Behavior of Reactive Powder Concrete reinforced with Hybrid Fibers containing Sustainable Materials

Saif Ibrahim Hendi
Department of Civil Engineering, University of Baghdad, Iraq
saif.hindi2201m@coeng.uobaghdad.edu.iq (corresponding author)

Nada Mahdi Fawzi Aljalawi
Department of Civil Engineering, University of Baghdad, Iraq
nada.aljalawi@coeng.uobaghdad.edu.iq

Received: 28 February 2024 | Revised: 14 March 2024 | Accepted: 15 March 2024

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: https://doi.org/10.48084/etasr.7167

ABSTRACT

This study investigates the behavior of recycled Reactive Powder Concrete (RPC), made from finely ground recycled raw materials and containing a certain percentage of recycled copper (electrical waste copper wire) and steel fibers. This concrete has a relatively low water-to-binder ratio and is composed of cement, fine aggregate, and ultrafine powders, such as quartz powder and silica fume. The properties of Fiber-Reinforced Reactive Powder Concrete (FR-RPC) containing micro-steel fibers, recycled copper fibers, and a mixture of steel-recycled and copper fibers were investigated. A micro-steel fiber RPC (MF1) was used as a reference mix, having 1% steel fibers by volume with 13 mm length and 0.2 mm diameter. Recycled copper fiber RPC (MF2) was prepared utilizing 1% recycled copper fibers by volume, with a diameter of 0.2 mm and a length of 10 mm. In addition, Hybrid FR-RPC (HFR-RPC) samples were prepared by mixing micro steel fibers and recycled copper fibers in proportions of 0.5-0.5% (MF3), 0.4-0.6% (MF4), and 0.3-0.7% (MF5), respectively. The compressive strength, flexural strength, and splitting tensile strength of these FR-RPC mixes were studied. The results displayed that MF3 achieved slightly lower compressive strength, flexural strength, and splitting tensile strength than MF1 and higher than MF2, MF4, and MF5. Although the mechanical strengths of MF3 were marginally lower than those of MF1, compressive strength, flexural strength, and splitting tensile strength were almost the same. Therefore, copper wire waste fibers can be employed along with steel fibers with excellent results.

Keywords-reactive powder concrete; sustainable materials; hybrid fibers; micro steel fiber; recycled copper fiber; mechanical properties

I. INTRODUCTION

Reactive Powder Concrete (RPC) is regarded as a composite material that has excellent durability and strength [1]. RPC has better compressive strength characteristics than conventional concrete due to fiber inclusion [2]. In RPC, a high dosage of cement is meant to help create a lot of C-S-H gel between the increased powder surface area, which improves the packing of the particles. The particle packing strategy revolves around two main concepts: the optimal gradation curve and the filling properties of powdered materials, such as fly ash, cement, silica fume, and quartz sand and powder. In the RPC mix, part of the cement grains remain dehydrated due to the reduced water content. Owing to their size, which is between that of quartz powder and silica fume, these cement grains are essential for the granular packing of the RPC particles, as they fill the gaps between the other particles and guarantee a well-packed combination [3]. Portland cement-based concrete deteriorates in adverse situations, either standard or extreme. The effects of corrosion and cracking on safety, design life, and service behavior are substantial [4]. The concrete's quasi-brittle properties and tensile destructive potential are greatly restored by short fibers [5]. When comparing RPC with traditional concrete, fiber inclusion improves its compressive strength characteristics [6]. When fibers are correctly connected in their hardened condition, they engage with the microcrack matrix at the microcrack level and efficiently bridge them. This creates a stress transfer medium that prevents microcracks from coalescing and growing unstably. The matrix tensile strength can increase if the fiber volume percentage is high enough. After the composite reaches its tensile strength and microcracks are consolidated and transformed into macrocracks, the fibers' ability to effectively bridge macro-cracks inhibits the opening and growth of new cracks based on their length and bonding properties [7]. The practice of using recycled waste for construction has gained worldwide popularity, as it can be deployed to manage waste sustainably and protect the environment balance by employing a variety of raw resources [8]. In [9], it was demonstrated that utilizing several fiber types can enhance the performance of concrete and produce superior results [9]. In [10], affordable materials were implemented to evaluate RPC castings. Various levels of cement and silica fume, as well as local specific steel fiber aspect ratios, were used as reinforcement for this concrete, and their mechanical properties were evaluated. In [11], the effect of partial replacement of cement with sustainable glass powder at various percentages by weight was investigated. Furthermore, steam curing was performed for 5 h at 90℃ directly after hardening the sample. The RPC was designed utilizing local cement, silica fume, and superplasticizer with a water/cement ratio of 0.2 to achieve a compressive strength of 96.3 MPa at 28 days. Using 20% sustainable glass powder increased RPC compressive strength by 4.2%, flexural strength by 15.3%, dry density by 0.49%, and reduced absorption by 31.7% at 28 days [11]. In [12], certain mechanical characteristics of high-strength green concrete were examined when deploying sustainable copper fiber with various aspect ratios. A high-strength cement mixture was employed with a compressive strength of 65 MPa following ACI 211.4R. In four distinct aspect ratio mixtures (20, 40, 60, and 120), 1% of the concrete volume consisted of copper fibers. The compressive strength, flexural strength, and split tensile strength of the samples were evaluated at 7, 28, and 60 days after standard curing. When comparing concrete with a high fiber aspect ratio (120) to concrete with a low fiber aspect ratio (20), there was a notable improvement in compressive strength of 2, 1.6, and 1.4% after 7, 28, and 60 days. Similar results were disclosed for flexure strength. The split tensile strength of concrete with a high aspect fiber ratio increased by 1.7, 1.5, and 1.6% during 7, 28, and 60 days, respectively, in contrast to concrete with a low fiber aspect ratio. Concrete mechanical characteristics were found to greater improve when using a high aspect ratio of fibers rather than a low one.

