Effect of Carbon Fibers on Some Properties of Sustainable Reactive Powder Concrete

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ABSTRACT

Reactive Powder Concrete (RPC) is an advanced type of Ultra-High-Performance Concrete (UHPC) known for its exceptional mechanical and durability properties. It consists of very fine powders, including cement, sand, Silica Fume (SF), Quartz Powder (QP), Superplasticizer (SP), and very low water to cementitious material ratio (w/cm). The effect of Carbon Fibers (CF) on the mechanical properties of the RPC containing nano-AL_2O_3 is the objective of this study. The CF were added to the RPC with three percentages, 0.5%, 1%, and 1.5% by volume of concrete. Compressive strength, flexural strength, and splitting tensile strength tests were performed. The findings exhibited that the optimal percentage of CF was 1.5%, where the compressive strength at 7, 28, and 60 days increased by 25.26%, 23.07%, and 20.86%, while the flexural strength increased by 56.92%, 52.94%, and 50%. Also, the splitting tensile strength increased by 39.41%, 36.85%, and 34.78%, respectively, in comparison to the reference mixture.

Keywords-RPC; carbon fibers; compressive strength; flexural strength; splitting tensile strength

I. INTRODUCTION

RPC is an ultra-high-performance cementitious composite, which was invented in 1995 [1]. It is a distinct variety of UHPC that omits coarse aggregates from its composition [2, 3]. This type of concrete possesses a comparatively low water-to binder ratio and comprises cement, fine aggregate, and ultrafine powders, including QP and SF [1, 4]. Relative to other types of traditional high-performance concretes, RPC demonstrates improved mechanical characteristics, durability, and strength [5, 6]. The need for RPC has risen significantly, particularly within the precast concrete manufacturing sector. Moreover, it is utilized in structures, bridges, tunnels, and nuclear facilities [7, 8]. Extensive research has shown that the inclusion of Steel Fibers (SF) can significantly enhance the mechanical properties of RPC [9–11].

However, the corrosion of SF remains a significant concern. As an alternative, CF, a microcrystalline form of graphite, offer several advantageous properties, including structural stability, high-temperature resistance, high tensile strength, a high modulus of elasticity, corrosion resistance, low specific gravity, and excellent toughness. Additionally, CF are commonly employed to enhance, fortify, cure, and reinforce the concrete materials [12-15]. The flexural and compressive performance of RPC was examined, with a focus on the interface adhesion of CF [16]. The samples underwent two types of curing. The findings indicate that the use of CF enhanced the flexural strength of RPC by as much as 28.8% for the untreated specimens and by up to 14.3% for the specimens subjected to two treatments. However, the incorporation of CF has little impact on the compressive strength.

Authors in [17] investigated the mechanical characteristics of RPC incorporating both single and hybrid fiber compositions of CF and SF after exposure to elevated temperatures for 2 h. The result showed that CF–RPC achieves 85-90% of the mechanical performance potential of the standard SF–RPC. Following exposure to 800°C, CFRPC exhibited approximately 2, 4, and 5 times greater residual compressive, splitting tensile, and flexural strength compared to the plain RPC, respectively. Authors in [18] evaluated the impact of CF on the mechanical and durability properties of reactive powder concrete. CF–RPC exhibited greater durability than SF–RPC; however, the overall durability performance of both composites was comparable. Moreover, CF–RPC demonstrated significantly higher fracture toughness, compressive strength, and splitting tensile strength compared to the plain RPC.

A multi-scale enhancement approach was used to improve the mechanical and fracture-resistant properties of UHPC through the inclusion of carbon microfibers and carbon nanotubes [19]. The results indicated substantial performance improvements in the UHPC samples incorporating 6 mm carbon microfibers (9 kg/m³) and varying doses of carbon nanotubes (0.11–0.54 wt.%). The use of carbon microfibers increased the compressive strength by 12%, while the inclusion of 0.54 wt.% carbon nanotubes further augmented the compressive strength by 24%. The combined reinforcement approach led to a 313% increase in the tensile strength compared to the reference mixture. The possible impacts of incorporating CF and nano-silica on RPC, specifically on compressive strength, flexural strength, density, and shrinkage, were assessed [20]. CF with 1cm lengths were blended with fresh concrete in specified proportions of 0.5%, 1.5%, and 2.0% of the concrete volume. The findings indicated a significant alteration in the characteristics of the generated RPC. The incorporation of CF in the specified ratios demonstrated an enhancement in the mechanical properties over the curing duration.

