigation on the impact of micro-steel fibers on the flat slabs' punching shear resistance. *Tikrit Journal of Engineering Sciences*, 30, 1–15.

- Hanoon, D. S., Zareej, S. A., Hassan, R. F., & Zafarani, M. M. (2025). Experimentally investigating hybrid two-way slabs behavior of fiber reinforced concrete slabs cast with different concrete types. *Structures*, 79. <https://doi.org/10.1016/j.istruc.2024.11.009>.
- Ali, L. H., Hassan, R. F., & Hussein, H. H. (2024). Experimental and analytical investigations of torsional strength in high-performance concrete beams with transverse openings. *Buildings*.
- Al-Salim, N. H., Hassan, R. F., Mohammed, N. S., Ali, L. H., & Hussein, H. H. (2024). Effect of fiber dosages and stirrup ratios on torsional strength of ultrahigh-performance concrete beams. *American Society of Civil Engineers*.
- Leng, Y., Lui, Y., Shi, Z., Fang, D., Wang, J., Yang, Y., Li, Q., & Hu, X. (2023). Development of an environmental high performance concrete (HPC) incorporating carbonated recycled coarse aggregate. *Construction and Building Materials*, 362, Article 129657. <https://doi.org/10.1016/j.conbuildmat.2022.129657>.
- Naidanjav, U., Ochirbud, M., & Choi, D. (2022). Development of 100-MPa green reactive powder concrete using 100% recycled aggregates. *Journal of Asian Concrete Federation*, 8(2), 9–22. <https://doi.org/10.1016/j.jacf.2022.04.002>.
- Polish Committee for Standardization. (2012). PN-EN 197-1: Cement—Composition, specifications and conformity criteria for common cements. Author.
- Polish Committee for Standardization. (2013). PN-B-19707:2013-10: Cement—Special cement: Composition, specifications and conformity criteria. Author.
- ASTM International. (2001). ASTM C494/C494M-01: Standard specification for chemical admixtures for concrete. ASTM International.
- Shaheen, E., & Shrive, N. J. (2006). Optimization of mechanical properties and durability of reactive powder concrete. *ACI Materials Journal*, 103, 444–451.
- Wang, C., Yang, C., Liu, F., Wan, C., & Pu, X. (2012). Preparation of high performance concrete with common technology and materials. *Cement and Concrete Composites*, 34(4), 538–544. <https://doi.org/10.1016/j.cemconcomp.2012.01.007>.
- ASTM International. (2017). ASTM C1856/C1856M-17: Standard specification for fabricating and testing specimens of high performance concrete. ASTM International.
- ASTM International. (2014). ASTM C230/C230M-14: Standard specification for flow table for use in tests of hydraulic cement. ASTM International.
- ASTM International. (2015). ASTM C1437-15: Standard test method for flow of hydraulic cement mortar. ASTM International.

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