This study aims to manufacture reactive powder concrete engaging sustainable materials and to investigate its mechanical properties. This will facilitate the mitigation of the environmental damage caused by the concrete industry. To reduce emissions, achieve sustainability in construction, and eliminate the cost of producing RPC, waste materials, such as quartz powder, silica fume, and recycled copper wire fiber were added to the concrete.

II. EXPERIMENTAL WORK

A. Materials

This study used OPC CEM-1 (42.5R), compatible with the Iraqi standards [13]. Tables I and II depict its physical and chemical characteristics, respectively.

TABLE I. PHYSICAL TEST AND SPECIFICATION LIMITS

Cement Property		**Test results**	**Specification limits 42.5 R CEM-1**
Setting time	Initial (mins)	149	Min. 45 (mins)
	Final (hrs.)	7	Max 10 (hrs.)
Compressive strength (MPa)	2 days	24	Min. 20
	28 days	47	Min. 42.5

TABLE II. CHEMICAL ANALYSIS AND SPECIFICATIONS LIMITS

Cement property		**Test results***	**Specification limits 42.5 R CEM-1**
SiO_2 %		19.8	-
AI_2O_3 %		6.15	-
Fe_2O_3 %		3.55	-
Cao %		61.72	-
MgO %		2.61	5 Max.
SO_3 %Max	3.5% <C_3A	2.15	2.5
	3.5% > C_3A	Not applicable	2.8
LOI %		2.16	Max 4
I R %		0.55	Max 1.5
C_3S %		48.18	-
C_2S %		20.49	-
C_3A %		10.29	-
C_4AF %		10.79	-

The Fine Aggregate (FA) material employed in the investigation was sieved, passing through a 0.6 mm sieve. Tables III and IV present the physical and chemical properties of FA. Sand satisfies Iraqi standards Zone 4 [14], according to test values. This study utilized drinkable water (W) for both curing and mixing, as recommended by the Iraqi specifications [15]. Silica Fume (SF), complying with ASTM C1240-15 [16], was used by replacing 10% cement by weight according to [17]. Tables V and VI portray the technical information on silica fume.

TABLE III. SAND GRADING

Sieve size (mm)	**Passing (%) of sand**	**Limits of IQS No.45/1984/Zone 4**
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	31	15-50
0.15	3	0-15

TABLE IV. CHEMICAL PROPERTIES OF SAND

Properties	**Test result of sand***	**Limits of IQS No. 45/1984**
Fineness modulus	1.68	-
Specific gravity	2.62	-
Absorption	1.04(%)	-
SO_3	0.17(%)	≤ 0.5(%)
Dry density	1670 (kg/m³)	-

TABLE V. PHYSICAL RESULTS OF SILICA FUME (SF)

Physical properties	**Test results**	**ASTM limits [16]**
% Retained on 45-μm (No. 325) sieve	7.4	≤10
Accelerated pozzolanic strength activity index at 7 days	111	≥105
Specific surface (m^2/g)*	16	≥15

TABLE VI. CHEMICAL PROPERTIES OF SF

Composition	**Test results (%) ***	**ASTM limits [16]**
SiO_2	92.3	≥85.0
AL_2O_3	0.34	---
MgO	0.35	---
Fe_2O_3	1.31	---
CaO	2.85	---
Loss on Ignition	2.17	≤6.0

Chemical additions increase the workability of fiber addition. Super-plasticizer (SP) was utilized to make the mixture stronger with less water and improve the flow at 0.5-1% dose. The superplasticizer used complies with ASTM C494 [18], and its details are provided in Table VII.

