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TECHNICAL PAPER

Optimizing characteristics of high-performance concrete incorporating hybrid polypropylene fibers

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Abstract

The purpose of this investigation is to assess and optimize the impact of hybrid polypropylene fibers (coarse monofilament and staple fibers) on the mechanical characteristics and resistance to elevated temperature of high-performance concrete. Concrete mixtures were designed using central composite design under response surface methodology. Slump test, compressive strength, flexural strength, impact test, elevated temperature resistance and microstructure of concrete were the tests performed. The slump values were slightly decreased with the addition of polypropylene fibers. Concrete mixtures reinforced with hybrid polypropylene fibers have significantly improved in terms of compressive strength and flexural strength ranged from 1.96% to 12% and 14.28% to 41.9%, respectively, at age 56 days compared to control mixture without fibers. The hybridization of 5 kg monofilament and 0.75 kg staple fibers achieved the highest compressive strength (84.6 MPa), flexural strength (14.9 MPa), and the optimum impact resistance at age 56 days. The increase of coarse monofilament fibers significantly improved the spalling resistance performance. The residual compressive strength of mixture containing 5 kg monofilament and 0.75 kg staple fibers up to 63.8% of the initial strength after exposure to 800 C0. Strong relationships were obtained for predicting and optimizing compressive and flexural strength of concrete incorporating hybrid polypropylene fibers.

Keywords Polypropylene fibers · High performance concrete · Optimization · Response surface methodology · Elevated temperature · Mechanical properties

Introduction

Concrete technology has developed in a new way to overcome conventional concrete limitations such as self-compact concrete (SCC), high-performance concrete (HPC) and ultra-high performance concrete (UHPC) [1, 2]. For the structural application of conventional concrete, two primary weaknesses have caused issues: weakness under tension, and brittle behavior which results in low ductility [3–7]. Concrete's tensile strength is commonly known to be far lower than its compressive strength, so that, the cracks can spread more quickly [8]. High performance concrete (HPC) and high strength concrete (HSC) are being used more widely everywhere. Along with greater strength, HPC distinguishes out for its high workability, durability, resistance to a variety of outside agents, and rapid hardening rate [9, 10]. The main drawbacks are brittleness, low tensile strength, and poor resistance to crack opening and propagation. Recently, Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) has offered notable advantages over other types of concrete. Akeed et al. carried out a comprehensive review on UHPC: developments, fresh and hardened properties, microstructure and durability [12–16]. Fibers are required to impose the ductility in compression required for structural safety. The concrete body has many micro-cracks throughout it even before the tensile testing starts, which hampers the proper transfer of tensile stress during the test, which causes the spread of crack [17, 18]. The concept of fiber-reinforced concrete (FRC) was invented to reinforce the brittle cement-based paste with various fibers, such as steel fiber, basalt fiber, synthetic fiber, carbon fibers, and natural fibers [19]. Tahwia [20] focused on the potential of polypropylene (PP) fibers to replace steel fibers. PP fibers act as sacrificial agents that create voids in the UHPC matrix, reducing internal pressure and

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preventing (or delaying) the spalling of the concrete subjected to high temperatures.

The addition of fiber to concrete is one of several modifications made to the material with the aim to reduce its weaknesses by raising its tensile strength. High strength concrete with polypropylene and steel hybrid fiber produced superior flexural toughness, tensile strength, and compressive strength than plain concrete and all FRCs with single, double, or triple types of fibers [21]. Fiber hybridization is one concept that has recently received a lot of interest. The idea is to randomly include reinforcement fibers into the concrete mix to prevent early cracking caused on by loading [22]. Fiber reinforcing has been shown to increase concrete's impact resistance, fracture toughness, fatigue resistance, and capacity to absorb energy [23]. When different types of fibers are properly combined, a hybrid is produced that benefits from each fiber's special qualities and reacts synergistically [23]. In reality, the best mechanical characteristics of single fiber-reinforced concrete are nonexistent [24]. The best FRC features are provided by combining two distinct types of fibers. In contrast, flexible single fibers increase the ductility and toughness of FRC while strong and stiff discrete fiber improves initial fracture strength and ultimate capacity [25]. Polypropylene fibers, at a ratio ranging from 0.5 to 3 kg/m^3, can be used to improve the concrete behavior at high temperatures [26].

The actual performance of concrete exposed to very high temperatures depends on a variety of environmental parameters, including the properties of the materials used, how the concrete was constructed, the rate at which it heated up, the highest temperature to which it was exposed, how long it was exposed, how it was cooled after reaching the maximum temperature, and its loading level at the time of cooling [27]. The risk of explosive spalling in HPC at high temperatures is reduced and fully eliminated by employing polypropylene (PP) fibers, according to previous studies [28].

It's significant to note that traditional methods for experimental design operate on the assumption that each factor may be manipulated separately from the others [29, 30]. Finding the optimal parameter becomes more time-consuming and ineffective, especially when considering the interactions between each component. Response surface methodology (RSM) can be used to solve this problem [31, 32]. The significance of the variables in terms of their influence on the response values may be assessed using these techniques to estimate experimental results using an analysis of variance (ANOVA) [33].

Research significant

The effects of combining two different types of fibers, such as carbon fibers and polypropylene, glass and polypropylene fibers, or carbon and glass fibers were the focus of earlier studies. However, there have not been many studies examining the effects of mixing the same type of fibers with different specifications on the properties of concrete. Also, there is a lack of available literature regarding the possibility of optimizing and predicting the properties of hybrid fiber-reinforced concrete (HFRC). In this research, the effect of hybrid polypropylene fibers (coarse monofilament and staple fibers) on the mechanical characteristics and resistance to elevated temperature of high-performance concrete was studied. Also, in order to optimize and predict the properties of concrete, central composite design (CCD) under response surface methodology (RSM) was used to design the concrete mixtures. The study provides insights into the optimal combinations of synthetic fibers for HFRC, which can be useful for the design of concrete structures with improved strength.

Response surface methodology

In recent years, the most widely utilized optimization technique was response surface methodology (RSM) [34, 35]. The response surface method's primary objective is to identify the variables' optimal values. RSM has the capability to estimate the relation between the independent variables and the responses, additionally to determine how each individual independent variable, or a combination of variables, affects the response [36]. As compared to the conventional method, using RSM can also reduce the number of planned experiments. The term "RSM" comes from the mathematical model's graphical approach [37, 38]. Equation (1) provides the relationship between the output and the input.

$$Y = \beta_0 + \Sigma\, \beta_{ij} x_i + \Sigma\, \beta_{ii}\, x_i + \Sigma\, \beta_{ij} x_i x_j \tag{1}$$

where Y is the response to anticipated, β_0 is the intercept of the model, β_i points to coefficients of linear, βii signifies quadratic coefficient, βij are coefficients of variable interaction and xi, xj are independent variables. Three steps can be used to divide optimal research using RSM. The initial step is the initial work where independent parameter determination and level determination are performed out. The next step is the chosen an experimental strategy, predicting the model equation, and verifying it. The next step is to identify the optimum points and obtain the response surface plot and response contour plot as functions of the independent parameters [39–42]. Figure 1 illustrates the steps of optimization technique used in this investigation.

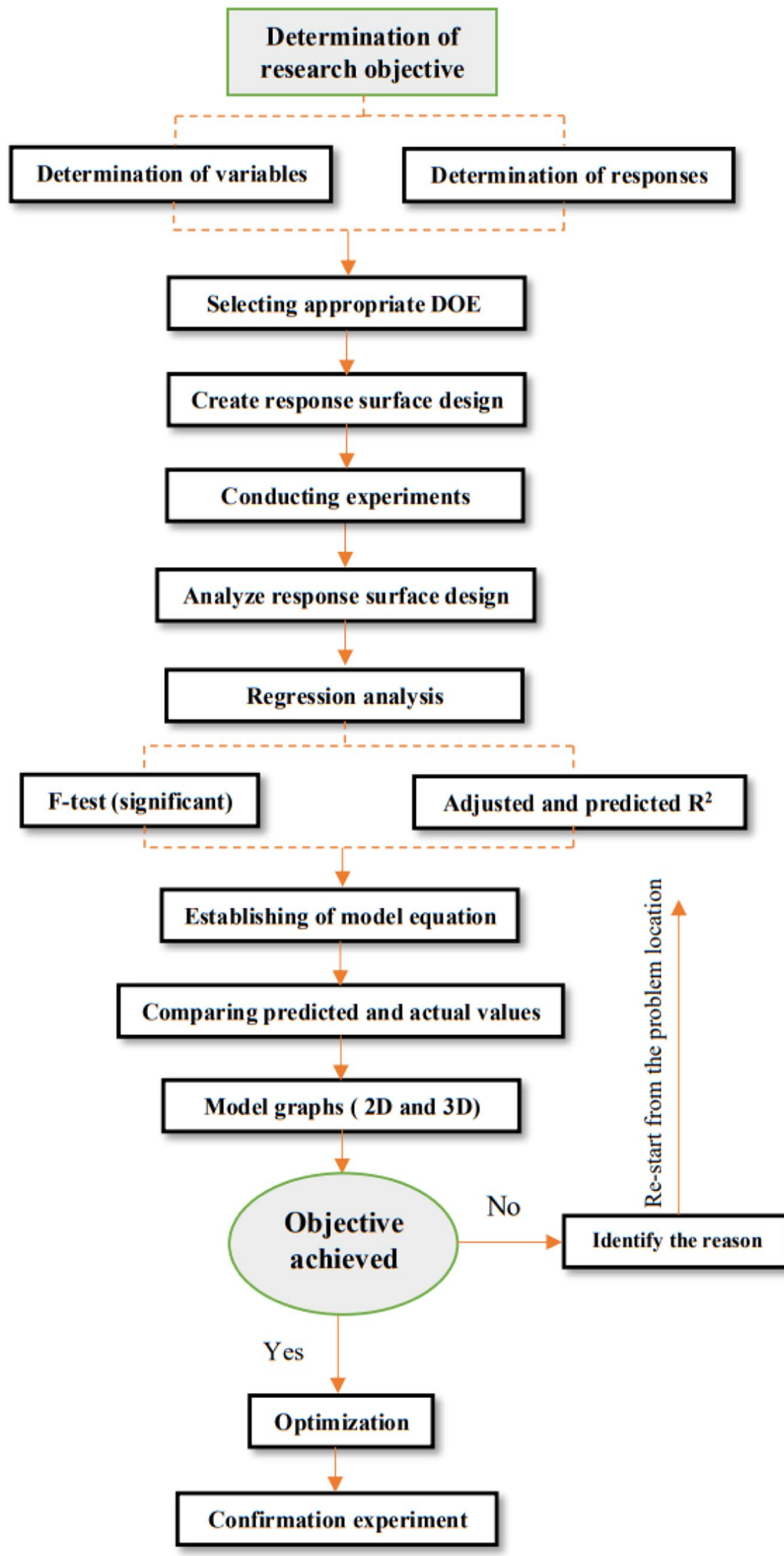


Fig. 1 Steps of optimization method

Table 1 Chemical composition of OPC and SF

Oxide component	CaO	SiO_2	MgO	Al_2O_3	P_2O_5	Na_2O	SO_3	K_2O	Fe_2O_3
OPC	64.93	21.6	1.61	4.18	0.09	0.09	3.35	0.78	3.32
SF	0.36	94.65	3.47	0.25	0.17	0.13	0.69	0.84	0.15