The influence of CF and nano-silica incorporation on the properties of RPC was investigated, with a particular emphasis on compressive strength, flexural strength, density, and shrinkage [20]. In this study, chopped CF with a nominal length of 1 cm were introduced into the fresh RPC mix at volumetric ratios of 0.5%, 1.5%, and 2.0%. The experimental findings revealed that the inclusion of CF significantly enhanced the mechanical performance of RPC throughout the curing period. These improvements are attributed to the fibers' ability to bridge the microcracks, delay the crack propagation, and improve the overall structural integrity and durability of the composite matrix.

The present research aims to assess the impact of various ratios of CF on some characteristics of sustainable RPC containing nano-alumina.

II. EXPERIMENTAL WORK

A. *Materials*

Ordinary Portland Cement (OPC) of type CEM I–42.5R was employed in all concrete mixtures. This type of cement complies with the requirements of the Iraqi Standard Specification IQS No. 5 [21]. The detailed chemical composition and physical characteristics of the cement used are presented in Tables I and II, respectively.

TABLE I. CHEMICAL PROPERTIES OF OPC

Oxide compositions	**Content (%)**	**[21] Limits**
CaO	62.7	-
SiO_2	20.3	-
Fe_2O_3	4.2	-
Al_2O_3	5.1	-
MgO	3.9	Max (5)
SO_3	2.5	$SO_3 \leq 2.8$ if $C_3A > 3.5$ $SO_3 \leq 2.5$ if $C_3A \leq 3.5$
IR	0.72	Max (1.5)
LOI	2.8	Max (4)
Cl	0.04	-
C_3S	53.50	-
C_2S	17.91	-
C_3A	6.41	-
C_4AF	12.76	-

TABLE II. PHYSICAL PROPERTIES OF OPC

Properties	**Results**	**[21] Limits**
Specific surface area (m^2/kg.)	382	≥280
Initial setting time (min)	170	≥45 min
Final setting time (hr: min)	4:25	≤10 hr
Soundness (%)	0.15	≤0.80%
Compressive strength (MPa)		
2-days	24	≥20
28-days	45	≥42.5

The fine aggregate utilized was classified as zone 4, according to IQS No.45 [22]. Table III presents the properties of the fine aggregate, while Table IV depicts the sand gradation.

TABLE III. PHYSICAL AND CHEMICAL PROPERTIES OF FINE AGGREGATE

Properties	**Results**	**[22] Limits**	**Standard test**
Specific gravity	2.6	-	ASTM- C128
Fineness modulus	1.62	-	I.R Guide No.500/3,2018
Dry density (kg/m^3)	1520	-	ASTM C29/C29M
Absorption (%)	1.05	-----	ASTM C128
Sulfate content (%)	0.23	Max (0.5%)	I.R guide No.500/3,2018

TABLE IV. FINE AGGREGATE GRADING

Sieve size (mm)	**Cumulative passing (wt. %)**	**[22] Limits**
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	100	80-100
0.3	35	15-50
0.15	3	0-15

SF was employed as an additive for all mixtures, complying with ASTM C1240 [23]. Tables V and VI display the properties of SF.

TABLE V. CHEMICAL PROPERTIES OF SF

Oxide compositions	**Content (%)**	**[23] Requirements**
SiO_2	92.62	≥ 85%
Al_2O_3	0.35	-
Fe_2O_3	1.24	-
CaO	0.52	-
MgO	0.93	-
L.O.I	3.4	≤ 6%

TABLE VI. PHYSICAL PROPERTIES OF SF

Properties	**Results**	**[23] Requirements**
Retained on (No.325) sieve (%)	3.5	Max. (10)
Strength activity index at 7 days (%)	115	Min. (105)
Specific surface area (m^2/g)	16	Min. (15)
Color	Grey	-

The quartz sand utilized in this study was classified as zone 4, according to IQS No.45 [22]. The gradation of the quartz sand is presented in Table VII and its properties are portrayed in Table VIII. The quartz sand is used as partial replacement from fine aggregate.