TABLE VII. PERFORMANCE DATA SHEET OF SP

Appearance	Light brownish liquid
Specific gravity	1.070 ± 0.005 (g/cm³)
PH- value	4-6
Typical dosage	0.5-1 (l/100 kg) of cement
Total chloride ion	Nil

This study employed Quartz Powder (QP) that was sufficiently refined to meet ASTM C 311 [19]. Table VIII shows the chemical and physical properties of the Quartz powder, along with its compliance with ASTM C618-15 [20]. The percentage of replacement was 18% by weight of cement, according to [21].

TABLE VIII. QUARTZ POWDER PROPERTIES

Composition	**Test result (%)**	**ASTM C618-15 class F requirements**
SiO_2	64.22	Min 70
AL_2O_3	9.6	
Fe_2O_3	5.2	
SO_3	2.15	Max 5
Cao	4.27	---
MgO	1.66	---
Loss of ignition	3.22	Max 6
% Retained on 45μm (No.325)	30(%)	Max 34(%)
Strength activity index (%) with OPC at 7 days.	102	Min (75)

Recycled copper wire fiber was used, obtained from several electrical and electronic device applications, such as refrigerators, computer parts, and windings of electrical machines. The fiber employed had an aspect ratio of 50, 10 mm length, and 0.2 mm diameter, as observed in Table IX.

TABLE IX. RECYCLED COPPER FIBER PROPERTIES

Description	**Specification**
Colour	Straw or gold
Fiber Shape	Straight
Length (mm)	10
Fibre diameter (mm)	0.2
Aspect ratio	50
Bulk density	8933 (kg/m³)
Tensile strength of fibres ($N/mm^{2)}$	966

Straight Micro Steel Fibers were put into service. The mild carbon steel that was used to create these fibers had an average tensile strength of 2600 MPa [22]. With a fiber diameter of 0.2 mm and a length of 10 mm, the aspect ratio (L/D = 50) is in line with ACI 544 [23], as shown in Table X.

B. Reactive Powder Concrete Design

A strength design of 95 MPa was employed to create RPC with the required properties. The RPC mix design that includes recycled copper wire fibers, micro steel fiber, and hybrid fiber of both by 1% per volume of concrete is exhibited in Table XI.

TABLE X. DATA OF MICRO STEEL FIBERS (MSF)

Description	**Specification**
Surface	Brass coated
Fiber Shape	Straight
Length (mm)	13
Fibre diameter (mm)	0.2
Aspect ratio	50
Bulk Density	7890 (kg/m³)
Tensile strength of fibres (N/mm^2)	2600
Melting point	1500ºC

TABLE XI. RPC MIX PROPORTION DETAILS FOR 1 m³, WEIGHT IN kg/m³

Mix	**SP (l/m^3)**	**W**	**Cem**	**FA**	**RCF by vol**	**MSF by vol**	**SF**	**QP**
MF1	8	220	792	1035	0	1%	110	198
MF2	8	220	792	1035	1%	0	110	198
MF3	8	220	792	1035	0.5%	0.5%	110	198
MF4	8	220	792	1035	0.6%	0.4%	110	198
MF5	8	220	792	1035	0.7%	0.3%	110	198

III. RESULTS AND DISCUSSION

A. Compressive Strength Test

The investigation was conducted following ASTM C109-20 [24] by using cubic specimens (50×50×50 mm), for five mixes containing 1% micro steel fibers (MF1), 1% recycled copper fibers (MF2), and three hybrid mixtures of 0.5-0.5%, 0.6-0.4%, and 0.7-0.3% recycled copper and micro steel fibers (MF3, MF4, MF5), respectively. Table XII indicates that the MF1 sample had higher compressive strength than all mixes, as also noticed in Figure 1, but the compressive strength of MF3 is nearly that of MF1.

