

Article

Impact of Hot Weather Conditions on the Performance of Supplementary Cementitious Materials Concrete

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Abstract: This study aimed to investigate the strength and permeability properties of binary and ternary systems for producing concrete mixes with a cure time of 7, 28, 90, and 180 days under high ambient temperatures (about 35–45 °C). The key variables were silica fume (SF) and fly ash (FA) and the water-to-binder ratio (0.18 to 0.55) needed for cementitious systems of normal to ultra-high-performance concrete (UHPC). The tests were conducted under BS 1881 and ASTM C 1202. Further, a parametric study was conducted using isoresponse curves and predictive models developed in the study. After 28 days with 5% SF, the SF-binary concrete mixes showed significant gains in compressive strength, while 10% and 15% showed no significant gains. With a water–binder ratio of 0.55, concrete showed slightly higher strength gains than concrete with ratios of 0.16, 0.25, and 0.40. A 5% SF addition to 0.25-based concrete reduced permeability by 70%, which was marginal for 10% and 15%. However, higher SF content did not significantly affect concrete permeability with water–binder ratios of 0.55 and 0.40. The SF-FA ternary cementitious system of UHPC resulted in negligible permeability. With the developed model, the predicted–tested strength and permeability ratio was between 0.96 and 1.01. The isoresponse pattern of permeability changes at 6% SF content, while adding SF increases permeability significantly. The parametric analysis revealed that strength development deteriorates after 120 days regardless of whether SF is added at 10% or 15%.

Keywords: binary and ternary systems; concrete; water–binder ratio; hot weather conditions; strength; durability



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1. Introduction

1.1. Background

In light of global climate change and the additional concern over the rising costs of renovation of existing concrete structures, the performance of concrete infrastructure under hostile atmospheric conditions has become an increasingly active research subject. In light of the escalating maintenance costs, concrete infrastructure must now last centuries rather than decades. However, the performance of concrete structures deteriorates much sooner than intended due to extreme weather conditions. To handle this problematic situation, supplementary cementitious materials (SCMs) are normally employed in combination with Portland or mixed types of cement to promote the concrete's properties. Examples of these pozzolanic materials are silica fume (SF), fly ash, granulated blast furnace slag, sugarcane bagasse, and natural pozzolan (e.g., metakaolin, calcined shale, and calcined clay) [1–4]. According to some, the twenty-first century marks the millennium of the use of SCMs and chemical admixtures in cement-based materials.

The cement-based materials are generally highly heterogeneous chemical and physical products due to their susceptibility to curing [5]. Some parts of the world, such as the Middle East, suffer from extremely hot and arid conditions that make concrete susceptible to decay and inhibit its development. In the context of concrete infrastructure, hostile environmental conditions are typically associated with several problems relating to the

production, transportation, and maintenance of concrete infrastructure. The dilemma can be further compounded by daily temperature and humidity fluctuations (up to 45 °C and 60% RH, respectively), solar radiation, and high wind speeds, which would cause noticeable cracks due to volume changes [4,6,7].

In the past few decades, extensive research has been conducted on SCMs as candidates to enhance concrete performance under these harsh conditions. In this regard, silica fume (SF) has been demonstrated to be the most effective SCM [8]. The implementation of environmental regulations in the mid-1970s led to the widespread recycling of SF; however, there were some instances when it was used for technical or economic purposes. Over the years, SF has been widely used to develop high-performance concrete (HPC) for infrastructure construction and retrofitting. The SF is an ultrafine pozzolanic material with sphere-shaped grains that results from silicon and ferrosilicon alloys melting in electric arc furnaces.

With a mean size of 150 nm, SF particles are 100 times smaller than cement, and their specific surface area ranges from 15,000 to 3000 m²/kg [9,10]. These features and SF's high amorphous pozzolanic (silica) content have made it a powerful additive to concrete [11]. Researchers [12–14] have demonstrated that the addition of SF to cement-based materials improves their durability properties by improving the microstructure. In spite of this, SF-based cementitious materials have lower workability (because of their ultrafine particles) and are prone to shrinkage cracks when exposed to ambient hot weather [7,15].

1.2. Study Significance and Objectives

A rising internal temperature of concrete can trigger various deterioration mechanisms, so this property of concrete is regulated by different international codes. ACI 305 and SBC 304 (the Saudi Building Code requirements for concrete structures) specify a maximum internal concrete temperature of 35 °C and require a minimum 7-day water curing period. Although these conditions appear achievable, retaining the upper-limit temperature for wide-scale applications remains an unanswered question. The literature has also devoted extensive attention to investigating and predicting the performance of silica fume concrete under extreme weather [11,16–18]. The readily available literature, however, does not provide much information on the strength and durability of SF-concrete at high ambient temperatures. The goal of this study was to look into the performance of the binary and ternary SF-concrete mixes in hot weather. Using different water-binder ratios, we studied the compressive strength and durability (chloride permeability) properties of SF-concrete. The research focused particularly on the impact of hot weather in Saudi Arabia's central region. Due to the high temperatures in this region, limiting the length of time for moist curing is necessary in order to speed up the construction process. In this study, efforts were also made to develop reliable models for predicting the strength and durability of SF and SF-FA-concrete mixes.

1.3. The Regional Hot and Arid Climate

In Riyadh (the Saudi Arabian capital), the weather is usually very hot in the summer (from May through September, Figure 1). The mean temperature of 43 °C in this period is significantly higher than that stated in ACI 305R-20 of 35 °C for concrete pouring in hot weather [11,19]. This standard predicts that concrete's 28-day compressive strength will decrease by 10–15% if the curing temperature is at 100 °F (38 °C) on the first day. A further decrease in strength is predicted following early exposure to the dry weather conditions (that prevailed in Riyadh during the summer) [20].

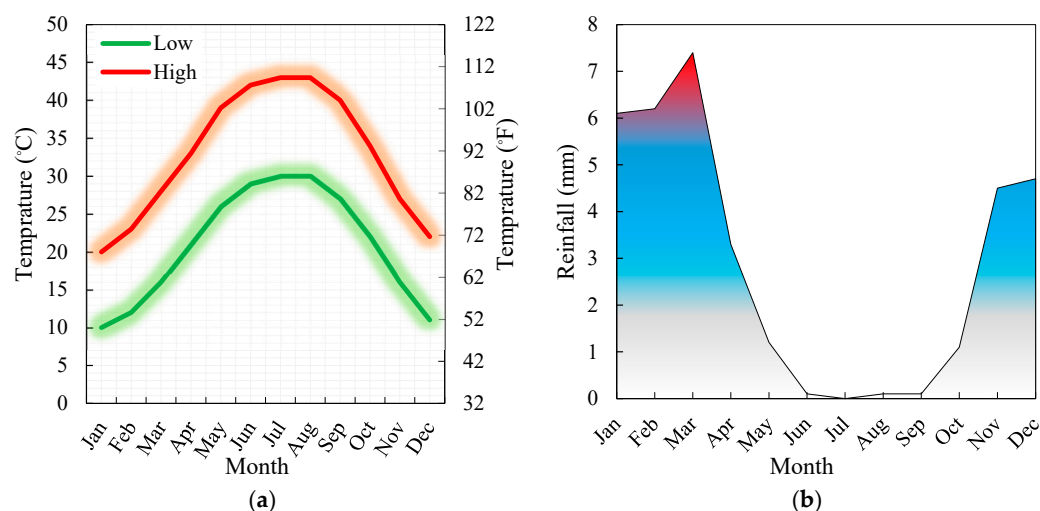


Figure 1. Average (a) temperature and (b) rainfall in Riyadh (2014–2022) [21].