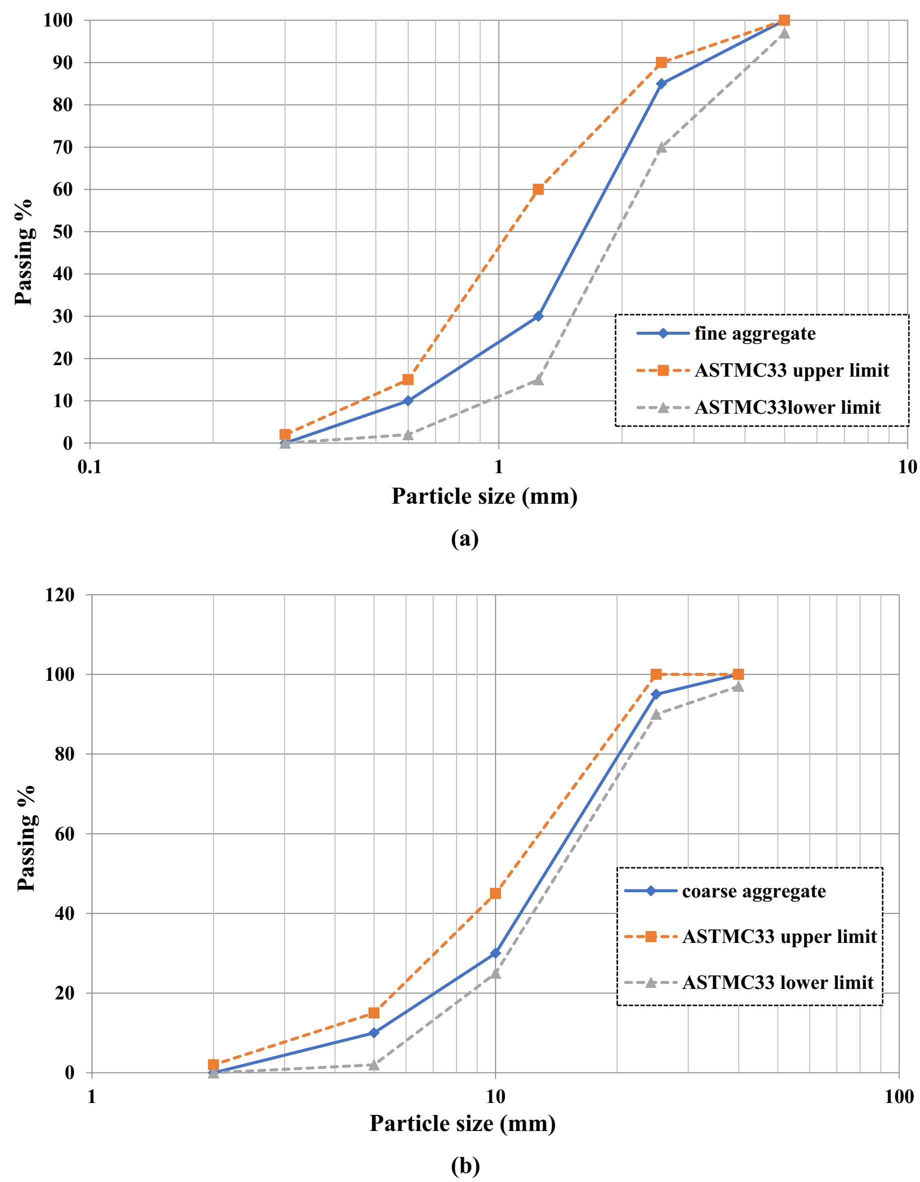


Fig. 2 Grading curves of used aggregate, **a** Fine aggregate and **b** Coarse aggregate

Experimental procedures

Materials

This investigation used ordinary Portland cement (OPC) CEM I 52.5 N in accordance with BS EN 197–1:2011 [43]. The cement was partially replaced by silica fume (SF), a cementitious substance. Table 1 summarizes the silica fume and cement's chemical compositions. As coarse aggregate, crushed dolomite with 12 mm nominal maximum size, 2.65 specific gravity, and water absorption of 0.98, and natural sand with 2.65 specific gravity and 0.62% water absorption rate were used. The coarse and fine aggregate met the grading requirements of BS EN 12620 [44]. Figure 2 demonstrates the grading curves for fine and coarse aggregate, respectively. A superplasticizer with a specific weight of 1.1 and compliance with ASTM C494 [45] type F was employed. The rate of water/cement was 0.25 for all concrete mixtures. The fibers are coarse monofilament (X_1) and staple (X_2) polypropylene fibers shown in Fig. 3. Tables 2 and 3 illustrate the physical characteristics of polypropylene (PP) fibers.

Mix proportion and design of experiments

During this experiment, 16 mixtures of concrete were designed, 13 mixes were designed using central composite design under response surface methodology in the Minitab program in accordance with Eq. (2), and (3) additional mixes (CO, CO-SF, CO-MF) were added as reference mixtures, where CO is a mixture without any fibers, CO-SF is a mixture with 0.75 kg/m^3 staple polypropylene fiber and CO-MF is a mixture with 4 kg/m^3 monofilament polypropylene fiber. The additional mixes were designed to make a good comparison between the properties of concrete without fibers and concrete using one type of polypropylene fibers to the concrete in which a hybrid of polypropylene fibers is used. The selection of control mixture was based on using the trial and error method to achieve compressive strength 65 ± 5 MPa at age 28 days and slump value in the range of 20 ± 2 cm without any segregation. Because low water-cement ratios are recommended when producing high performance concrete in order to increase strength, the ratio of water to cementitious materials (OPC + SF) was maintained at 0.25. To achieve the desired workability and to eliminate the expected negative effect of polypropylene fiber, super plasticizer was used at a rate of 2.5% of the weight of the cementitious materials.

$$N = 2^k? + 2k? + n, \quad (2)$$

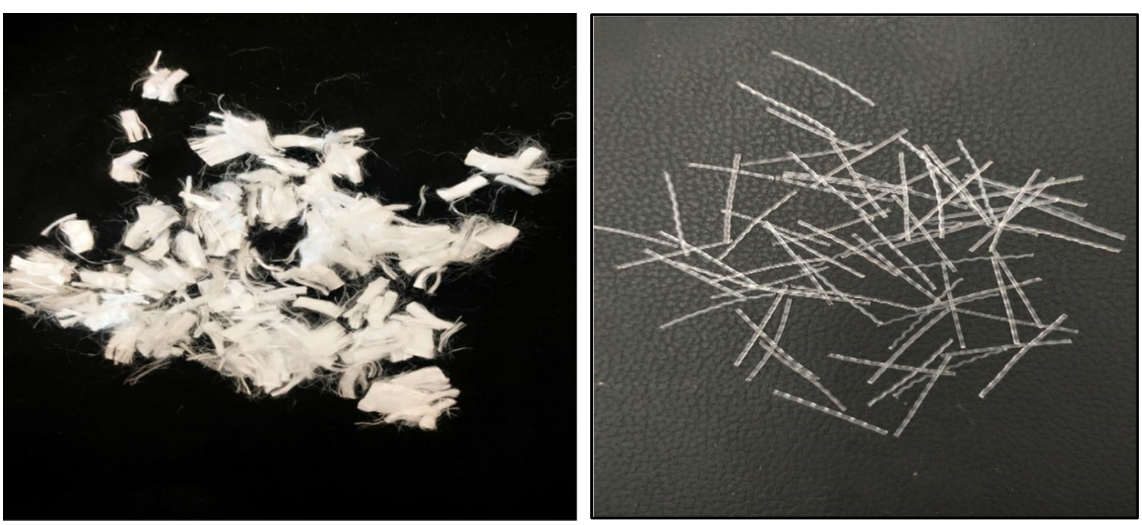
where N refers to the number of experiments; k refers to the numb of variables studied; n refers to the number of replicates [46]. In the test program, there were two independent variables. Including monofilament (X_1) and staple (X_2). The portion coded value is set at $\alpha = (2^k)^{0.25} = 2^{20.25} = 1.414$ with five different levels $-1.414, -1, 0, +1, +1.414$ refer to the final coded value. The variables' values and coded values are shown in Table 4. The proportion of HPC mixtures (kg/m^3) are shown in Table 5.