TABLE XII. COMPRESSIVE STRENGTH TEST RESULTS

Mix	**Compressive strength (MPa)**		
	7 days	**28 days**	**60 days**
MF1	83	116	129
MF2	74	108	116
MF3	81	112	123
MF4	77	109	119
MF5	75	108	117

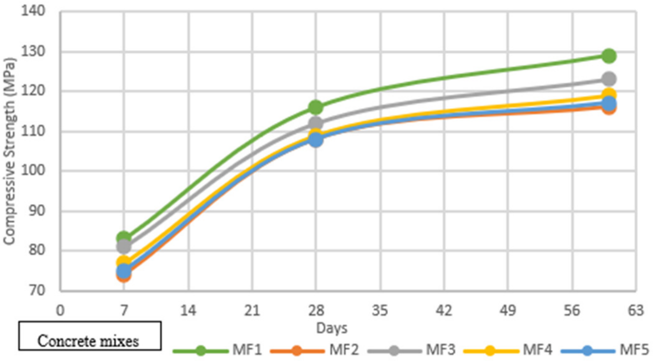

Fig. 1. Relationship between compressive strength and age for all mixes.

The compressive strength of MF4 is higher than those of MF5 and MF2. When comparing MF3 with MF1, at 7 days the compressive strength was reduced by approximately 2.4%, at 28 days by 3.4%, and at 60 days by 4.6%. This discrepancy may be attributed to variations in the tensile strength of the two fiber types, as displayed in Tables IX and X. This result agrees with the findings of [25-27].

B. Flexural Strength Test

The specific examination was conducted following ASTM C293-19 [28], using prisms (250×50×50 mm), for the five mixes. As depicted in Table XIII and Figure 2, MF1 had a higher flexural strength than all the other mixes. However, MF3 had a flexural strength almost equal to that of MF1. MF4, MF5, and MF2 had lower flexural strengths than MF3. When comparing MF3 with MF1 at 7 days, the flexural strength was reduced by approximately 4.4%, at 28 days by 5%, and at 60 days by 5%. This variation may also be caused by variations in the tensile strength of the two fiber types, as illustrated in Tables IX and X. This outcome agrees with [12, 29].

TABLE XIII. FLEXURAL STRENGTH TEST RESULTS

Mix	**Flexural Strength (MPa)**		
	7 days	**28 days**	**60 days**
MF1	13.5	15.7	15.8
MF2	9.7	12.6	13
MF3	12.9	14.9	15
MF4	11.8	14	14.3
MF5	10.9	13	13.1

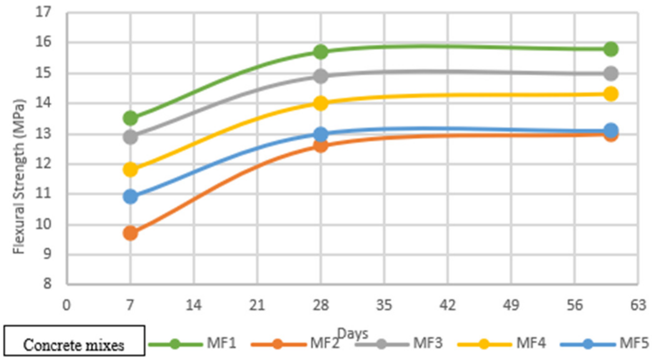

Fig. 2. Relationship between flexural strength and age for all mixes.

C. Splitting Tensile Strength

A 200×100 mm cylinder was utilized to evaluate the splitting tensile strength for the five mixes, following ASTM C496-17 [30]. As shown in Table XIV and Figure 3, MF1 had stronger splitting tensile strength than all other mixes.

TABLE XIV. SPLITTING TENSILE STRENGTH TEST RESULTS

Mix	**Splitting Tensile Strength (MPa)**		
	7 days	**28 days**	**60 days**
MF1	11.7	14.2	15.2
MF2	8.2	10.6	11.9
MF3	11.2	13.9	14.8
MF4	9.2	12.9	13.5
MF5	8.8	11	12.3

However, MF3 had a splitting tensile strength value nearly comparable to MF1. When comparing MF1 and MF3, the splitting tensile strength of the latter was reduced by approximately 4.2% at 7 days, 2.1% at 28 days, and 2.6% at 60 days. This variation may be caused by variations in the tensile strength of the two types of fiber, as exhibited in Tables IX and X. This result agrees with [31].