2. Material and Methods

2.1. Materials

The key binder for this experimental program was Portland cement (PC, type-I) which meets ASTM C150 requirements. Furthermore, imported silica fume (SF) and fly ash (FA), which meet ASTM C1240 and C618 specifications, were utilized as supplementary cementitious materials. Table 1 lists the physicochemical properties of the employed PC, SF, and FA, whereas Figure 2 depicts the particle-size distributions of the used powders. Additionally, Figure 3 displays the microstructural characteristics of the fine powders.

Table 1. The physicochemical properties of PC and SF.

	PC	SF	FA
Physical Properties			
Bulk density (kg/m^3)	1362	400–720	540–860
Specific gravity (g/m^3)	3.14	2.2	2.6
Fineness (m^2g^{-1})	0.371	15–20	0.364
Average particle size (μm)	11	0.26	10
Compressive strength (MPa), 50 mm cubes			
03 days	19.4	-	-
07 days	24.9	-	-
28 days	35.7	-	-
Chemical composition (%)			
SiO_2	20.9	90.0	55.23
Al_2O_3	5.2	1.0	25.95
Fe_2O_3	2.3	1.0	10.17
MgO	2.8	0.6	0.31
CaO	64.4	0.3	1.32
SO_3	2.9	0.3	0.18
LOI	1.0	-	5.0
Insoluble residue	0.2	-	-

In this investigation, locally abundant fine (silica sand (SS) and crushed sand (CS)) and coarse aggregates (with a maximum size of 10 mm and 20 mm) were employed in the developed concrete mixtures. In accordance with ASTM C127 and ASTM C128, the physical properties (Table 2) of the employed aggregates were investigated. Here, 60% SS and 40% CS were mixed to meet ASTM C 33 specifications. Likewise, 20% and 80% of 10 mm and 20 mm coarse aggregates, respectively, were blended for the same purpose. Figure 4

depicts the particle-size distribution of the blended aggregates. In this investigation, two superplasticizers (SP), a sulfonated naphthalene polymer-based and a polycarboxylate ether-based (known as Conplast SP430 and Glenium 51, respectively) that comply with the ASTM C 494 requirements were employed to ensure the high flowability of the developed mixes (with a slump of 90–160 mm). The physicomaterial properties of microsteel fibers are shown in Table 3.

Table 2. The physical properties of the employed aggregates.

Aggregate		Unit Weight kg/m ³	Bulk Specific Gravity			Absorption %
			Apparent	Oven Dry	Saturated	
Fine	SS	1644	2.66	2.54	2.59	1.76
	CS	1774	2.67	2.66	2.66	0.24
Coarse	10 mm	1592	2.68	2.61	2.63	1.03
	20 mm	1566	2.67	2.58	2.61	1.17

Table 3. Physicomaterial properties of microsteel fibers.

Type	Length (mm)	Diameter (μm)	Unit Weight (kg/m ³)	Tensile Strength (MPa)
Microsteel fiber	13	200–350	7850	2600

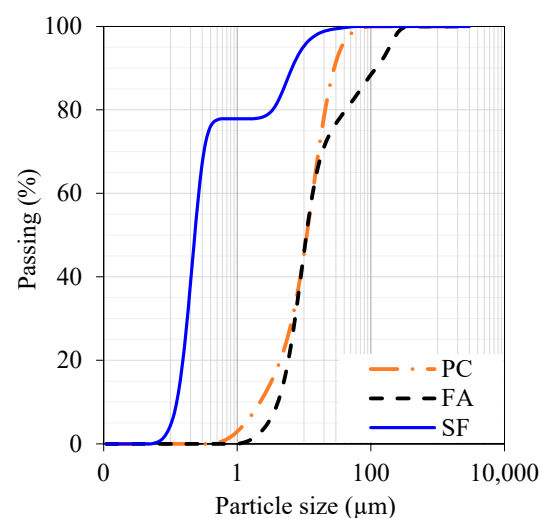
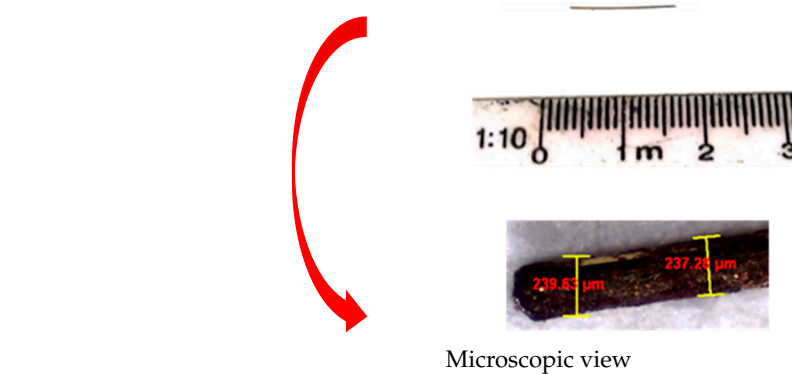


Figure 2. Particle grading distribution of PC, SF, and FA.