Table 2 Configuration and physical properties of monofilament fiber

Base	100% Virgin polypropylene		
Color	White	Water absorption	0.01- 0.02%
Fiber length	30 mm	Ignition point	590 ºC
Width	1.0 / 1.3 mm	Crack tensile strength	450/500 MPa
Thickness	0.30 / 0.50 mm	Young's elastic modulus	3.5 kN/mm^2
Density	0.90 gm /	Compressive strength	550/80 MPa

Table 3 Physical and mechanical properties of staple fiber

Fiber shape	straight
color	White
Fiber length (mm)	12
Diameter (mm)	0.038
Aspect ratio (l/d)	210
Density (kg/m^3)	1300
Tensile strength (MPa)	1620
Elastic Modulus (MPa)	42.5



(a) Staple fibers (b) Monofilament fibers

Fig.3 Photos of polypropylene fibers. **a** Staple fiber, **b** Monofilament fibers

Table 4 Limits and coded value of factors

Factor	Coded value				
	−1.141	−1	0	1	1.141
Monofilament (X_1)	3	3.292	2.5	4.707	5
Staple (X_2)	0.5	0.573	0.75	0.927	1

Samples preparations

To determine compressive strength and wet density, 100 mm cubic samples of fresh concrete were cast. The impact test was performed on cylindrical samples that measure 30 cm in height and 15 cm in diameter. Flexural tests were carried out on prismatic beams measuring 10 × 10x50 cm. In every test, three samples were examined for each curing age. The concrete resistance to elevated temperature was determined by exposing prismatic beams and concrete cubes to various temperatures at 200 °C, 400 °C, and 800 °C.

Mixing and curing

All concrete mixes were prepared in a fixed horizontal pan mixture with a capacity of 0.07 m^3. The coarse and fine aggregates were dry mixed for a minute prior to mixing. After adding the cement, the dry blending continued for another minute. Following the addition of water, the mixture was continued for an additional two minutes. The required amount of fibers was then added to the wet concrete. To make sure the fibers were evenly distributed throughout the concrete, the mixture was mixed for three minutes. After 24 h, all molds were removed, and the samples were left to cure in a water cabinet.

Tests methods

For fresh concrete, the slump test was conducted in accordance with ASTM C143 [47]. The compressive strength is carried out according to ASTM C39 [48] using a cube with a side length of 10 cm after 7-, 28-, and 56-days moist curing at ambient temperature. Testing was performed at a loading rate of 0.4 MPa/s on a 1000 kN capacity electronic servo testing machine. Flexural strength was performed on 10 cm × 10 cm × 50 cm prisms specimen according to ASTM C 1018 [49] using three point loading. The clear span of the beam is 40 cm. For compressive strength and flexural strength tests, three samples were examined per mix, and the average value was reported. Excellent impact resistance is one of FRC's most important features (dynamic energy absorption as well as strength). In order to examine the resistance of hybrid polypropylene fibers-reinforced HPC against impact, the concrete disks were made according to ACI 544.2R Standard [50]. The impact test was carried out on concrete cylinders cut with a masonry saw from 15 × 30 cm cylinder to four pieces 15 cm diameter and 6 cm thickness. The average number of blows required to start the first crack and finally cause failure at age 56 days was determined for all combinations. The drop-weight impact test is performed using a standard, manually operated 13.5 kg compaction hammer and it was dropped from a height equal to 50 cm. Using a heavier mass, such as 13.5 kg, which is better at transmitting impact loads, reduces the number of blows [51]. To study the effect of elevated temperature on compressive strength and flexural strength of concrete mixtures, the specimens were subjected to 200 °C, 400 °C, and 800 °C for 1 h. The heating rate was 20 °C/min. After such a treatment, the specimens were allowed to cool with

Table 5 Mixtures proportions (kg/m^3)

Mix No	OPC	SF	Coarse aggregate	Fine aggregate	water	SP	X_1	X_2
C_O	450	50	1110	740	125	12.5	–	–
C_{O-SF}	450	50	1110	740	125	12.5	–	0.75
C_{O-MF}	450	50	1110	740	125	12.5	4	–
M1	450	50	1110	740	125	12.5	4	0.75
M2	450	50	1110	740	125	12.5	4	1
M3	450	50	1110	740	125	12.5	4	0.75
M4	450	50	1110	740	125	12.5	4.707	0.573
M5	450	50	1110	740	125	12.5	4.707	0.927
M6	450	50	1110	740	125	12.5	5	0.75
M7	450	50	1110	740	125	12.5	3.292	0.573
M8	450	50	1110	740	125	12.5	3.292	0.927
M9	450	50	1110	740	125	12.5	4	0.75
M10	450	50	1110	740	125	12.5	3	0.75
M11	450	50	1110	740	125	12.5	4	0.75
M12	450	50	1110	740	125	12.5	4	0.5
M13	450	50	1110	740	125	12.5	4	0.75

a rate of 2 °C/min. Then, the specimens were stored in dry condition at room temperature for 2 h until testing. Also, the generated mixtures were examined using scanning electron microscopy (SEM).

Results, analysis, and optimization

Slump test

In order to assure consistency of polypropylene fiber-reinforced concrete from batch to batch, the slump test can be employed as a quality control test. The uniform distribution of the fibers inside the concrete, how they interact with the cement matrix, and how well the concrete may be cast or sprayed all affect the quality of fibers. The hybrid fiber must be completely covered with cement paste in order for it to have any benefit in the concrete. The slump started changing slightly as a result of the different fiber types and content. For concrete without fibers, the slump is 20.5 cm. The addition of monofilament or staple polypropylene fibers resulted in slightly decrease in slump results. Also, the slump of polypropylene hybrid fiber-reinforced concrete mixtures slightly decreased as compared to the other specimens without or with single fiber. Combining two different fibers can create a network structure that prevents mixes from segregating and flowing concrete, hence the slump has decreased. Due to their high content and surface area, the fibers will absorb more cement paste to wrap around, and the rise in mixture viscosity results in slump loss. Figure 4 illustrates the relation between the amount of fiber and slump, it's noticed that when the amount of hybrid polypropylene fibers increases, the slump decreases. This result agreed with A. A. Ramezanianpour et.al. [52], B. Chen and J. Liu [53], and C. Sakthipriya [54]. The fiber-reinforced concrete mixture test results are shown in Table 6.

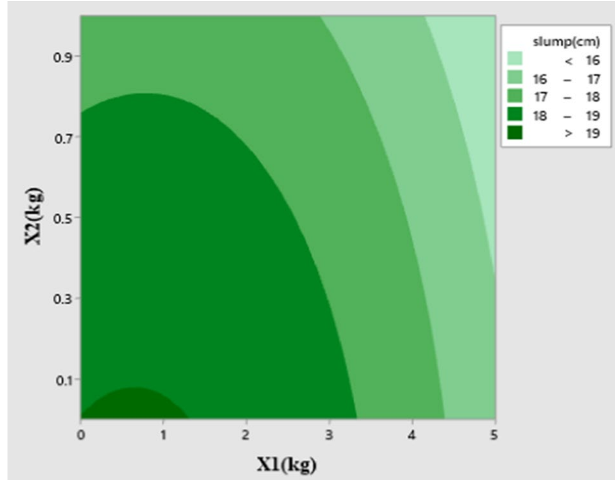


Fig. 4 Effect of monofilament fibers and staple fibers on concrete slump

Compressive strength

Compressive strength is one of the most important characteristics of hardened concrete, which is typically used as a characteristic material value for concrete classification. Fiber content has an effect on concrete's characteristics. It has been noted that hybrid-reinforced fiber concrete has greater compressive strength than concrete without polypropylene (PP) fibers. Compared with concrete without PP fibers, adding monofilament fiber at 4 kg/m^3 can increase compressive strength by 1.2%, while using staple fiber at 0.75 kg/m^3 can increase the compressive strength by 0.6%. Compressive strengths of polypropylene hybrid reinforced concrete have remarkably improvement ranged from 3.8 to 14.29%. As a result, it can be seen from the observations that the maximum percentage of increase in compressive strength can be obtained from the hybridization (5 kg monofilament and 0.75 kg staple) in the mix 6 and was equal to 14.29% compared with the control mix (C_O) at age 28 days, this result is in agreement with M. Hsie et.al [55]. The reason for this is that monofilament fiber has a high elastic modulus and rigidity for pretty tough shapes. Because these mixes contained fibers, the improvement in control over the crack formation and growth under axial stress led to the rise in compressive strength. The inclusion of silica fume enhances the connection between aggregate particles and cement paste while also increasing cement paste density, which improves cement strength. The effect of independent variables on the mixes was identified when the response surface of experimental test results was performed. The model's estimate and validation depended on the P-values. P-values above 0.05 are confirmed as insignificant, whereas for 95% confidence intervals, values below 0.05 indicate that the model terms are significant. On the other hand, Figs. 5, 6, and 7 show the impact of hybrid polypropylene fibers on compressive strength at 7, 28 and 56 days. It has been found that the compressive strength improves along with the increase of hybrid fibers. The analysis of variance for compressive strength at 28 days is presented in Table 7. Equation (3) was used to set up the models' formula as follows:

$$\text{Fc 28 days (MPa)} = 67.235 - 1.794X_1 + 2.459X_2 + 0.5026X_1 * X_1 - 2.683X_2 * X_2 + 1.491X_1 * X_2 \quad (3)$$

Table 6 Results of mixtures of the fiber-reinforced concrete

Mix No	Slump (cm)	Compressive strength (MPa)						Flexural strength (MPa)			
		7 days	28 days	56 days				56 days			
				20 °C	200 °C	400 °C	800 °C	20 °C	200 °C	400 °C	800 °C
C_O	20.5	58.8	67.20	75.52	73.9	53.7	40.0	10.50	9.80	4.0	2.4
$C_{O\text{-}SF}$	18	59.3	67.60	75.90	74.0	54.0	42.0	10.80	10.00	4.8	3.1
$C_{O\text{-}MF}$	17.2	61.2	68.00	77.80	75.0	57.0	45.0	11.00	10.20	5.9	3.6
M1	16.5	64.0	72.80	80.00	80.0	64.7	43.0	13.00	12.00	7.6	4.2
M2	16	65.0	73.75	81.00	79.0	61.3	44.8	13.67	12.17	8.4	4.3
M3	16.5	64.0	72.80	80.00	80.0	64.7	43.0	13.00	12.00	7.6	4.2
M4	16.2	65.6	74.40	82.00	80.0	63.0	49.2	13.90	13.20	9.7	5.5
M5	15.7	67.0	76.40	84.00	83.0	69.0	51.4	14.50	14.20	10.0	6.0
M6	15.5	67.4	76.80	84.60	83.5	70.4	54.0	14.90	14.40	11.0	6.8
M7	17.6	62.0	70.20	77.60	76.0	56.4	35.7	12.00	11.00	5.7	2.8
M8	17	63.0	71.60	79.00	78.0	60.0	39.0	12.40	11.50	6.0	3.5
M9	16.5	64.0	72.80	80.00	80.0	64.7	43.0	13.00	12.00	7.6	4.2
M10	17.5	61.5	69.80	77.00	75.7	55.0	35.7	12.20	11.00	5.5	3.2
M11	16.5	64.0	72.80	80.00	80.0	64.7	43.0	13.00	12.00	7.4	3.8
M12	16.8	63.5	72.00	79.20	79.0	62.8	40.8	12.50	11.00	7.0	3.0
M13	16.5	64.0	72.80	80.00	80.0	64.7	43.0	13.00	12.00	7.6	4.2