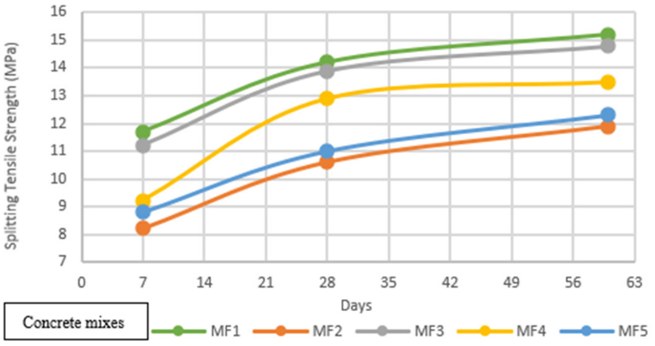

Fig. 3. Relationship between splitting tensile strength and age for all mixes.

IV. CONCLUSIONS

After the contucted laboratory experiments, the following findings were determined when comparing the results of the RPC reference mixture (MF1), having only steel fibers, with MF2, MF3, MF4, and MF5 containing copper or copper and steel fiber mixtures.

- The optimum hybrid reinforced RPC mixture was MF3, as it gave the highest compressive strength and its results were very close to the reference mixture MF1.
- For flexural strength results, MF3 was the optimum hybrid mixture, as it achieved the highest flexural strength compared to the other hybrid mixtures.
- In terms of splitting tensile strength, MF3 was the best of the hybrid mixtures, while it also had a small difference from MF1.

These results reveal that the use of a proper amount of waste electrical copper wire as fiber in RPC along with micro steel fibers (0.5-0.5%) as a hybrid fiber concrete mix achieved excellent results, which were very close to an RPC with only 1% micro steel fibers. The particular finding can lead to a reduction in the cost of concrete production.

REFERENCES

[1] 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.

[2] J. Xu *et al.*, "Behaviour of ultra high performance fibre reinforced concrete columns subjected to blast loading," *Engineering Structures*, vol. 118, pp. 97–107, Jul. 2016, https://doi.org/10.1016/j.engstruct.2016.03.048.

[3] O. A. Mayhoub, E.-S. A. R. Nasr, Y. A. Ali, and M. Kohail, "The influence of ingredients on the properties of reactive powder concrete: A review," *Ain Shams Engineering Journal*, vol. 12, no. 1, pp. 145–158, Mar. 2021, https://doi.org/10.1016/j.asej.2020.07.016.

[4] S. S. Hussein and N. M. Fawzi, "Influence of Using Various Percentages of Slag on Mechanical Properties of Fly Ash-based Geopolymer Concrete," *Journal of Engineering*, vol. 27, no. 10, 2021.

[5] L. Facconi, F. Minelli, G. Plizzari, and P. Ceresa, "Experimental study on steel fiber reinforced concrete beams in pure torsion," in *Proceedings of the fib Symposium 2019 Concrete-Innovations in Materials, Design and Structures*, 2019, pp. 1811–1818.

[6] N. M. Fawzi and Z. F. Muhsin, "Effect of Fly Ash on Some Properties of Reactive Powder Concrete," *Journal of Engineering*, vol. 27, no. 11, 2021.

[7] A. Swarup and G. Pathan, "A Review on Steel Fiber Reinforced Concrete," *International Journal of Advance Research in science and Engineering*, vol. 1, no. 10, pp. 2319–8354, 2017.

[8] M. Asim *et al.*, "A Review on Pineapple Leaves Fibre and Its Composites," *International Journal of Polymer Science*, vol. 2015, Oct. 2015, Art. no. e950567, https://doi.org/10.1155/2015/950567.

[9] A. N. Dalaf and S. D. Mohammed, "The Impact of Hybrid Fibers on Punching Shear Strength of Concrete Flat Plates Exposed to Fire," *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7452–7457, Aug. 2021, https://doi.org/10.48084/etasr.4314.

[10] M. M. Kadhum, "Studying of Some Mechanical Properties of Reactive Powder Concrete Using Local Materials," *Journal of Engineering*, vol. 21, no. 7, pp. 113–135, Jul. 2015, https://doi.org/10.31026/j.eng.2015.07.09.

[11] Z. A. Hussain and N. Aljalawi, "Effect of Sustainable Glass Powder on the Properties of Reactive Powder Concrete with Polypropylene Fibers," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8388–8392, Apr. 2022, https://doi.org/10.48084/etasr.4750.