TABLE VII. QUARTZ SAND GRADING

Sieve size (mm)	Cumulative passing (wt. %)	[22] Limits
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	100	80-100
0.3	50	15-50
0.15	6	0-15

TABLE VIII. PHYSICAL AND CHIMECAL PROPERTIES OF QUARTZ SAND

Properties	Results	[22] Limits	Standard test
Specific gravity	2.65	-	ASTM C128
Fineness modulus	1.44	-	Iraqi reference guide No.500/3,2018
Dry density (kg/m^3)	1540	-	ASTM C29/C29M
Absorption (%)	1.17	-	ASTM C128
Sulfate content (%)	0.09	Max (0.5) %	Iraqi reference guide No.500/3,2018

QP was used in this experiment, complying with ASTM-C618 [24]. Tables IX and X present the chemical and physical properties of QP.

TABLE IX. CHEMICAL PROPERTIES OF QP

Oxide compositions	Content (%)	[24] Requirements
SiO_2	99.18	Min. (70%)
Al_2O_3	0.32	
Fe_2O_3	0.02	
CaO	0.1	-
MgO	0.295	-
L.O.I	0.010	Max. (6%)

TABLE X. PHYSICAL PROPERTIES OF QP

Properties	Results	[24] Requirements
% Retained on (No.325) sieve	32	Max. 34
Strength activity index at 7 days (%)	85	Min. 75
Specific surface area (m^2/g)	15.4	Min. 15
Color	White	-

TABLE XI. PROPERTIES OF SP

Properties	Specifications
Appearance	Light yellow
Specific gravity	(1.07 ± 0.02)
PH	(5 – 7)
Dosage	(0.5 - 3.5) L/100 kg of cementitious materials
Chloride content(%)	0

An SP was included into the mixture to lower the water content and increase the concrete strength. This enhancement broadened the flow abilities, and it complies with ASTM C494 [25], type G. The SP properties are listed in Table XI.

TABLE XII. PROPERTIES OF NANO AL_2O_3

Property	Specification
Appearance	White
Type	Alpha
Purity	99.9%
Form	Powder
Average particle size	50 nm
Density	3.5-3.98 g/cm^3

Potable water was employed to adequately combine and cure the samples used in this study. The water utilized is suitable for its intended purpose and complies with the standard requirements specified in IQS. No.1703 [26]. The Nano Al_2O_3 (NA) used in this work was obtained from SkySpring-Nanomaterials company. It had a diameter of 50 nm and it was used as cement replacement. Table XII shows the physical properties of the NA.

TABLE XIII. PROPERTIES OF CARBON FIBERS

Properties	Details
Color	Black
Density (kg/m^3)	1800
Tensile strength (MPa)	4000
Modulus of elasticity (MPa)	230,000
Elongation (%)	1.7
Length (mm)	5
Diameter (μm)	7

Chopped CF were utilized for reinforcement, as illustrated in Figure1, with their characteristics outlined in Table XIII.

Fig. 1. Chopped CF.

B. *Reactive Powder Concrete Mix Design*

The mixtures were designed according to the method proposed in [1]. The reference mix involved replacing 10% of the fine aggregate with quartz sand by weight. Subsequently, 1% of the cement was replaced with nano-Al_2O_3 by weight. CF were then incorporated into the reference mix at three volumetric ratios: 0.5%, 1%, and 1.5%. For all mixtures, the w/cm was 0.19. The binder composition included 219 kg/m^3 of SF, 371 kg/m^3 of QP, and 2.9 L of SP per 100 kg of cementitious material. Table XIV outlines the mix proportions.

TABLE XIV. MIX PROPORTIONS OF RPC WITH VARYING CARBON FIBER CONTENT

Mix	Cem	FA	Nano Al_2O_3	QS	SF	QP	SP L/100 kg of binder	W	% CF by vol.
MR	940.5	940.5	9.5	104.5	219	371	2.9	222	-
M1	940.5	940.5	9.5	104.5	219	371	2.9	222	0.5
M2	940.5	940.5	9.5	104.5	219	371	2.9	222	1
M3	940.5	940.5	9.5	104.5	219	371	2.9	222	1.5

C. *Mixing Procedure*

The RPC was produced according to [27]. For the RPC concrete, the cement, SF, QP, and nano-Al_2O_3 were blended in a dry state for about 3 min to achieve their uniform distribution inside the cement particles, followed by the incorporation of sand. The mixture was blended for 5 min. The SP had to dissolve in water, and so the resultant solution was gradually incorporated during the mixing phase, followed by a mixing of the whole mixture for 3 min. However, the mixer operation stopped, necessitating manual mixing, especially in regions inaccessible to the mixer blades. The mixer had been functioning for 5 min to get sufficient fluidity. The CF had been uniformly incorporated into the mixture for 3 min, and then a further 2 min of mixing followed. The complete mixing of one batch needs around 15 min following the incorporation of water into the mixture.