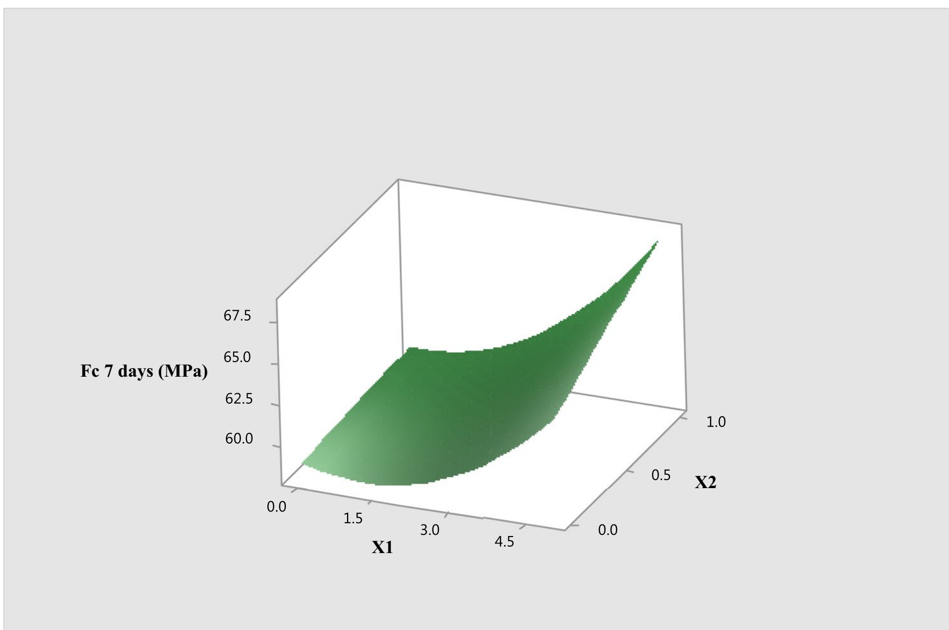


Fig. 5 Surface plot for compressive strength vs monofilament and staple fibers at age 7 days

Figure 8 presents the compressive strength of concrete mixtures after heating to 200 °C, 400 °C, and 800 °C. For all of the mixes, a slight decrease in residual strength compared to room temperature occurred after heating to 200 °C. After being heated to 400 °C and 800 °C, all mixtures showed a significant reduction in compressive strength. This is because such a compact structure experiences extra extensive inner cracking as a result of pressure buildup brought on by the evaporation of chemically and physically bonded water. According to some experts, the breakdown of calcium hydroxide is mostly to blame for this strength reduction. The decomposition of C-S–H,

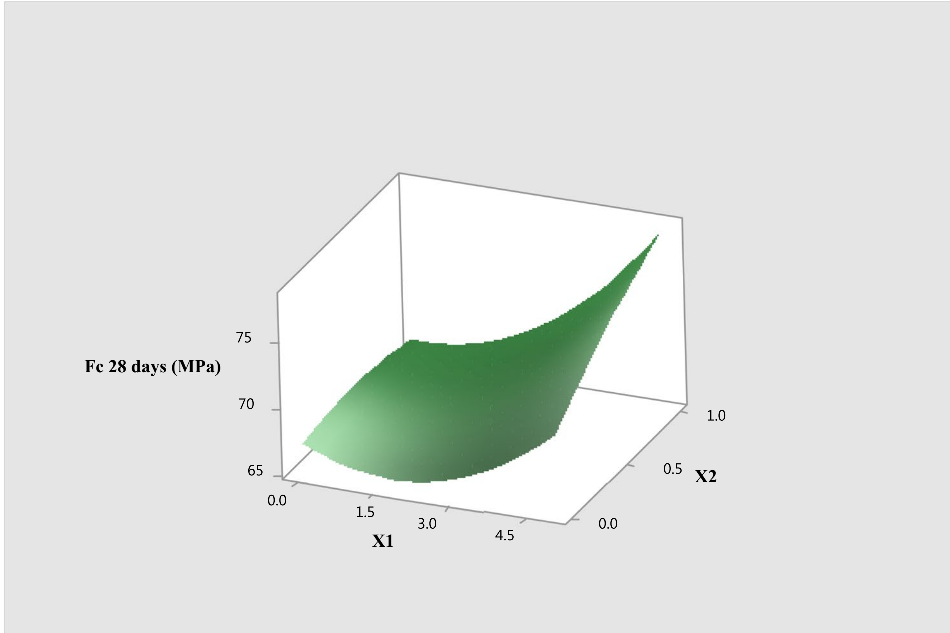


Fig. 6 Surface plot for compressive strength vs monofilament and staple fibers at age 28 days

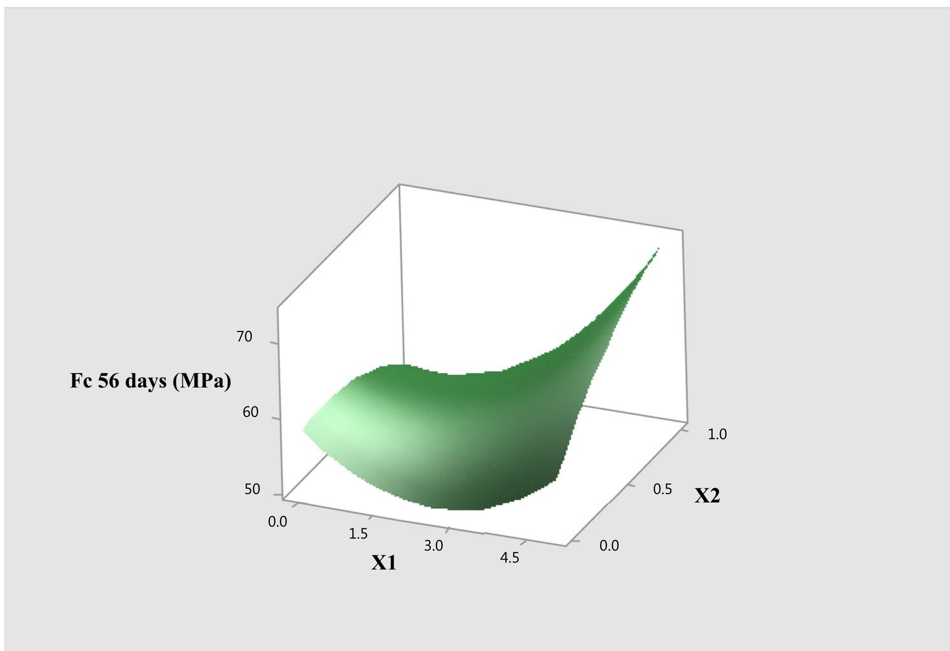


Fig. 7 Surface plot for compressive strength vs monofilament and staple fibers at age 56 days

$Ca(OH)_2$, and $CaCO_3$ was the cause of the residual compressive strength decreasing above 400 °C.

Flexural strength

Polypropylene hybrid fibers achieve an effective improvement on flexural strength. This result agreed with A. Nkem Ede and A. Oluwabambi Ige [26]. A compressive strength case is significantly less important than the positive impact of fiber content of flexural strength. The hybrid fibers can resist tensile stress in the tensile zone directly under the neutral axis when loads are applied to the beams. Coarse monofilament fibers can spread the stress of macro-cracks and bridge failures of tiny staple fibers until they are no longer able to manage the load. Increasing fiber content and bonding effect are the most important factors in enhancing flexural characteristics. Due to the completion of the reaction, the flexural strength of the polypropylene paste increased over time. The fracture faces and fibers distribution of polypropylene fiber-reinforced concrete are shown

Table 7 The analysis of variance for 28 days compressive strength

Source	DF	Adj SS	Adj MS	*F*–Value	*P*–Value
Model	6	120.701	20.1168	506.17	0.000
X_1	1	45.720	45.719	1150.37	0.000
X_2	1	4.621	4.621	116.28	0.000
X_1*X_1	1	12.477	12.476	313.9	0.000
X_2*X_2	1	0.616	06157	15.49	0.003
X_1*X_2	1	6.027	6.027	151.65	0.000
Error	9	0.358	0.0397	–	–
Lack–of–Fit	6	0.358	0.0596	–	–
R^2–Adjusted	99.51%	–	–	–	–
R^2– Predicted	94.04%	–	–	–	–

in Fig. 9. The high effect of hybrid polypropylene fiber on flexural strength is shown in Fig. 10. The analysis of variance for flexural strength at 56 days is summarized in Table 8.