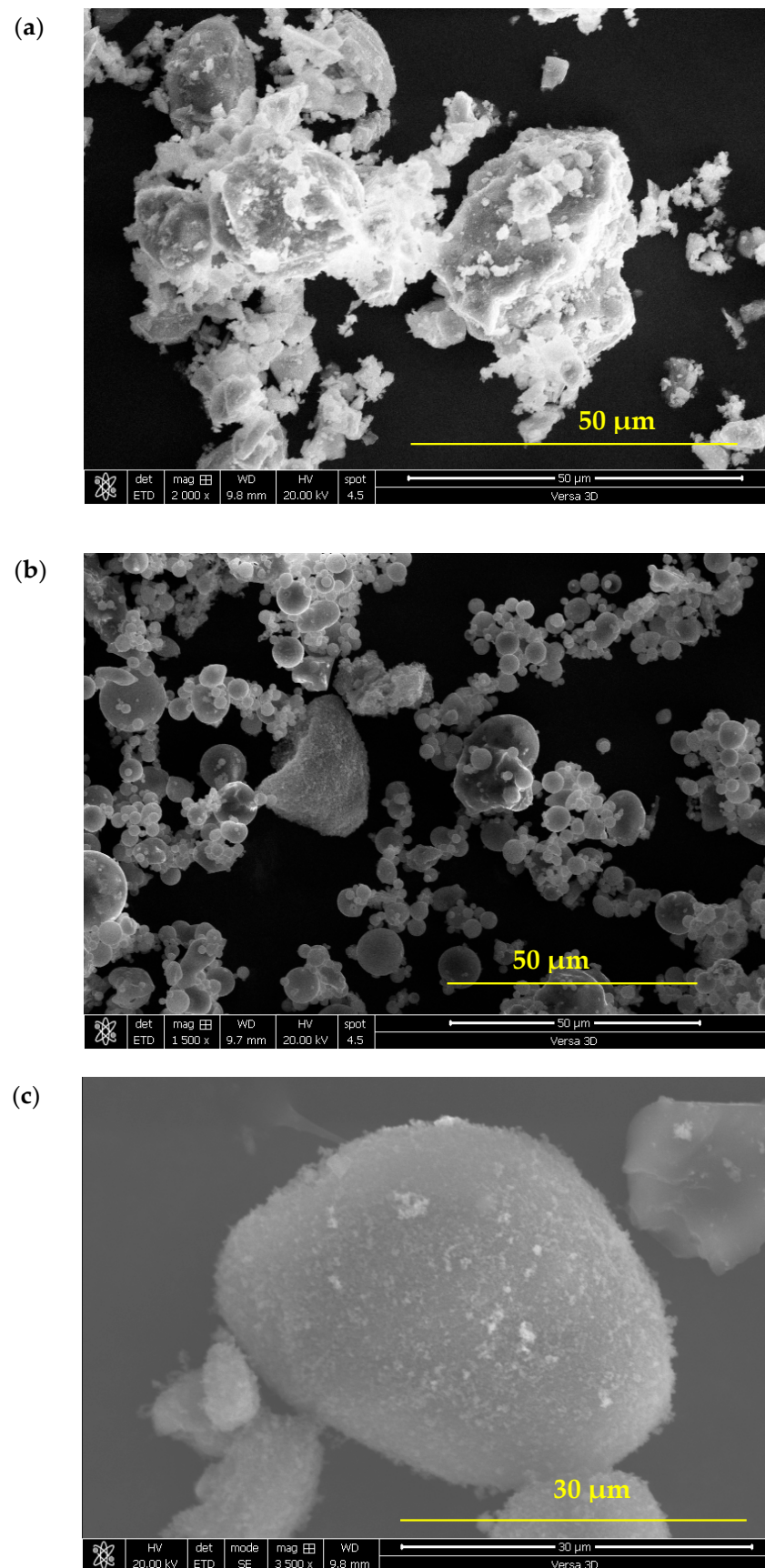


Figure 3. Microstructural analysis of (a) cement, (b) fly ash, and (c) condensed silica fume.

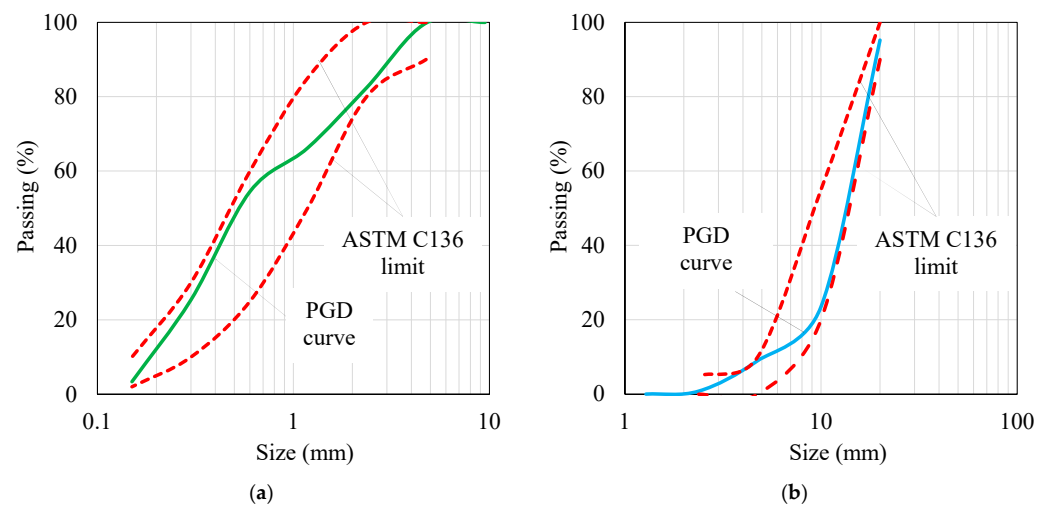


Figure 4. Particle grading distribution (PGD) of blended: (a) fine and (b) coarse aggregate.

2.2. Methods

2.2.1. Mix Details

Table 4 lists the mixed proportion of all mixes in the study, with the water-to-binder ratio (w/b) kept at 0.18, 0.25, 0.40, and 0.55. In this table, the identification (ID) of the mix, the unit weight of binders (values in parenthesis represent the wt. % of PC), and SP are summarized. This selection of the w/b was made because it is the most common practice for the production of normal (N)-, high (H)-, and ultra (U)-performance and ultra-high (UH)-performance concrete. In this research, the SF was employed as supplementary cementitious materials with replacement levels of 0, 5, 10, and 15 wt. %. The N, H, and U mixtures contained 710 kg/m³ of fine aggregates and 1043 kg/m³ of coarse aggregates, while the UH mixture contained only 719 kg/m³ of fine aggregates. UH-SF contained an equal mix of crushed and natural sands, while UH-SF-FA was composed mainly of natural sand and 175 kg/m³ microsteel fibers. The mix UH-SF is a transitional mix between U and UH mixes where fine and coarse aggregates are excluded.

Table 4. Proportions of the mixes.

Mix		PC	SF	FA	Microsteel Fiber	SP	w/b
No.	ID		kg/m ³ (%)		kg/m ³	L/m ³	
1	UH-SF	1041	332 (24.2)	-	175	27	0.18
2	UH-SF-FA	9889 (72)	301 (22)	83 (6)	-	37	
3	U00	563 (100)	-	-	-	18	
4	U05	535 (95)	28 (05)	-	-	18	0.25
5	U10	507 (90)	56 (10)	-	-	18	
6	U15	479 (85)	85 (15)	-	-	18	
7	H00	446 (100)	-	-	-	4	0.40
8	H05	424 (95)	22 (05)	-	-	6	
9	H15	401 (90)	45 (10)	-	-	6	
10	H20	379 (85)	67 (15)	-	-	9	
11	N00	369 (100)	-	-	-	0.8	0.55
12	N05	351 (95)	19 (05)	-	-	1.8	
13	N15	332 (90)	37 (10)	-	-	2.8	
14	N20	314 (85)	55 (15)	-	-	3.8	

2.2.2. Mixing, Casting, and Curing

In this investigation, the regular-titled concrete mixer was used in the preparation of N and H concrete mixes while a concrete mixer (Hobart, with a 30 L capacity) was utilized

for preparing the U and UH concrete mixes. It is well known that the introduction of SF to cement-based materials significantly impacts the mixing process; thus, a successful mixing scheme is crucial. Here, the mixing procedure reported in [22] was adopted. It is worth noting that the temperature (all mixes were found to have an internal temperature of 29.1–31.5 °C) and slump of the concrete mixes were checked before pouring into the test molds (within the range of 90–160 mm), as shown in Figure 5.



Figure 5. Typical concrete slump range for all N, H, and U concrete mixes.

The casting procedure in the concrete mold was accomplished in two layers, and external vibration was applied to ensure the proper compaction of the concrete. For 24 h, the concrete mold was covered by hessian burlap and polyethylene sheets. After that, the concrete specimen was demolded and retained in water at a temperature of 20 ± 3 °C for the first 7 days, then exposed to the hot weather in outdoor conditions in Riyadh (May–September (Figure 1a), with an air temperature of 35–45 °C). Notably, the mixing and casting were performed under room conditions (25 ± 2 °C—22% RH). Figure 6 exhibits the concrete specimens under various curing regimes.

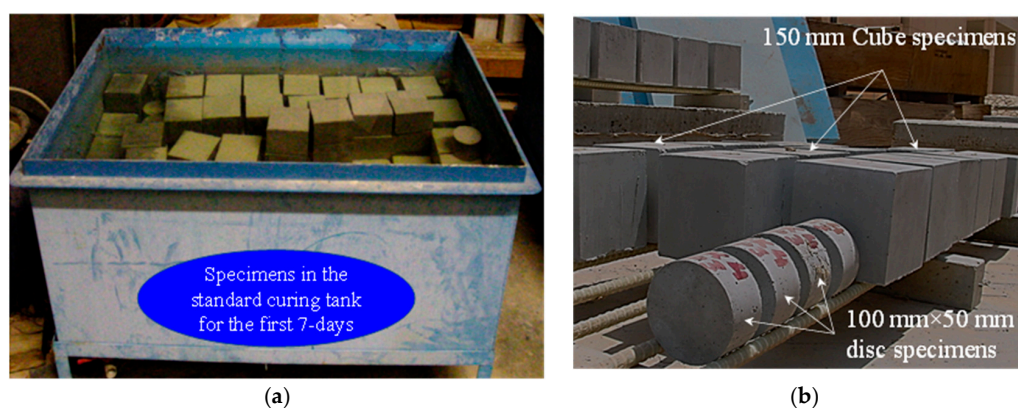


Figure 6. Curing systems: (a) standard water curing and (b) hot weather exposure.