III. PREPARATION OF SPECIMENS AND EXPERIMENTAL LAB TESTS

Upon completion of the mixing method, the steel molds were prepped and cleaned. Thereafter, the concrete was poured into the molds with vibration. Nylon covers were subsequently laid over the specimens. The molds were removed afterwards to a 24 h interval. The samples were subsequently cured in hot water at 70°C for 7, 28, and 60 days.

A. *Compressive Strength Test*

The compressive strength of the RPC specimens was found based on the ASTM C109 [28] by using a compression device. The cubes utilized in this test had dimensions of 50 x 50 x 50 mm. The test was conducted on concrete cubes aged 7, 28, and 60 days. The compressive strength was established by means 3 of the samples for each age. Each cube's compressive strength was calculated based on:

$$F = \frac{P}{A} \tag{1}$$

where F is the compressive strength in MPa, P is the maximum applied load in N, and A is the loaded surface area in mm².

B. *Flexural Strength Test*

The flexural strength of the RPC samples was found according to ASTM C293 [29], using a flexural device. The prismatic samples used in this test had dimensions of 250 x 50 x 50 mm. The test was conducted on a concrete prism aged 7, 28, and 60 days. The flexural strength was established by mean (3) of the samples for each age. Each prism's flexural strength was calculated by:

$$F_r = \frac{3Pl}{2bd^2} \tag{2}$$

where Fr is the flexural strength in MPa, P is the maximum applied load in N, l is the distance between the rollers of support in mm, b is the width of the specimen in mm, and d is the thickness of the specimen in mm.

C. *Splitting Tensile Strength Test*

The splitting tensile strength of the RPC samples was found according to ASTM C496 [30], using a compressive device. The cylindrical specimens were used in dimensions of 100 x 200 mm. This test was conducted on concrete cylinders aged 7, 28, and 60 days. The splitting tensile strength was established by mean (3) of the samples for each age. Each cylinder's splitting tensile strength was calculated by:

$$T = \frac{2P}{\pi DL} \tag{3}$$

where T is the splitting tensile strength in MPa, P is the maximum applied load in N, D is the diameter of specimen in mm, and L is the length of specimen in mm.

IV. RESULTS AND DISCUSSION

A. *Compressive Strength Test*

As displayed in Table XV and Figure 2, the compressive strength increased with the addition of 0.5%, 1%, and 1.5% CF compared to the MR. This can be attributed to the high tensile strength and elastic modulus of CF. These properties help control the microcracks and improve the stress distribution, leading to a better compressive performance [31].

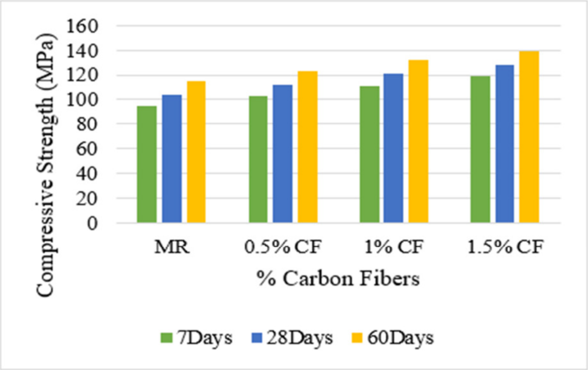

Fig. 2. Effect of CF on the compressive strength of RPC mixtures.

TABLE XV. RESULTS OF COMPRESSIVE STRENGTH

Mix type	Compressive strength (MPa)			% Increase in compressive strength		
	7 days	28 days	60 days	7 days	28 days	60 days
MR	95	104	115	-	-	-
0.5% CF	103	112	123	8.42%	7.69%	6.95%
1% CF	111	121	132	16.84%	16.34%	14.78%
1.5% CF	119	128	139	25.26%	23.07%	20.86%

B. *Flexural Strength Test*

As illustrated in Table XVI and Figure 3, the flexural strength increased when adding 0.5%, 1%, and 1.5% of CF compared to the MR, this impact is attributed to the mechanism of the CF, which augmented the stress in the matrix prior to cracking and elevated the maximum load in flexure [16].