The following formula was used to set up the models in Eq. (4), and the pareto chart derived from the analysis of the response surface design a.

re shown in Fig. 11 to show how the standardized effects of all variables on flexural strength are shown.

$$\text{Flexural strength 56 days (MPa)} = 10.423 - 0.7273X_1 + 1.693X_2 + 0.2146X_1 * X_1 - 1.411X_2 * X_2 + 0.5514X_1 * X_2 \quad (4)$$

The effect of temperature on reinforced concrete was studied on flexural strength after curing for 56 days. According to the results, which concur with D. Zeng et al. [56], H. U. Ahmed et al. [57], and Tahwia et al. [58]. The flexural strength dropped as temperature increased. Hybrid polypropylene fibers can assist avoid explosive spalling of concrete at high temperatures because they dissolve to reduce

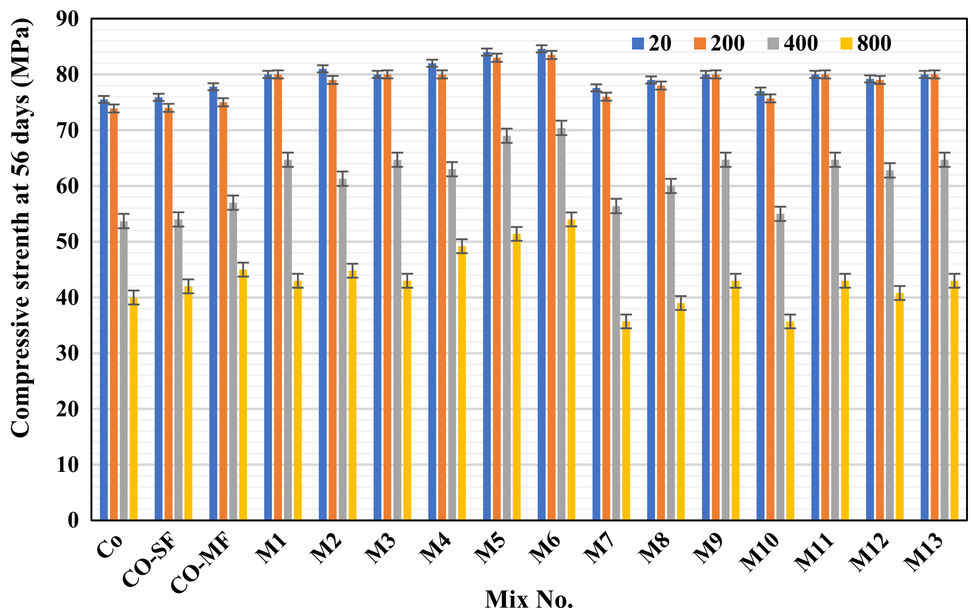


Fig. 8 Effect of elevated temperature on compressive strength at age 56 days

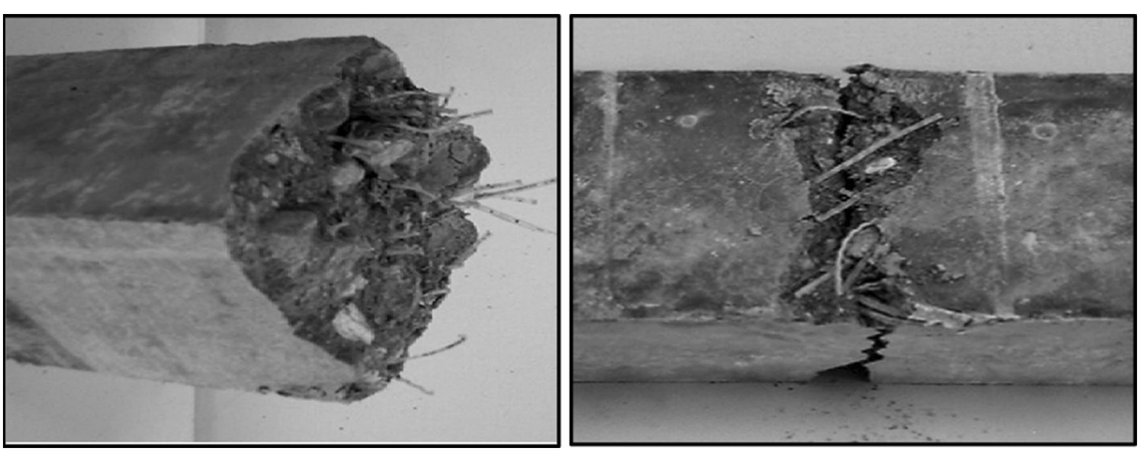


Fig. 9 Fracture faces of polypropylene fiber reinforced concrete

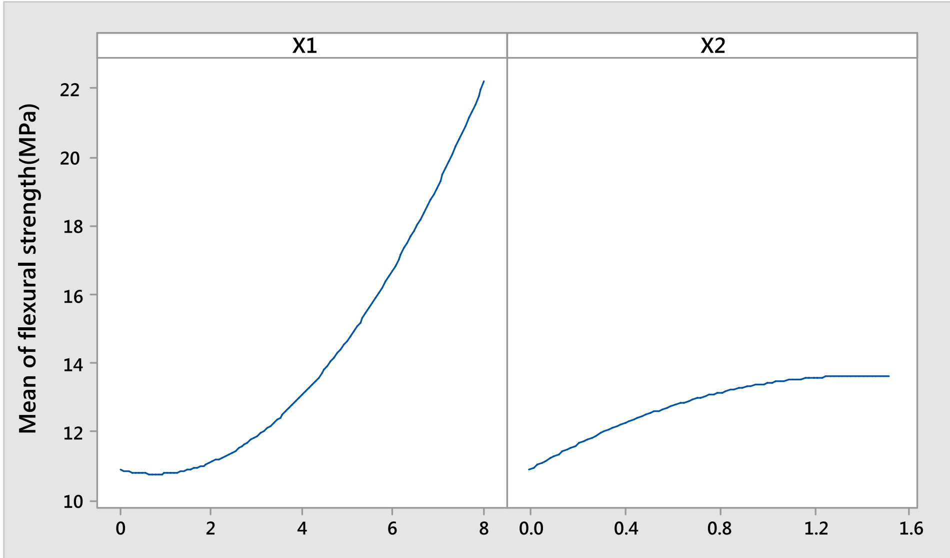


Fig. 10 Main effect plot for flexural strength at age 56-days

Table 8 Analysis of variance for 56 days flexural strength

Source	DF	Adj SS	Adj MS	*F*–Value	*P*–Value
Model	6	22.9294	3.82157	181.3	0.000
Linear	2	8.6643	4.33215	205.56	0.000
X_1	1	8.0410	8.0410	381.54	0.000
X_2	1	0.7583	0.7583	35.980	0.000
X_1*X_1	1	2.2744	2.2744	107.92	0.000
X_2*X_2	1	0.1703	0.1703	8.08	0.019
X_1*X_2	1	0.8242	0.82417	39.11	0.000
Error	9	0.1897	0.02108	–	–
Lack–of–Fit	6	0.1897	0.03161	–	–
R–Sq	99.18%	–	–		–
R^2– Adjusted	98.63%	–	–	–	–

pore pressure prior to spalling. Flexural strength is mostly unchanged at 200 °C despite the dehydration of monosulfoaluminate, ettringite, and C-S–H, as well as the evaporation of free water in capillary pores [58, 59]. The results of flexural strength after exposure to different temperature are shown in Fig. 12.

Figure 13 a, b, c, and d illustrates the impact of hybrid polypropylene fiber on flexural strength after exposure to a different temperature, the results show that hybrid polypropylene fibers have a highly significant effect for resist high temperatures, these results agree with J. Xiao and H. Falkner [60]. Figure 14 shows how the optimization process could be used to determine the ideal values of factors to get the desired values of responses. The suggested mixture composed of 5 kg/m^3 of monofilament fiber and 1 kg/m^3 of staple fiber. The predicted results are 81 MPa compressive strength, 13.5 MPa flexural strength, and 16.37 cm slump.

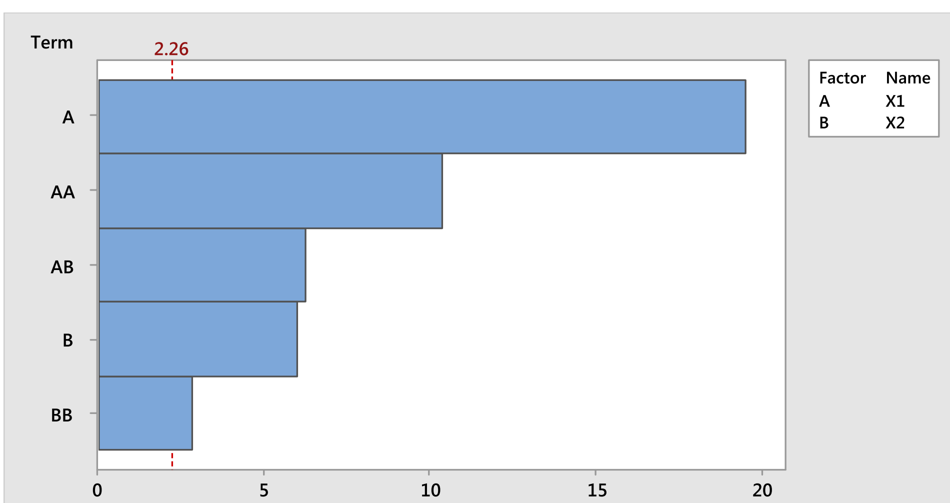


Fig. 11 Pareto chart of standard effects of the input parameters in flexural strength at age 56-days

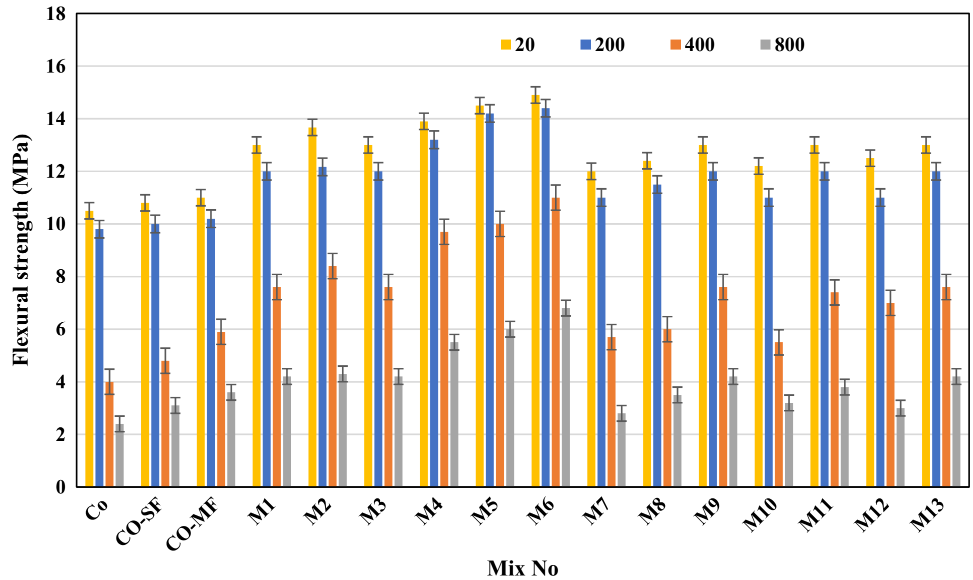


Fig. 12 Effect of elevated temperature on flexural strength at age 56 days

Figure 15a shows the electric oven that was utilized in this study, additionally; Fig. 15b illustrates the shape of the sample after the heating process.