2.2.3. Compressive Strength Test

In this investigation, the compressive strength of the 12 concrete mixes was investigated at various ages (7, 28, 90, at 180 days) using the BS 1881 guidelines. In total, 144 cubic (of size $150 \times 150 \times 150$ mm) specimens (three samples for each mix and age) were tested, and the average value is reported.

2.2.4. Chloride Permeability Test

According to ASTM C1202, concrete discs with a diameter of 50 mm and a length of 100 mm were tested for chloride permeability. These concrete samples were vacuum-soaked

according to RELIM [23] to maintain a full saturation level. Diffusion characteristics cannot be determined by chloride permeability tests [24]. This test was, however, sufficient for performing parametric studies of the type described in this report. Figure 7 shows the test cell filled with concrete cylinders to measure chloride permeability (in coulombs). In this study, we measured the chloride permeability at three different ages (28, 90, and 190 days) and compared the mean values. A total of 108 discs were tested for chloride permeability as part of this experimental program. Following ASTM C1202, Table 5 illustrates how concrete permeability can be classified using rapid chloride permeability results.

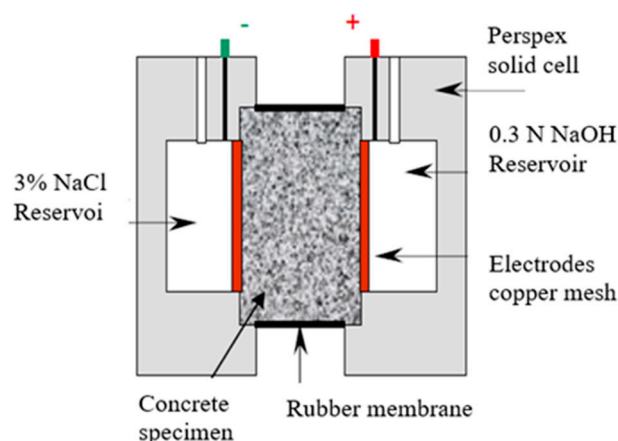


Figure 7. The test cell of the rapid chloride permeability test.

Table 5. Classes of concrete's chloride permeability, as per ASTM C 1202 [24].

Penetrability	Negligible	Very Low	Low	Moderate	High
Charge Passed (Coulombs)	<100	100–1000	1000–2000	2000–4000	>4000

3. Results and Discussion

With lowered water content, the need for superplasticizer becomes critical, greatly affecting the final setting time, especially in ultra-high-performance concrete (UH) mixes. It was highly recommended to investigate the effect of SF and FA content on the setting time under an optimum SP dosage. Different UH paste mixes were prepared for workability and setting time. Workability was optimized using a modified mini-slump flow table with a flow diameter of 240 ± 20 mm or less, as shown in Figure 8. In UH mixes, the content of both SF and FA has reached up to about 24%, as shown in Figure 9. Different binary paste mixes containing the same cementitious matrices with individual contents of SF and FA were prepared. From the figure, it is evident that the setting time reduces with SF while it increases with FA. The optimum combination of SF and FA should provide a balanced effect on setting time, as presented in Table 4.

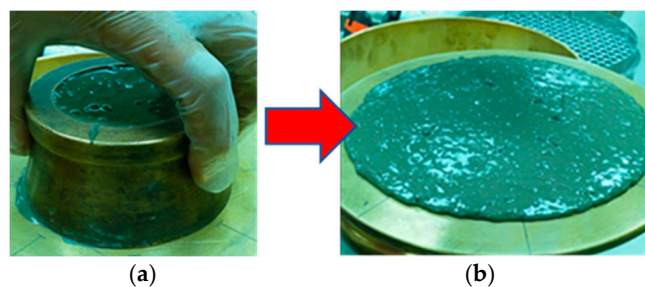


Figure 8. Workability adjustment (a) pouring in brass cone and (b) measuring the flow diameter.

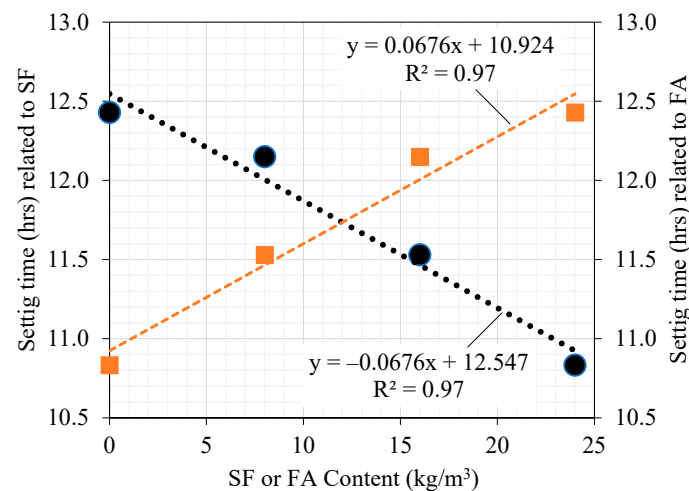


Figure 9. The individual effect of SF and FA on the setting time of UH paste mixes.

3.1. Chloride Permeability

The results of chloride permeability tests (Sections 2.2.3 and 2.2.4) conducted on the developed SF-concrete mixes (Table 3) are summarized in Table 6. In the following sections, the strength and durability of SF-based HPC systems along with a comprehensive analysis of their performance was discussed.

Table 6. Summary of the experimental results.

Mix		Chloride Permeability					
		(Coulombs)			Class (Table 4)		
No.	ID	28-d	90-d	180-d	28-d	90-d	180-d
1	UH-SF	30	24	23	Very low	Very low	Very low
2	UH-SF-FA *	165	150	110	Negligible	Negligible	Negligible
3	U00	931	1812	220	Very low	Low	Very low
4	U05	230	275	134	Very low	Very low	Very low
5	U10	222	341	218	Very low	Very low	Very low
6	U15	201	324	241	Very low	Very low	Very low
7	H00	4751	3653	3445	High	Moderate	Moderate
8	H05	1536	2173	1454	Low	Moderate	Low
9	H15	676	1143	945	Very low	Low	Very low
10	H20	428	800	700	Very low	Very low	Very low
11	N00	8726	5246	4965	High	High	High
12	N05	4870	3594	3630	High	Moderate	Moderate
13	N15	2777	2389	2478	Moderate	Moderate	Moderate
14	N20	1696	1640	1780	Low	Low	Low

* samples were prepared without fibers.

3.2. Compressive Strength

Prior to evaluating the compressive strength development of the UH mixes, the effect of microsteel fiber content on compressive strength at an early age was assessed. It is noted that the fiber's strength increases with an increase in the fiber content up to 174 kg/m³. After this dosage, a notable decline in strength was noted due to the separation of the agglomerated fibers at the bottom of the mix, as illustrated in Figure 10. Therefore, the microsteel content of 174 kg/m³ was selected as the optimum content to incorporate in the ternary UH-SF-FA mix.