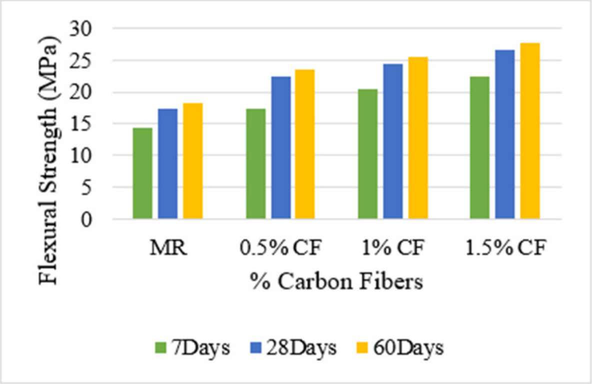

Fig. 3. Effect of CF on the flexural strength of RPC mixtures.

TABLE XVI. RESULTS OF FLEXURAL STRENGTH

Mix type	Flexural strength (MPa)			% Increase in flexural strength		
	7 days	**28 days**	**60 days**	**7 days**	**28 days**	**60 days**
MR	14.3	17.34	MR	14.3	17.34	MR
0.5% CF	17.34	22.44	0.5% CF	17.34	22.44	0.5% CF
1% CF	20.4	24.48	1% CF	20.4	24.48	1% CF
1.5% CF	22.44	26.52	1.5% CF	22.44	26.52	1.5% CF

C. Splitting Tensile Strength Test

As depicted in Table XVII and Figure 4, the splitting tensile strength increased when adding 0.5%, 1%, and 1.5% of CF compared to the MR, this could be ascribed to the enhanced resistance to sliding of pre-existing micro-cracks, which diminishes the source of energy for crack propagation. Moreover, regardless of whether the fibers are aligned with the crack propagation direction or laterally to the compressive axis, they enhance the fracture toughness via crack bridging [32].

TABLE XVII. RESULTS OF SPLITTING TENSILE STRENGTH

Mix type	Splitting tensile strength (MPa)			% Increase in tensile strength		
	7 days	**28 days**	**60 days**	**7 days**	**28 days**	**60 days**
MR	8.55	9.36	10.35	-	-	-
0.5% CF	9.71	10.84	11.93	13.56%	15.81%	15.26%
1% CF	10.86	11.75	12.88	27.01%	25.53%	24.44%
1.5% CF	11.92	12.81	13.95	39.41%	36.85%	34.78%

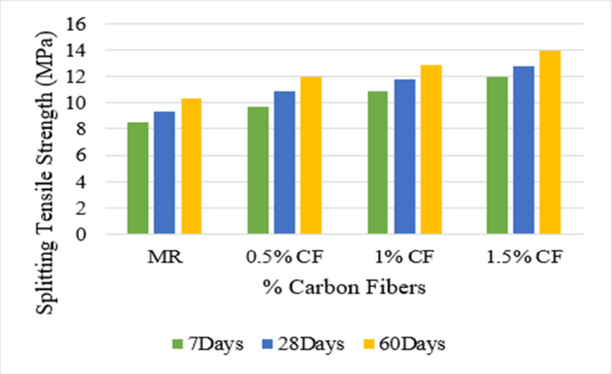

Fig. 4. Effect of CF on the splitting tensile strength of RPC mixtures.

V. CONCLUSIONS

The findings of this study confirm that the incorporation of Carbon Fibers (CF) significantly improves the mechanical performance of Reactive Powder Concrete (RPC). Among the tested mixtures, the one containing 1.5% CF by volume demonstrated the highest enhancements in the compressive, flexural, and splitting tensile strength. At 28 days, the compressive strength increased by 7.69%, 16.34%, and 23.07% with the addition of 0.5%, 1%, and 1.5% CF, respectively. The frlexural strength exhibited even more pronounced gains, rising by 29.41%, 41.17%, and 52.94% for the same fiber contents. Similarly, theb splitting tensile strength improved by 15.81%, 25.53%, and 36.85%, indicating that the fiber content has a consistent and positive influence on all key mechanical properties.