Impact test

Impact resistance is one of FRC's important characteristics. The test can be utilized to compare the benefits of hybrid polypropylene fiber on concrete. The failure behavior of specimens under impact load is depicted in Fig. 16. The number of blows required at the initial crack and complete failure is shown in Table 9. It's noticed that the number of blows increased with the addition of hybrid polypropylene fiber. This result is in agreement with O. A. Ahmad and M. Awwad [61]. The blow numbers of ultimate failure in plain concrete were found to be nearly similar to those of the initial crack, indicating that the plain concrete specimen fails immediately once the crack occurs. Hybrid fiber concrete's brittleness was successfully decreased, and its impact resistance was increased, by the addition of polypropylene fibers.

Microstructure

The concrete specimens' microstructure is examined using scanning electron microscopy (SEM). Materials' mechanical characteristics and their microstructure are closely related. SEM images of hybrid polypropylene fibers and non-fiber concrete are shown in Fig. 17. The results show that all mixes are cohesive, compacted, and density and the percentage of voids is low with the presence of some micro-cracks in the control mixture (without fibers) as shown in Fig. 17a. However, the microstructure of concrete is improved by the presence of staple polypropylene fibers (Fig. 17b) or monofilament polypropylene fibers (Fig. 17c). It is observed from Fig. 17d the microstructure of hybrid polypropylene fiber is the most compact, homogeneous, and the C-S–H gels also exhibit excellent development. It was difficult to notice the existence of micro-cracks, these findings agree with Z. Yuan and Y. Jia [62]. The results of SEM agreed with the results of compressive and flexural strength. SEM analysis proves that hybridization of polypropylene fibers plays an important role in improvement in all mechanical properties of concrete.

Conclusion

This study aims to evaluate, optimize, and predict the effect of hybrid polypropylene fibers (coarse monofilament and staple fibers) on the mechanical characteristics and resistance to elevated temperature of high-performance concrete. The key conclusions in this paper can be summarized as follows:

- Concrete mixtures reinforced with hybrid polypropylene fibers have significantly improved in terms of compressive strength, flexural strength ranged, impact resistance, and resistance to elevated temperature while the workability slightly decreased.
- The compressive strength and flexural strength of hybrid polypropylene fiber-reinforced concrete increased by (1.9 to 12%) and (14.28 to 41.9%), respectively, at age 56 days compared to control mixture without fibers.
- The hybridization of 5 kg monofilament and 0.75 kg staple fibers achieved the highest compressive strength (84.6 MPa), flexural strength (14.9 MPa), and the optimum impact resistance at age 56 days. The increase of

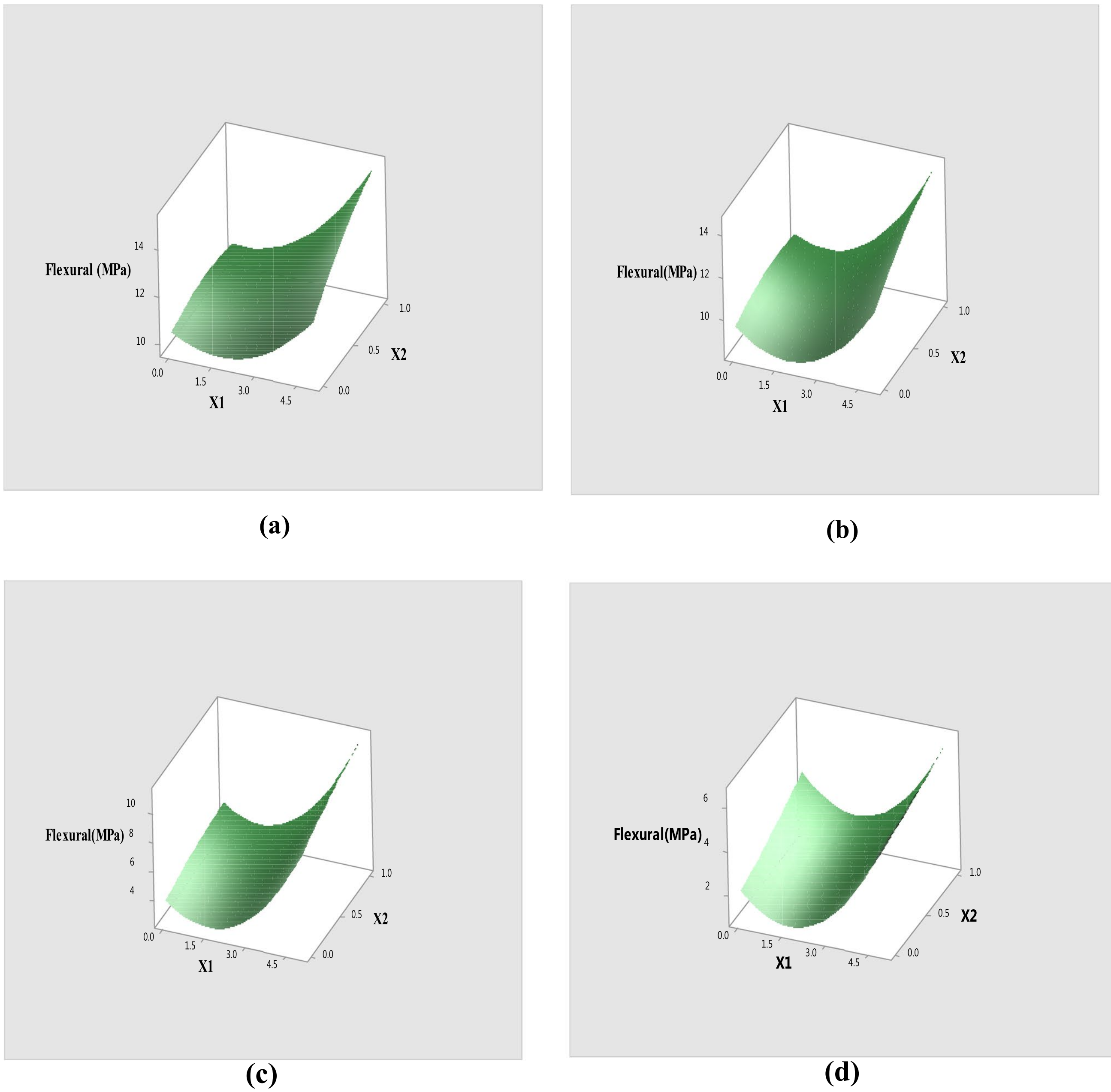


Fig. 13 Surface plot of flexural strength at **a** 20 °C and after exposed to **b** 200 °C, **c** 400 °C and **d** 800 °C

coarse monofilament fibers significantly improved the spalling resistance performance.

- The residual compressive strength of mixture containing 5 kg monofilament and 0.75 kg staple fibers up to 63.8% of the initial strength after exposure to 800 ^{0}C.
- Investigations using (SEM) technology demonstrated that adding hybrid polypropylene fibers to concrete could enhance interfacial transition zones and the matrix between aggregates and the polypropylene matrix. Subsequently, improved the mechanical properties.
- Using RSM, the regression model offers a detailed analysis of the hybrid polypropylene fibers-reinforced concrete properties over the selected range of fiber volume fraction. The results of the lack-of-fit test along with the high values of the coefficients of multiple determinations (R^2) demonstrated that the polynomial regression model was enough to forecast the necessary performance of hybrid polypropylene fiber concrete. The ANOVA results also confirmed, based on a very low P-value, that the inclusion of all model parameters is statistically significant.

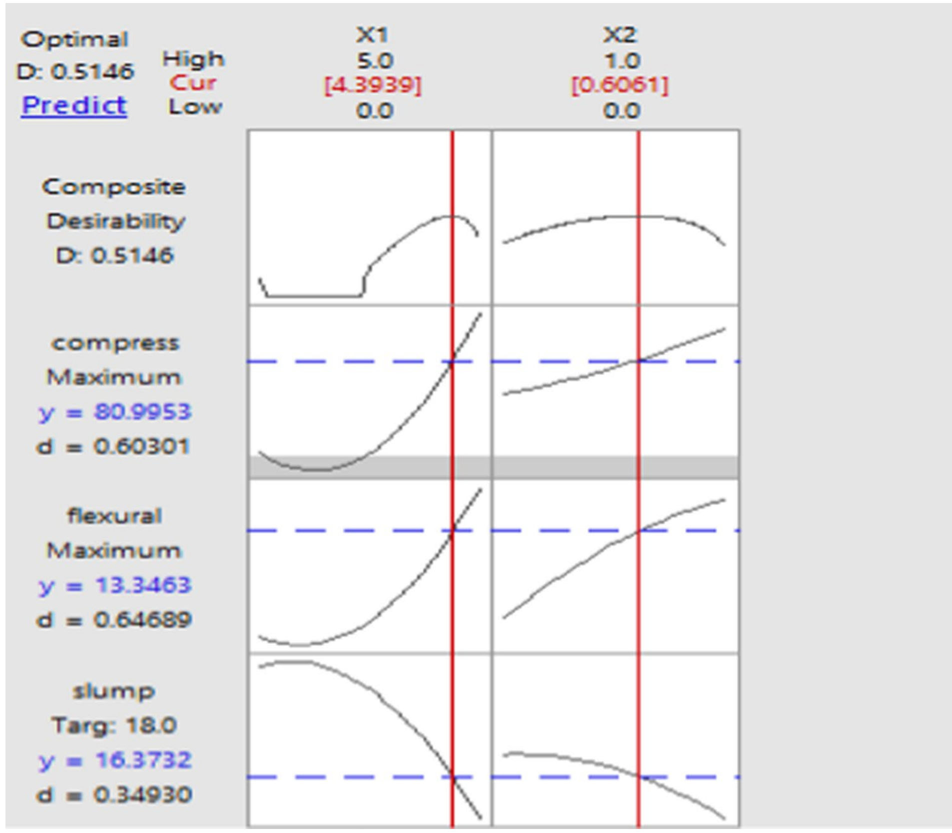


Fig. 14 Optimum content of variables to achieve the desirable values of responses

(a) (b)

Fig. 15 View of the heating process of the samples and the channels produced in the samples when the polypropylene fibers melted

The authors suggest that future research examine the impact of hybrid polypropylene fibers on the mechanical properties, durability, and resistance to elevated temperature of ultra-high-performance concrete and geopolymer concrete in order to gain a deeper understanding through the research society's collaborative efforts.