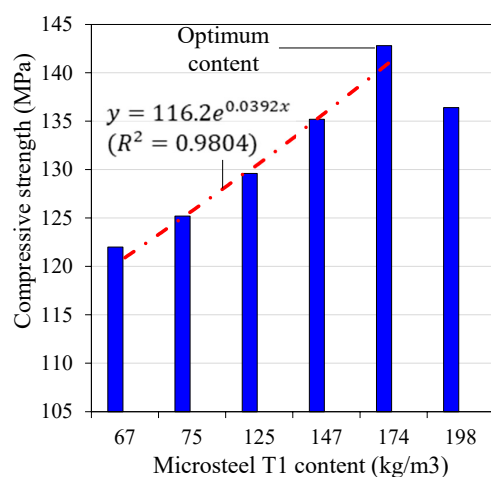


Figure 10. Effect of micro steel content on the 7-d compressive strength of UHPC.

The temperature profiles of UH mixes are shown in Figure 11. The presence of FA with SF in their ternary mix caused a notable reduction in the temperature peak and its right shift to a longer final setting time, but still within less than 15 h when compared to UH-SF. This increase in setting time allows for sufficient time for compacted microstructure. The results of the compressive strength of UH mixes under hot weather conditions are shown in Figure 12. The early compressive strength value of over 120 MPa is noted at a curing age of 7 days for both mixes with and without microsteel fiber. The compressive strength at 28 days has surpassed 120 MPa for the mix with microsteel fiber (UH-SF-FA). The compressive strength at 90 and 180 days stagnated in UH-SF-FA and slightly declined in UH-SF. This demonstrates the significance of microsteel fibers and the lack of coarser grains than 200 μm , with a negligible interstitial transition zone (ITZ) due to the presence of very fine aggregates and the absence of free water, where the escape of water becomes difficult. Autogenous shrinkage is the most common type of shrinkage in UH mixes, and it occurs during the early hours.

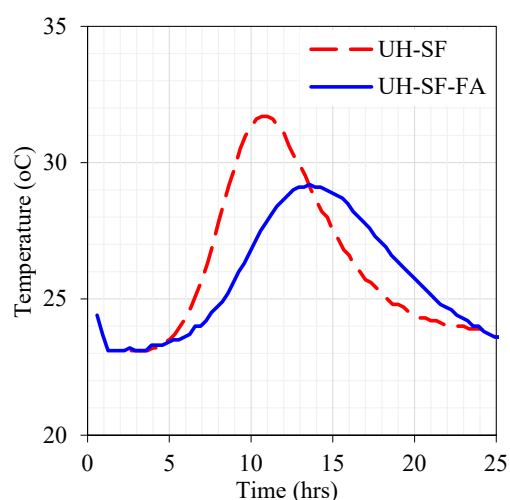


Figure 11. Temperature profiles of the UH-SF and UH-SF-FA mixes.

The effect of water-to-cement ratios of 0.25, 0.4, and 0.55 on the cement pastes corresponding to the N, H, and U concrete mixes are shown in Figure 13. It is notable that the temperature peak increases with the reduction of the W/C ratio and shifts to a lower setting time. Similarly, the temperature profiles of the N concrete mixes are shown in Figure 14. The temperature profile is a net product of the SF content and SP dosage. To localize within the target slump range, the higher SF content required a higher SP dosage, which led to a

shift of the temperature peak to longer setting times. The SF content slightly increased the temperature peak compared to the control mix. The H mixes with the same trend shift to a lower time, while U and UH shift to a longer time due to the elevated PS dosages.

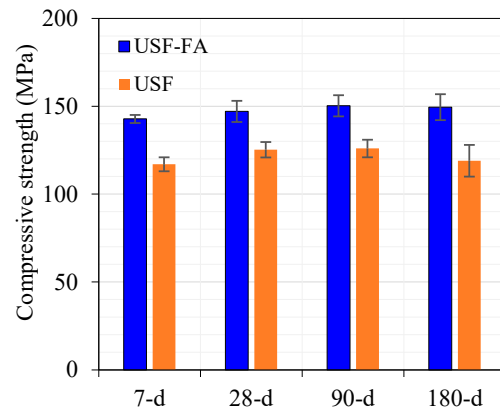


Figure 12. Development of compressive strength of UH-SF and UH-SF-FA mixes.

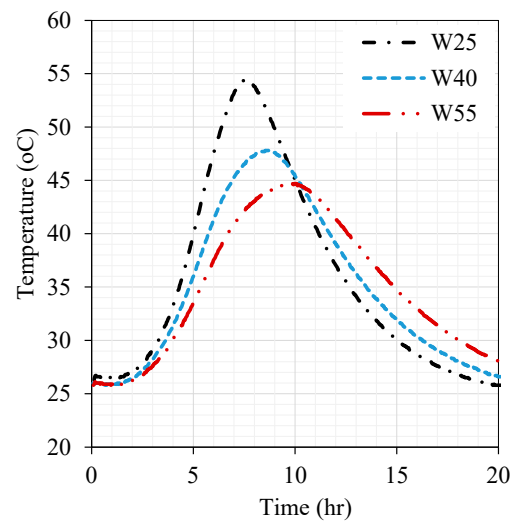


Figure 13. Effect of water-to-binder ratio on the temperature profiles of corresponding cement pastes for N, H, and U concrete mixes.

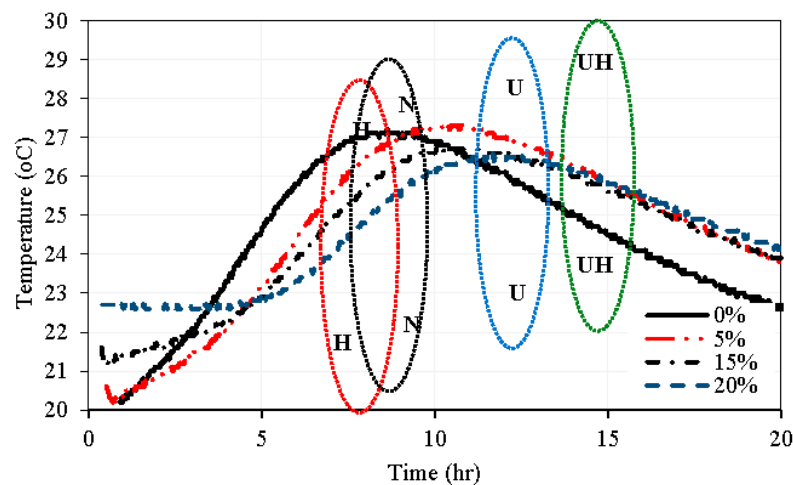


Figure 14. The temperature profile of N concrete mixes with corresponding temperature slots for N, H, U, and UH concrete mixes.

Figure 15 illustrates the compressive strength of concrete with SF contents of varying amounts, cured in hot weather conditions (Section 2.2.2), prepared with water–binder ratios of 0.25, 0.40, and 0.55. It is evident that the SF–concrete mixes showed significant increases (in the range of about 11–15%, 8–11%, and 3–12% for U-, H-, and N-mixes, respectively) in compressive strength after 28 days compared to the control. Overall, the strength enhancement rate of SF–concrete was greater than that of plain cement HPC. It is relevant to note that this conclusion agrees with that reported in [7,15]. Due to the high pozzolanicity of SF, this phenomenon is believed to result in a more compact and enhanced microstructure compared to PC. In well-documented studies [25–27], SF reduces porosity by refining pore structure, resulting in increased compressive “strength”.