This research contributes to a deeper understanding of how the CF reinforcement affects the structural behaviour of RPC. The results suggest that the CF reinforced RPC can be a viable material for structural applications where both high strength and ductility are required. Practical uses include bridges, seismic-resistant structures, and marine environments. The enhanced performance can improve the load-bearing capacity of beams, columns, and piers, while also offering opportunities for structural retrofitting, functional modifications, and correction of design or construction deficiencies.

REFERENCES

[1] P. Richard and M. Cheyrezy, "Composition of reactive powder concretes," *Cement and Concrete Research*, vol. 25, no. 7, pp. 1501–1511, Oct. 1995, https://doi.org/10.1016/0008-8846(95)00144-2.

[2] S. D. Mohammed, H. K. Awad, and R. K. Aboud, "Compressive Strength Performance of Reactive Powder Concrete Using Different Types of Materials as a Partial Replacement of Fine Aggregate," *Key Engineering Materials*, vol. 857, pp. 39–47, 2020, https://doi.org/10.4028/www.scientific.net/KEM.857.39.

[3] H. Al-Quraishi and A. Fuad, "Finite Element Analysis of UHPC Corbels," *Journal of Engineering*, vol. 23, no. 9, pp. 78–88, Aug. 2017, https://doi.org/10.31026/j.eng.2017.09.06.

[4] S. I. Hendi and N. M. F. Aljalawi, "Behavior of Reactive Powder Concrete reinforced with Hybrid Fibers containing Sustainable Materials," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 13878–13882, Jun. 2024, https://doi.org/10.48084/etasr.7167.

[5] Z. K. Abbas, H. A. Al-Baghdadi, R. S. Mahmood, and E. S. Abd, "Reducing the Reactive Powder Concrete Weight by Using Building Waste as Replacement of Cement," *Journal of Ecological Engineering*, vol. 24, no. 8, pp. 25–32, Aug. 2023, https://doi.org/10.12911/22998993/164748.

[6] R. M. Qasim and N. M. F. Aljalawi, "The Effect of Different Curing Temperatures on Properties of Reactive Powder Concrete Reinforced by Micro Steel Fibers," *Journal of Engineering*, vol. 30, no. 06, pp. 57–66, Jun. 2024, https://doi.org/10.31026/j.eng.2024.06.04.

[7] W. Zheng and X. Lv, "Literature review of reactive powder concrete," vol. 36, pp. 44–58, Oct. 2015, https://doi.org/10.14006/j.jzjgxb.2015.10.006.

[8] S. Sanchayan and S. J. Foster, "High temperature behaviour of hybrid steel–PVA fibre reinforced reactive powder concrete," *Materials and Structures*, vol. 49, no. 3, pp. 769–782, Mar. 2016, https://doi.org/10.1617/s11527-015-0537-2.

[9] W. Zheng, H. Li, and Y. Wang, "Compressive stress–strain relationship of steel fiber-reinforced reactive powder concrete after exposure to elevated temperatures," *Construction and Building Materials*, vol. 35,

pp. 931–940, Oct. 2012, https://doi.org/10.1016/j.conbuildmat.2012.05.031.

[10] Y. Yoo and Y.-S. Yoon, "Structural performance of ultra-high-performance concrete beams with different steel fibers," *Engineering Structures*, vol. 102, pp. 409–423, Nov. 2015, https://doi.org/10.1016/j.engstruct.2015.08.029.

[11] Y.-S. Tai, H.-H. Pan, and Y.-N. Kung, "Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800°C," *Nuclear Engineering and Design*, vol. 241, no. 7, pp. 2416–2424, Jul. 2011, https://doi.org/10.1016/j.nucengdes.2011.04.008.

[12] A. Katz and A. Bentur, "Mechanical properties and pore structure of carbon fiber reinforced cementitious composites," *Cement and Concrete Research*, vol. 24, no. 2, pp. 214–220, Jan. 1994, https://doi.org/10.1016/0008-8846(94)90046-9.

[13] S. Ivorra, P. Garcés, G. Catalá, L. G. Andión, and E. Zornoza, "Effect of silica fume particle size on mechanical properties of short carbon fiber reinforced concrete," *Materials & Design*, vol. 31, no. 3, pp. 1553–1558, Mar. 2010, https://doi.org/10.1016/j.matdes.2009.09.050.