Fig. 16 The shapes of failure on hybrid polypropylene reinforced concrete under impact load

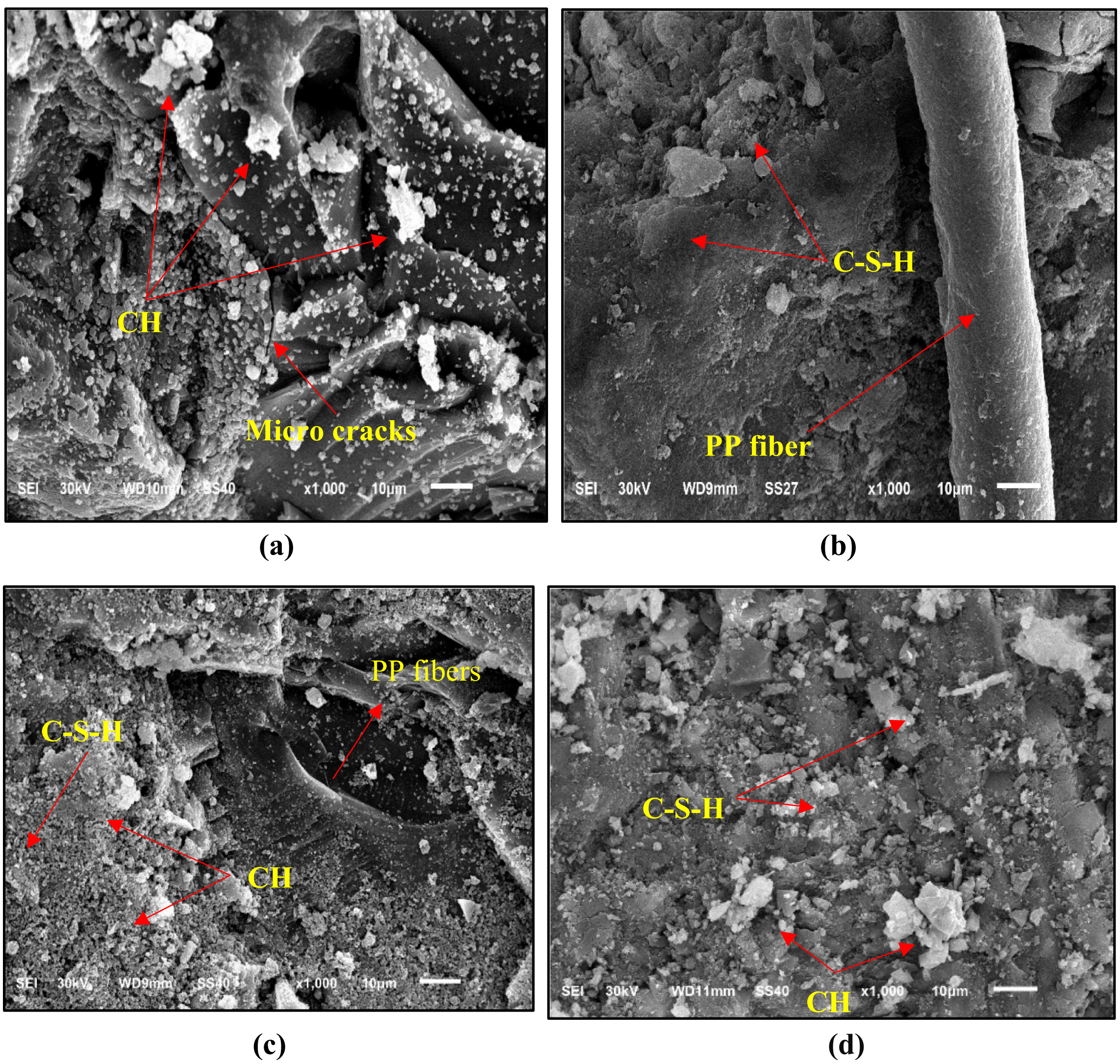


Fig. 17 SEM images for **a** mix C_O, **b** mix $C_{O\text{-}SF}$, **c** mix $C_{O\text{-}MF}$, **d** mix 6

Table 9 The impact test results

Number of blows	Mixture number															
	C_O	C_{O-SF}	C_{O-MF}	1	2	3	4	5	6	7	8	9	10	11	12	13
Initial crack	3	5	7	13	15	13	17	18	20	9	11	13	8	13	14	13
Failure crack	4	7	10	15	18	15	20	22	25	11	14	15	10	15	17	15

Authors contribution The participation of the authors in this investigation was made with an equal amount of contributions.

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Data availability The research data associated with a paper is available.

Declarations

Conflict of interest All authors have participated in (a) conception, design, analysis and interpretation of the data; (b) drafting the article and revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Ethics approval The corresponding author is ready to prepare to send all documentation of compliance with ethical standards and send if requested during peer review or after publication. The manuscript has not been submitted anywhere other than this journal (silicon). The submitted work is original and has not been published elsewhere in any form or language.
Results are presented clearly, honestly, and without fabrication, falsification or in appropriate data manipulation (including image-based manipulation). Authors were required to adhere to discipline –specific rules for acquiring ,electing and processing data.
No data, text, or theories by others are presented as they were authors own (plagiarism).

Consent to participate Ok.
Consent for publication The authors agreed to transfer the copy right of the article to the publisher (subscription).

References

1. Afroughsabet V, Ozbakkaloglu T (2015) Mechanical and durability properties of high- strength concrete containing steel and polypropylene fibers. Constr Build Mater 94:73–82. https://doi.org/10.1016/j.conbuildmat.2015.06.051
2. Tahwia AM, Elgendy GM, Amin M (2022) (2022) Mechanical properties of affordable and sustainable ultra-high-performance concrete. Case Studies in Construction Materials 16:e01069. https://doi.org/10.1016/j.cscm.2022.e01069
3. Brandt AM (2008) Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. Compos Struct 86(1–3):3–9. https://doi.org/10.1016/j.compstruct.2008.03.006
4. Mohammadi Y, Singh SP, Kaushik SK (2008) Properties of steel fibrous concrete containing mixed fibres in fresh and hardened state. Constr Build Mater 22(5):956–965. https://doi.org/10.1016/j.conbuildmat.2006.12.004
5. Yazici Ş, Inan G, Tabak V (2007) Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. Constr Build Mater 21(6):1250–1253. https://doi.org/10.1016/j.conbuildmat.2006.05.025
6. Thomas J, Ramaswamy A (2007) Mechanical properties of steel fiber-reinforced concrete. J Mater Civil Eng 19:385–392
7. Afroughsabet, V., Biolzi, L., & Ozbakkaloglu, T. (2016). High-performance fiber-reinforced concrete: a review. In: Journal of Materials Science, Springer. US. https://doi.org/10.1007/s10853-016-9917-4
8. Karahan O, Atiş CD (2011) The durability properties of polypropylene fiber reinforced fly ash concrete. Mater Des 32(2):1044–1049. https://doi.org/10.1016/j.matdes.2010.07.011
9. Tahwia AM, El-Far O, Amin M (2022) Characteristics of sustainable high strength concrete incorporating eco-friendly materials. Innov Infrastruct Solut. https://doi.org/10.1007/s41062-021-00609-7
10. Sridhar R, Prasad R (2019) Study on mechanical properties of hybrid fiber reinforced engineered cementitious composites. Revista Roman Mater/ Romanian J Mater 49(3):424–433. https://doi.org/10.1088/1755-1315
11. Turba, Y., Solodkyy, S., & Markiv, T. (2020). Strength and fracture toughness of cement concrete, dispersedly reinforced by combination of polypropylene fibers of two types. In: lecture Notes in Civil Engineering (Vol. 47). Springer International Publishing. https://doi.org/10.1007/978-3-030-27011-7_62
12. Akeed MH, Qaidi S, Ahmed HU, Faraj RH, Mohammed AS, Emad W, Tayeh BA, Azevedo ARG (2022) Ultra-high-performance fiber-reinforced concrete part I: developments, principles, raw materials. Case Studies Construct Mater 17:e01290. https://doi.org/10.1016/j.cscm.2022.e01290
13. Akeed MH, Qaidi S, Ahmed HU, Faraj RH, Mohammed AS, Emad W, Tayeh BA, Azevedo ARG (2022) Ultra-high-performance fiber-reinforced concrete part II: hydration and microstructure. Case Studies in Construction Materials 17:e01289. https://doi.org/10.1016/j.cscm.2022.e01289
14. Akeed MH, Qaidi S, Ahmed HU, Emad W, Faraj RH, Mohammed AS, Tayeh BA, Azevedo ARG (2022) Ultra-high-performance fiber-reinforced concrete part III: fresh and hardened properties. Case Studies Construct Mater 17:e01265. https://doi.org/10.1016/j.cscm.2022.e01265