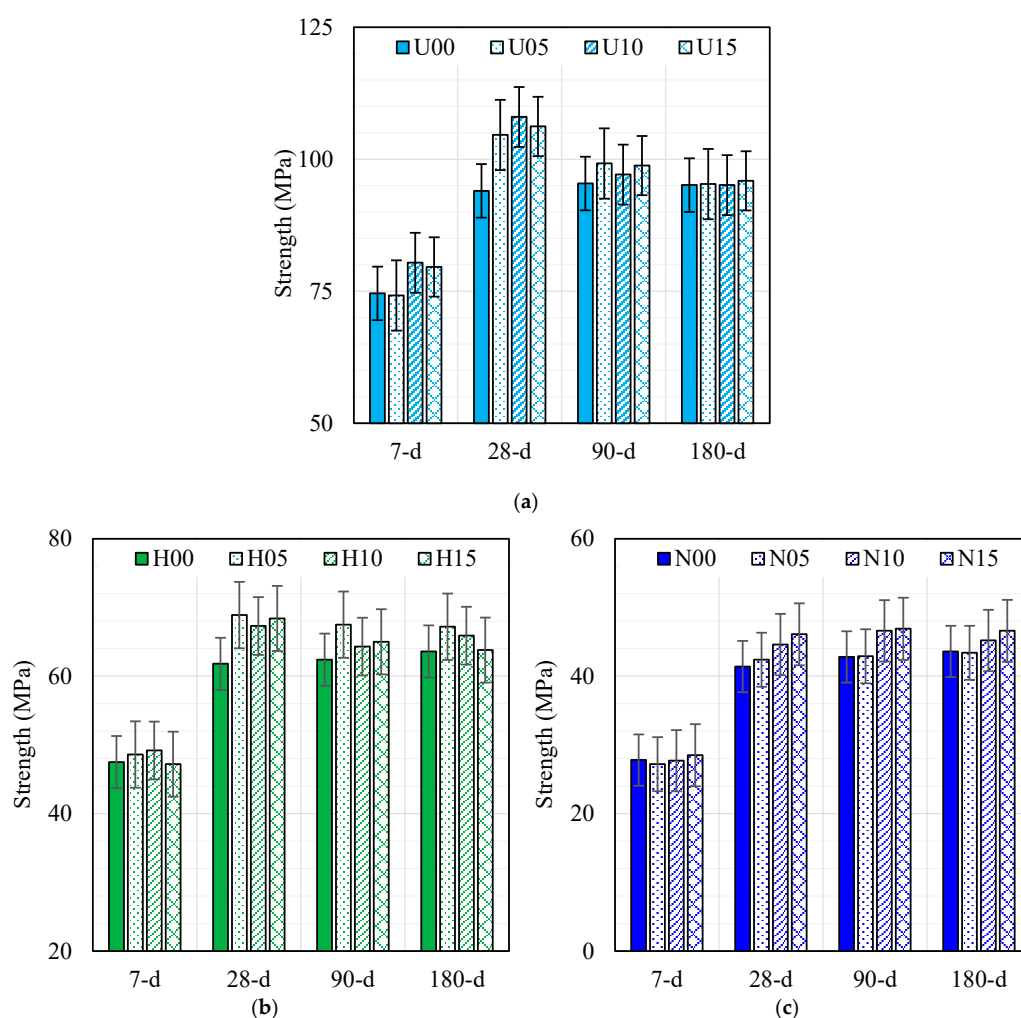


Figure 15. Compressive strength of concrete with w/b of (a) 0.25, (b) 0.40, and (c) 0.55.

Further, incorporating 5% of SF improved strength at 28 days, while 10% and 15% were not significantly beneficial. As SF levels increased to 5, 10%, and 15%, almost horizontal lines appeared after 28 days. This indicated that there was no longer any effect on strength from the presence of SF. There is, however, also a connection between this effect and the curing condition. Figure 15 also showed that under standard curing, SF–concrete did not perform well after 28 days. However, this finding needs to be analyzed as shown in Figure 16. In addition, SF–concrete with various water–binder ratios showed almost similar strength development patterns at 28 days. The strength gained after 28 days for concrete with a water–binder ratio of 0.55 was slightly higher than that with 0.25 and 0.40 ratios. This conclusion could be explained by the higher water content in the mix that could be consumed for hydration after 28 days.

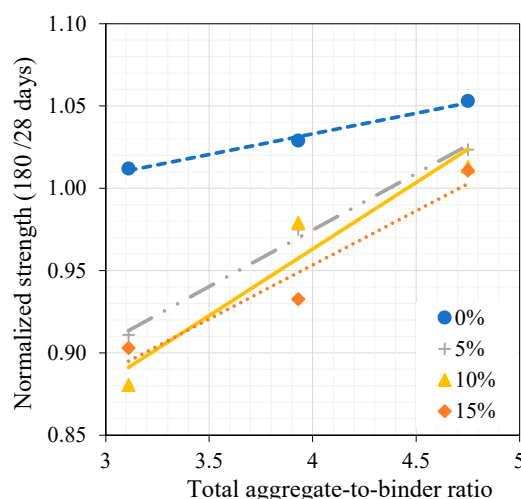


Figure 16. Relationship between total aggregate-to-binder ratio and normalized strength.

The majority of drying shrinkage happens during the early months of concrete curing [28]. The presence of high content of coarse aggregates at the expense of paste content leads to lower water content and, accordingly, a lesser amount of drying shrinkage. The total aggregates-to-binder ratios were calculated for N, H, and U mixes as they contained a fixed amount of aggregates and plotted against the normalized compressive strength at 180 days with respect to the curing age of 28 days, as demonstrated in Figure 16 and Table 7. It is evident that there is a linear relationship between the total aggregates-to-binder ratio and the normalized compressive strength ratio. As a result, it is obvious that lowering the total aggregate-to-binder ratio results in a loss of strength due to an increase in binder content and a decrease in coarse aggregate content. These ratios lead to higher shrinkage and crack formation under the severe curing conditions of the Gulf, according to [28].

Table 7. Best-fit equation of relationships (Figure 16).

SF Content (%)	Best-Fit Equation	R^2
0	$y = 0.025x + 0.933$	0.99
5	$y = 0.0687x + 0.700$	0.99
10	$y = 0.081x + 0.640$	0.93
15	$y = 0.0657x + 0.691$	0.94

3.3. Chloride Permeability

The chloride permeability of concrete containing various SF contents and cured under hot weather conditions with water–binder ratios of 0.25, 0.40, and 0.55 is shown in Figure 17. With a water–binder ratio of 0.25 (Figure 17a), adding 5% SF reduced permeability by about 70%; however, adding 10% and 15% had little significance relative to 5% SF. In contrast, the permeability of concrete with water–binder ratios of 0.40 and 0.55 decreased as SF content increased. According to this finding, hot weathering had less effect on concrete permeability when a higher water–binder ratio (i.e., 0.40–0.5) was used. The authors previously reported [11] a similar conclusion about concrete containing SF and fly ash. A particular finding of interest is that the permeability class (Table 5) for concrete with a water–binder ratio of 0.25 always remained the same (very low) regardless of the dosage of SF or the concrete’s age.

It is possible that the higher water–binder ratio prolonged the hydration dynamics, and as a result, the concrete’s permeability was less affected by the hot ambient conditions. The SF inclusion improved chloride permeability significantly and efficiently compared to compression strength development. As SF refines the pore size distribution and pore structure, the permeation properties of concrete are reduced [13,29]. Furthermore, water–

binder ratios of 0.40 and 0.55 showed nearly identical chloride permeability patterns over time; however, the values for the higher ratio were understandably higher. There was also a similar pattern of chloride permeability for water–binder ratios of 0.40 and 0.55 (Figure 17a,b). It appears that the water–binder of 0.55 showed greater permeability results, which follows the theory.