[12] A. N. Abdullah and N. M. Fawzi, "The Effect of Using Different Aspect Ratios of Sustainable Copper Fiber on Some Mechanical Properties of High-Strength Green Concrete," *Journal of Engineering*, vol. 29, no. 11, 2023.

[13] "IQS 5: Portland Cement Specialties." Iraqi Standard Specification, 2019.

[14] "IQS 45: Aggregate from Natural Sources for Concrete, Central Agency for Standardization and Quality Control." Iraqi Standard Specification, 1984.

[15] "IQS 1703: Water Used for Concrete and Mortar." Iraqi Standard Specification, 2018.

[16] "ASTM C1240-15: Standard Specification for Silica Fume Used in Cementitious Mixtures." ASTM, 2015, https://doi.org/10.1520/C1240-15.

[17] B. Uzbas and A. C. Aydin, "Microstructural Analysis of Silica Fume Concrete with Scanning Electron Microscopy and X-Ray Diffraction," *Engineering, Technology & Applied Science Research*, vol. 10, no. 3, pp. 5845–5850, Jun. 2020, https://doi.org/10.48084/etasr.3288.

[18] "ASTM C494/C494M-17: Standard Specification for Chemical Admixtures for Concrete." ASTM, 2013, https://doi.org/10.1520/C0494_C0494M-13.

[19] "ASTM C311/C311M-16: Standard Test Methods for Sampling and Testing Coal Ash or Natural Pozzolans for Use in Concrete." ASTM, https://doi.org/10.1520/C0311_C0311M-16.

[20] "ASTM C618-15: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." ASTM, 2015, https://doi.org/10.1520/C0618-15.

[21] L. R. C. Tavares, J. F. T. Junior, L. M. Costa, A. C. da Silva Bezerra, P. R. Cetlin, and M. T. P. Aguilar, "Influence of quartz powder and silica fume on the performance of Portland cement," *Scientific Reports*, vol. 10, no. 1, Dec. 2020, Art. no. 21461, https://doi.org/10.1038/s41598-020-78567-w.

[22] M. H. Muhsin and I. H. AbdElzahra, "Studying the Combination Effect of Additives and Micro Steel Fibers on Cracks of Self-Healing Concrete," *Journal of Engineering*, vol. 22, no. 1, pp. 49–67, Jan. 2016, https://doi.org/10.31026/j.eng.2016.01.04.

[23] "ACI 544.2R-89: Measurement of Properties of Fiber Reinforced Concrete (Reapproved 2009)." ACI, 2009.

[24] "ASTM C109/C109M-02: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)." ASTM, 2002, https://doi.org/10.1520/C0109_C0109M-02.

[25] A. R. Kurup and K. S. Kumar, "Novel Fibrous Concrete Mixture Made from Recycled PVC Fibers from Electronic Waste," *Journal of Hazardous, Toxic, and Radioactive Waste*, vol. 21, no. 2, Apr. 2017, Art. no. 04016020, https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000338.

[26] S. S. Hussein and N. M. Fawzi, "Behavior of Geopolymer Concrete Reinforced by Sustainable Copper Fiber," *IOP Conference Series: Earth and Environmental Science*, vol. 856, no. 1, Jun. 2021, Art. no. 012022, https://doi.org/10.1088/1755-1315/856/1/012022.

[27] D. Suhirkam, B. H. Fuady, L. Flaviana, and Suhadi, "The Copper Fiber On Compressive Strength And Elastic Modulus On Concrete Fc'25," *Journal of Physics: Conference Series*, vol. 1500, no. 1, Dec. 2020, Art. no. 012085, https://doi.org/10.1088/1742-6596/1500/1/012085.

[28] "ASTM C293/C293M-16: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)." ASTM, 2016, https://doi.org/10.1520/C0293_C0293M-16.

[29] B. Shobana, B. N. B. Bright, and P. G. Student, "Experimental Investigation on High Performance Concrete by Using Electric Copper Wire," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 6, no. 5, 2017.

[30] "ASTM C496/C496M-17: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens." ASTM, https://doi.org/10.1520/C0496_C0496M-17.

[31] M. H. Naser, F. H. Naser, and M. K. Dhahir, "Tensile behavior of fiber reinforced cement mortar using wastes of electrical connections wires and galvanized binding wires," *Construction and Building Materials*, vol. 264, Dec. 2020, Art. no. 120244, https://doi.org/10.1016/j.conbuildmat.2020.120244.