15. Akeed MH, Qaidi S, Ahmed HU, Faraj RH, Mohammed AS, Emad W, Tayeh BA, Azevedo ARG (2022) Ultra-high-performance fiber-reinforced concrete part IV: durability properties, cost assessment, applications, and challenges. Case Studies in Construct Mater 17:e01271. https://doi.org/10.1016/j.cscm.2022.e01271
16. Akeed MH, Qaidi S, Ahmed HU, Faraj RH, Majeed SS, Mohammed AS, Emad W, Tayeh BA, Azevedo ARG (2022) Ultra-high-performance fiber-reinforced concrete part V: mixture design, preparation, mixing, casting, and curing. Case Studies in Construct Mater 17:e01363. https://doi.org/10.1016/j.cscm.2022.e01363
17. Cao M, Zhang C, Lv H (2014) Mechanical response and shrinkage performance of cementitious composites with a new fiber hybridization. Constr Build Mater 57:45–52. https://doi.org/10.1016/j.conbuildmat.2014.01.088
18. Ahmed HU, Faraj RH, Hilal N, Mohammed AA, Sherwani AFH (2021) Use of recycled fibers n concrete composites: a systematic comprehensive review. Compos B Eng 215(March):108769. https://doi.org/10.1016/j.compositesb.2021.108769
19. Tahwia AM, Helal KA, Youssf O (2023) Chopped basalt fiber-reinforced high-performance concrete: an experimental and analytical study. J Compos Sci 7:250. https://doi.org/10.3390/jcs7060250
20. Tahwia AM (2017) Performance of ultra-high performance fiber reinforced concrete at high temperatures. Int J Eng Innov Technol 6(10):1–7
21. Noumowe A (2005) Mechanical properties and microstructure of high strength concrete containing polypropylene fibres exposed to temperatures up to 200 °C. Cem Concr Res 35(11):2192–2198. https://doi.org/10.1016/j.cemconres.2005.03.007
22. Hussein HH, Rejeb SK, & Abd HT (2014) ISSN : 1813–162X Tikrit Journal of Engineering Sciences available online at : http://www.tj - es . com Effect of Hybrid Fibers on the Mechanical Properties of High Strength Concrete Engineering Technical College / Mosul," vol. 70, 2014.
23. Pangestuti EK, Handayani S, Adila H, Primerio P (2021) The effect of polypropylene fiber addition to mechanical properties of concrete. IOP Conf Series Earth Environl Sci. https://doi.org/10.1088/1755-1315/700/1/012057
24. Banthia N, Nandakumar N (2003) Crack growth resistance of hybrid fiber reinforced cement composites. Cement and Concrete Compos 25:3–9
25. Hsie M, Tu C, Song PS (2008) Mechanical properties of polypropylene hybrid fiber-reinforced concrete. Mater Sci Eng, A 494(1–2):153–157. https://doi.org/10.1016/j.msea.2008.05.037
26. Approach D, Synthetic U, Fibers D (2018) effect of hybrid discrete fibers on mechanical properties of FRC effect of hybrid discrete fibers on mechanical properties. Mater Sci Eng. https://doi.org/10.1088/1757-899X/454/1/012170
27. Yermak N, Pliya P, Beaucour AL, Simon A, Noumowé A (2017) Influence of steel and/or polypropylene fibres on the behaviour of concrete at high temperature: Spalling, transfer and mechanical properties. Constr Build Mater 132:240–250. https://doi.org/10.1016/j.conbuildmat.2016.11.120
28. Guan S (2006) "Influence of polypropylene fiber on concrete performance", Jianzhu Jiegou Xuebao/Journal Build. Struct 27:44–49
29. Behnood A, Ghandehari M (2009) Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures. Fire Saf J 44(8):1015–1022. https://doi.org/10.1016/j.firesaf.2009.07.001
30. Tahwia AM, Hamido MA, Elemam WE (2023) Using mixture design method for developing and optimizing eco-friendly ultra-high performance concrete characteristics. Case Studies Construct Mater 18:e01807. https://doi.org/10.1016/j.cscm.2022.e01807
31. Zahiri F, Eskandari-Naddaf H (2019) Optimizing the compressive strength of concrete containing micro-silica, nano-silica, and polypropylene fibers using extreme vertices mixture design. Front Struct Civ Eng 13(4):821–830. https://doi.org/10.1007/s11709-019-0518-6
32. Abdellatief M, Elemam WE, Alanazi H, Tahwia AM (2023) Production and optimization of sustainable cement brick incorporating clay brick wastes using response surface method". Ceram Int 49(6):9395–9411. https://doi.org/10.1016/j.ceramint.2022.11.144
33. Ahmed TW, Ali AAM, Zidan RS (2020) Properties of high strength polypropylene fiber concrete containing recycled aggregate. Constr Build Mater 241:118010. https://doi.org/10.1016/j.conbuildmat.2020.118010
34. Abd Ellatief M, Abd Elrahman M, Elgendy GM, Bassioni G, Tahwia AM (2023) Response surface methodology-based modelling and optimization of sustainable UHPC containing ultrafine fly ash and metakaolin. Constr Build Mater 388:131696. https://doi.org/10.1016/j.conbuildmat.2023.131696
35. El-Kholy AM, Tahwia AM, Elsayed MM (2022) Prediction of simulated cost contingency for steel reinforcement in building projects: ANN versus regression-based models. Int J Constr Manag 22(9):1675–1689. https://doi.org/10.1080/15623599.2020.1741492
36. Asghar A, Raman AAA, Daud WMAW (2014) A Comparison of central composite design and taguchi method for optimizing fenton process. Sci World J. https://doi.org/10.1155/2014/869120
37. Danmaliki GI, Saleh TA, Shamsuddeen AA (2017) Response surface methodology optimization of adsorptive desulfurization on nickel/activated carbon. Chem Eng J 313:993–1003. https://doi.org/10.1016/j.cej.2016.10.141
38. Köksal F, Şahin Y, Gencel O, Yiğit I (2013) Fracture energy-based optimisation of steel fibre reinforced concretes. Eng Fract Mech 107:29–37. https://doi.org/10.1016/j.engfracmech.2013.04.018
39. Elemam WE, Abdelraheem AH, Mahdy MG, Tahwia AM (2020) Optimizing fresh properties and compressive strength of self-consolidating concrete. Constr Build Mater 249:118781. https://doi.org/10.1016/j.conbuildmat.2020.118781
40. Elemam WE, Abdelraheem AH, Mahdy MG, Tahwia AM (2022) Prediction and optimization of self-consolidating concrete properties. ACI Mater J 119(1):91–104
41. Ba D, Boyaci IH (2007) Modeling and optimization i: usability of response surface methodology. J Food Eng 78(3):836–845. https://doi.org/10.1016/j.jfoodeng.2005.11.024
42. Barazandeh A, Jamali HA, Karyab H (2021) Equilibrium and kinetic study of adsorption of diazinon from aqueous solutions by nano-polypropylene-titanium dioxide: optimization of adsorption based on response surface methodology (RSM) and central composite design (CCD). Korean J Chem Eng 38(12):2436–2445. https://doi.org/10.1007/s11814-021-0863-8
43. BS EN 197-1:2011 (2011), Cement–Part 1: composition, specifications and conformity criteria for common cements," British Standards Institution, London, UK
44. BS EN 12620:2002 (2002), "Aggregates for Concrete," British Standards Institution, London, UK, 50
45. ASTM C494/C494M-08 (2008), Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA. 10
46. Balcikanli Bankir M, Sevim UK (2020) Performance optimization of hybrid fiber concrete according to mechanical properties.

Constr Build Mater 261:119952. https://doi.org/10.1016/j.conbuildmat.2020.119952
47. ASTM C-143 (2015). Standard test method for slump of hydraulic- cement concrete, ASTM International, West Conshohocken, PA,
48. ASTM C 3939M-21 (2021). Standard Test Method For Compressive Strength of Cylindrical Specimens. ASTM International. West Conshohocken, PA.
49. ASTM C 1018–97(1997). Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading). ASTM International, West Conshohocken, PA.
50. ACI Committee 544.2R-89 (2009) Measurement of properties of fiber reinforced concrete. ACI Committee 544.
51. Zhang MH, Sharif MSH, Lu G (2016) Impact resistance of high-strength fibre-reinforced concrete. Concrete Res. https://doi.org/10.1680/macr.2007.59.3.199
52. Ramezanianpour AA, Esmaeili M, Ghahari SA, Najafi MH (2013) Laboratory study on the effect of polypropylene fiber on durability, and physical and mechanical characteristic of concrete for application in sleepers. Constr Build Mater 44:411–418. https://doi.org/10.1016/j.conbuildmat.2013.02.076
53. Chen B, Liu J (2005) Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability. Cem Concr Res 35(5):913–917. https://doi.org/10.1016/j.cemconres.2004.07.035
54. Sakthipriya C (2021) Experimental investigation on hybrid fiber reinforced green cement concrete. Inter J Res Appl Sci Eng Technol 9(2):238–240
55. Nkem Ede A, Oluwababmi Ige A (2014) Optimal polypropylene fiber content for improved compressive and flexural strength of concrete. IOSR J Mech Civil Eng 11(3):129–135. https://doi.org/10.9790/1684-1134129135
56. Zeng D, Cao M, Ming X (2021) Characterization of mechanical behavior and mechanism of hybrid fiber reinforced cementitious composites after exposure to high temperatures. Mater Struct Mater Construct 54(1):1–11. https://doi.org/10.1617/s11527-02
57. Ahmed HU, Mohammed AA, Mohammed AS (2023) effectiveness of silicon dioxide nanoparticles (Nano SiO2) on the internal structures, electrical conductivity, and elevated temperature behaviors of geopolymer concrete composites. J Inorg Organomet Polym. https://doi.org/10.1007/s10904-023-02672-2
58. Tahwia AM, Abd Ellatief M, Bassioni G, Ashraf Heniegal M, Abd Elrahman AM (2023) Influence of high temperature exposure on compressive strength and microstructure of ultra-high performance geopolymer concrete with waste glass and ceramic. J Mater Res Technol 23:5681–5697
59. Ahmed HU, Mohammed AA, Mohammed AS (2023) Effectiveness of nano-SiO2 on the mechanical, durability, and microstructural behavior of geopolymer concrete at different curing ages. Archiv Civil and Mech Eng 23(2):129. https://doi.org/10.1007/s43452-023-00668-w
60. Xiao J, Falkner H (2006) On residual strength of high-performance concrete with and without polypropylene fibres at elevated temperatures. Fire Saf J 41(2):115–121. https://doi.org/10.1016/j.firesaf.2005.11.004
61. Ahmad OA, Awwad M (2015) The effects of polypropylene fibers additions on compressive and tensile strengths of concrete. Int J Civil Environ Eng 37(1):17018285
62. Yuan Z, Jia Y (2021) Mechanical properties and microstructure of glass fiber and polypropylene fiber reinforced concrete: an experimental study. Constr Build Mater 266:121048. https://doi.org/10.1016/j.conbuildmat.2020.121048