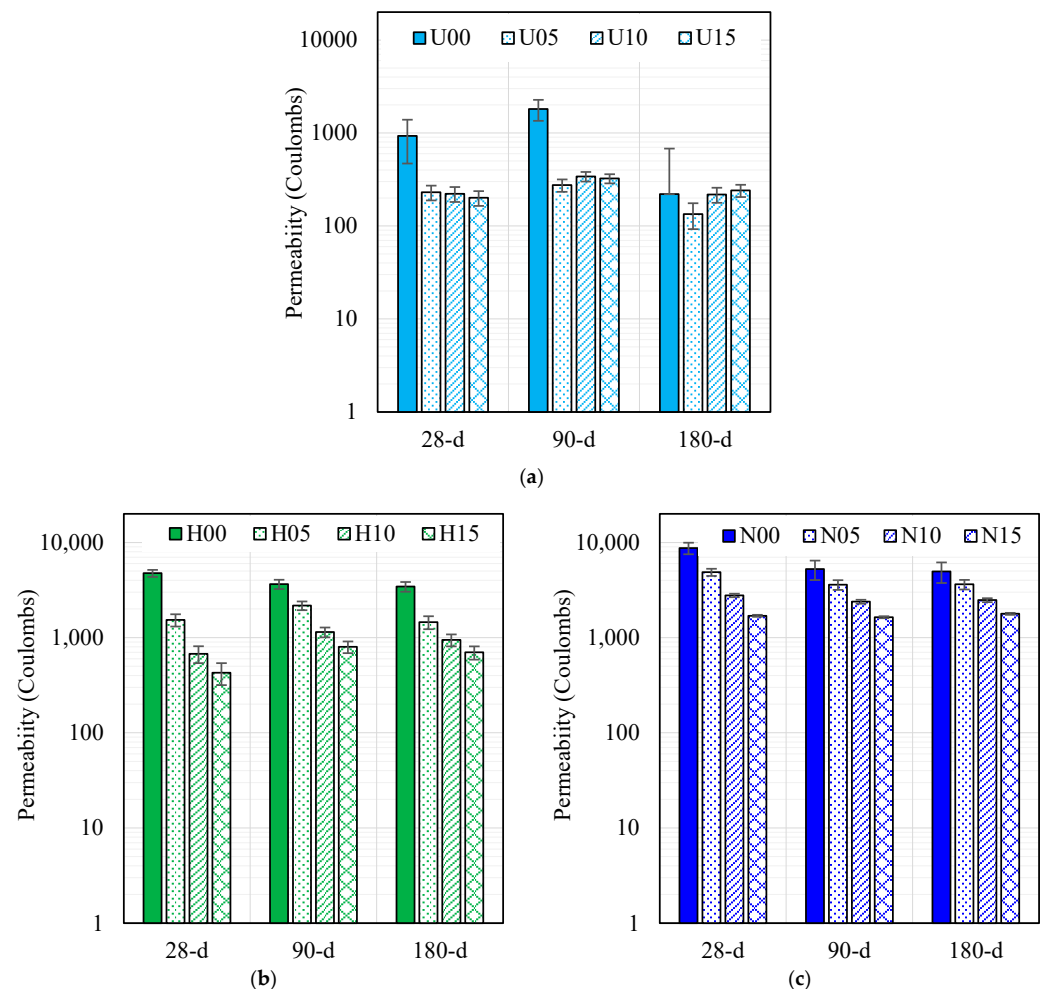


Figure 17. Permeability of concrete with w/b of (a) 0.25, (b) 0.40, and (c) 0.55.

4. Prediction Model

4.1. Development of the Proposed Model

This study developed a prediction model using the design of experiments with a response surface methodology (DOE with RSM) module to predict the strength (f_{cu}^{Pred}) and permeability (ρ^{Pred}) properties of SF-concrete under hot weather conditions. By focusing on fluctuations made by independent variables, the DOE tool aids in examining the response of specific factors. The result is a quadratic prediction formula (Equation (1) and Table 8), which was developed using the statistical analysis software Minitab® [30]. There were 93.6 and 94.1% correlation coefficients (R^2) for y_1 and y_2 , respectively (Table 6).

$$y_i = \alpha_i + \beta_i x_1 + \gamma_i x_2 + \delta_i x_3 + \epsilon_i x_1^2 + \epsilon_i x_2^2 + \zeta_i x_3^2 + \eta_i x_1 x_2 + \theta_i x_1 x_3 + \vartheta_i x_2 x_3 \quad (1)$$

$i = 1, 2$

where $y_1 = f_{cu}^{Pred}$, $y_2 = \rho^{Pred}$ and x_1 , x_2 and x_3 represent the water–binder ratio, concrete age (days), and SF content (%wt. of PC), respectively.

Table 8. Constants of Equation (1).

i	α_i	β_i	γ_i	δ_i	ε_i	ϵ_i	ζ_i	η_i	θ_i	ϑ_i	R^2
1	158.8	−378.2	0.3204	0.876	250	1.44×10^{-3}	−0.0248	0.058	−0.43	-1.31×10^{-3}	93.6%
2	−1478	11,235	−4.25	−129	10,244	0.0129	13.86	−21.3	−877	0.846	94.1%

4.2. Performance of the Proposed Model

The predicted performance of the proposed model is further detailed in Table 9 and illustrated in Figure 18. Several outliers were generated by the proposed model for ρ^{Pred} (represented as “×” in Table 9). There were most outliers for concrete with a water–binder ratio of 0.25, indicating the model for permeability will most likely produce accurate results with ratios of 0.40 and 0.55. In Table 7, the tested strength and permeability results are denoted by f_{cu}^{Exp} and ρ^{Exp} , respectively. As for strength, the average (μ) and variance coefficient (COV) for the predicted–tested ratios were 1.009 and 9.4%, respectively. In terms of chloride permeability, these statistical distribution parameters were 0.96 and 15.5%, respectively. The performance capability of ρ^{Pred} is superior to that of ρ^{Pred} , since the former has a higher error rate (which was significant for the outliers) and variability. Furthermore, Figure 18 demonstrates the proposed model’s reasonable ability to predict SF–concrete testing properties, as the predicted–tested data points are close to the equality line and fell within $\pm 90\%$ accuracy.

Table 9. Prediction performance of the proposed models (Equation (1)).

w/b	Age (Days)	SF (% wt.)	f_{cu}^{Exp} (MPa)	f_{cu}^{Pred} (MPa)	ρ^{Exp} (Coulombs)	ρ^{Pred} (Coulombs)	$\frac{f_{cu}^{Pred}}{f_{cu}^{Exp}}$	$\frac{\rho^{Pred}}{\rho^{Exp}}$
0.25	7	0	74.6	82.1	-	-	1.101	-
	28	0	94.0	88.1	931	×	0.937	-
	90	0	95.4	98.3	1812	×	1.031	-
	180	0	95.1	93.4	220	×	0.982	-
	7	5	74.2	85.3	-	-	1.150	-
	28	5	104.6	91.2	230	×	0.872	-
	90	5	99.2	101.0	275	200	1.018	0.726
	180	5	95.3	95.4	134	×	1.001	-
	7	10	80.4	87.3	-	-	1.085	-
	28	10	108.0	93.0	222	×	0.861	-
	90	10	97.1	102.3	341	×	1.054	-
	180	10	95.1	96.2	218	×	1.012	-
	7	15	79.6	88.0	-	-	1.105	-
	28	15	106.2	93.5	201	×	0.881	-
	90	15	98.8	102.5	324	251	1.037	0.773
	180	15	95.9	95.8	241	×	0.999	-
0.40	7	0	47.5	49.9	-	-	1.050	-
	28	0	61.8	56.0	4751	4308	0.906	0.907
	90	0	62.4	66.7	3653	3610	1.070	0.988
	180	0	63.6	62.6	3445	2774	0.984	0.805
	7	5	48.6	52.7	-	-	1.085	-
	28	5	68.9	58.7	1536	×	0.852	-
	90	5	67.5	69.1	2173	1938	1.023	0.892
	180	5	67.2	64.3	1454	1483	0.957	1.020
	7	10	49.2	54.3	-	-	1.104	-
	28	10	67.3	60.2	676	×	0.895	-
	90	10	64.3	70.1	1143	960	1.091	0.840
	180	10	65.9	64.8	945	885	0.983	0.937
	7	15	47.2	54.7	-	-	1.159	-
	28	15	68.4	60.4	428	584	0.884	1.365
	90	15	65.0	70.0	800	674	1.076	0.842
	180	15	63.8	64.0	700	×	1.004	-