[14] Z. H. Mahdi, R. H. Al-Suhaili, and Z. A. Raouf, "Some properties of carbon fiber reinforced magnetic reactive powder concrete containing nano silica," *Journal of Engineering*, vol. 22, no. 8, Aug. 2016, pp. 103–124.

[15] N. A.- Jalawi, "SOME PROPERTIES OF HIGH PERFORMANCE CARBON FIBRES CEMENT COMPOSITES," *Journal of Engineering*, vol. 15, no. 04, pp. 4409–4416, Dec. 2009, https://doi.org/10.31026/j.eng.2009.04.21.

[16] M. Helmi and Q. Alraimi, "Effects of Carbon Fiber on Mechanical Properties of Reactive Powder Concrete," *Journal of the Civil Engineering Forum*, vol. 10, pp. 239–248, Sep. 2024, https://doi.org/10.22146/jcef.12439.

[17] S. S. Raza and L. A. Qureshi, "Effect of carbon fiber on mechanical properties of reactive powder concrete exposed to elevated temperatures," *Journal of Building Engineering*, vol. 42, Oct. 2021, Art. no. 102503, https://doi.org/10.1016/j.jobe.2021.102503.

[18] E. Shaheen and N. Shrive, "Optimization of mechanical properties and durability of reactive powder concrete," *ACI Materials Journal*, vol. 103, pp. 444–451, Nov. 2006.

[19] J. D. R. Martínez, J. D. Ríos, H. Cifuentes, and C. Leiva, "Multi-Scale Toughening of UHPC: Synergistic Effects of Carbon Microfibers and Nanotubes," *Fibers*, vol. 13, no. 4, Art. no. 49, Apr. 2025, Art. no. 49, https://doi.org/10.3390/fib13040049.

[20] N. Fawzi *et al.*, "EFFECT OF NANOMATERIAL ON PROPERTIES OF REINFORCED REACTIVE POWDER CONCRETE BY CARBON FIBER," vol. 32, pp. 16873–16880, Sep. 2021.

[21] *Iraqi Specifications IQS 5: Portland Cement Specialties*. Iraq: Central Agency for Standardization and Quality Control, 2019.

[22] *Iraqi Specifications IQS 45:* Aggregate from Natural Sources for Concrete, Central Agency for Standardization and Quality Control. Iraq: Central Agency for Standardization and Quality Control, 1984.

[23] ASTM C1240-15, Standard Specification for Silica Fume Used in Cementitious Mixtures. West Conshohocken, PA, USA: ASTM International, 2020.

[24] ASTM C618-15, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, PA, USA: ASTM International, 2015.

[25] ASTM C494/C494M-17, Standard Specification for Chemical Admixtures for Concrete. West Conshohocken, PA, USA: ASTM International, 2013.

[26] *Iraqi Specifications IQS 1703: Water Used for Concrete and Mortar*. Iraq: Central Agency for Standardization and Quality Control, 2018.

[27] L. S. Danha, W. Ismail Khalil, and H. M. Al-Hassani, "Mechanical Properties of Reactive Powder Concrete (RPC) with Various Steel Fiber and Silica Fume Contents," *Engineering and Technology Journal*, vol. 31, no. 16, pp. 3090–3108, Sep. 2013, https://doi.org/10.30684/etj.31.16A.8.

[28] ASTM C109/C109M-02, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). West Conshohocken, PA, USA: ASTM International, 2002.

[29] ASTM C293/C293M-16, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading). West Conshohocken, PA, USA: ASTM International, 2016.

[30] ASTM C496/C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. West Conshohocken, PA, USA: ASTM International, 2002.

[31] S. S. Raza, L. A. Qureshi, B. Ali, A. Raza, and M. M. Khan, "Effect of different fibers (steel fibers, glass fibers, and carbon fibers) on mechanical properties of reactive powder concrete," *Structural Concrete*, vol. 22, no. 1, pp. 334–346, 2021, https://doi.org/10.1002/suco.201900439.

[32] A. B. Kizilkanat, "Experimental Evaluation of Mechanical Properties and Fracture Behavior of Carbon Fiber Reinforced High Strength Concrete," *Periodica Polytechnica Civil Engineering*, vol. 60, no. 2, pp. 289–296, Feb. 2016, https://doi.org/10.3311/PPci.8509.