Table 9. Cont.

w/b	Age (Days)	SF (% wt.)	f_{cu}^{Exp} (MPa)	f_{cu}^{Pred} (MPa)	ρ_{cu}^{Exp} (Coulombs)	ρ_{cu}^{Pred} (Coulombs)	$\frac{f_{cu}^{Pred}}{f_{cu}^{Exp}}$	$\frac{\rho_{cu}^{Pred}}{\rho_{cu}^{Exp}}$
0.55	7	0	27.8	28.8	-	-	1.036	-
	28	0	41.4	35.1	8726	7363	0.849	0.844
	90	0	42.8	46.4	5246	6468	1.085	1.233
	180	0	43.6	43.0	4965	5344	0.987	1.076
	7	5	27.2	31.3	-	-	1.152	-
	28	5	42.4	37.5	4870	4771	0.885	0.980
	90	5	42.9	48.4	3594	4138	1.129	1.151
	180	5	43.4	44.4	3630	3395	1.024	0.935
	7	10	27.7	32.6	-	-	1.178	-
	28	10	44.6	38.7	2777	2873	0.868	1.034
	90	10	46.6	49.2	2389	2502	1.055	1.047
	180	10	45.2	44.6	2478	2140	0.987	0.863
	7	15	28.5	32.7	-	-	1.147	-
	28	15	46.1	38.6	1696	1667	0.838	0.983
	90	15	46.9	48.7	1640	1558	1.038	0.950
	180	15	46.6	43.5	1780	1577	0.934	0.886
							μ	1.009
							COV	0.094
								0.960
								0.155

×: Outlier data point.

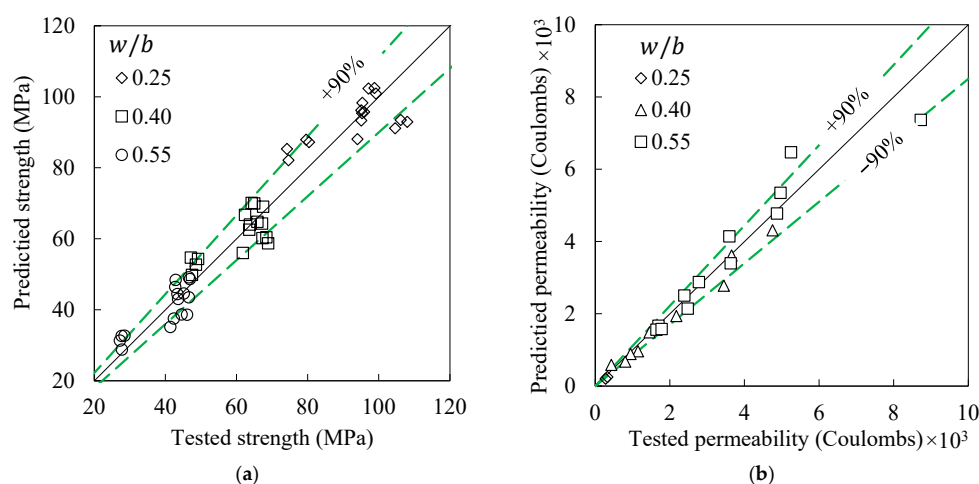


Figure 18. Prediction performance of the proposed models: (a) strength and (b) permeability.

4.3. Isoresponses Based on the Proposed Model

The current study developed a set of isoresponse curves using earlier validated predictive models and test data within the scope of the interaction independent variable. These curves, based on the hypothesis test (the p -value approach), provide insight into the impact of different pairs of variables on a specific response. In addition, these curves can be used in the design of materials, the prediction of their properties, and the optimization of those properties. Strength and permeability were thus plotted against SF- w/b and SF-concrete age. In addition, it is important to point out that it is likely that the applied prediction method is limited to those data which are within the bounds of the inputs. The result of an interpolation of that prediction would, therefore, be reasonable; however, an extrapolation would result in a significant bias in the outcome.

Figure 19 illustrates the isoresponse contour curves of SF-concrete cured at high temperatures. In agreement with the previous conclusion (Section 3.1), Figure 19a confirms the insignificance of SF content on concrete's compressive strength at relatively low water-binder ratios (0.25–0.35). In contrast, higher strength appears to be provided by more SF content at the water-binder ratios of 0.35–0.55. Additionally, Figure 19b expands on what is

discussed in 3.2 about how SF inclusion contributes to the improved durability of concrete in hot weather.

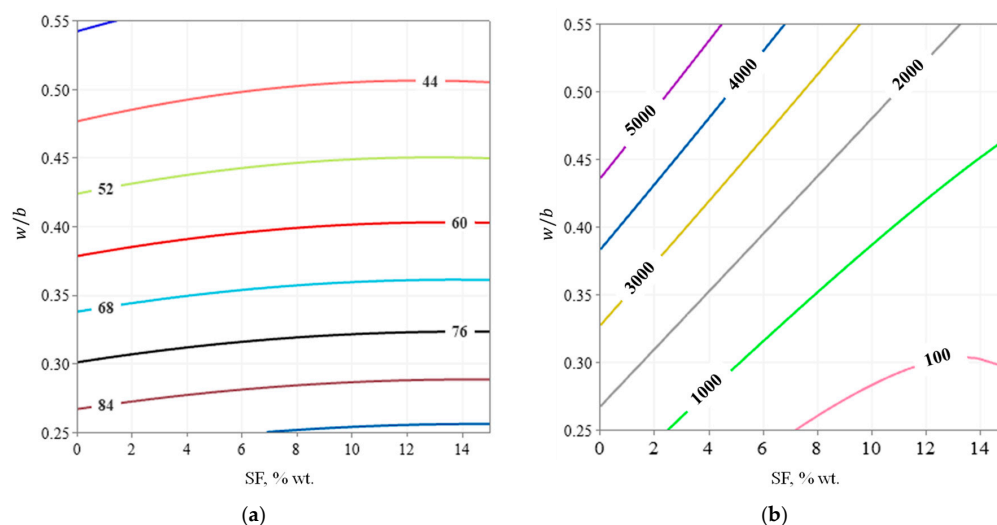


Figure 19. Isoresponse contour plots for the 28-day (a) compressive strength (MPa) and (b) chloride permeability (coulombs).

According to the earlier developed predictive formula (Equation (1)), Figure 20 shows the contour responses for concrete's compressive strength that cured under hot environmental conditions. In concrete with different water–binder ratios (i.e., 0.25, 0.40, and 0.55), the response was plotted at different SF contents and concrete ages. The figure shows that the strength contour displays the same pattern, regardless of the water–binder ratio that determines concrete's strength class. Moreover, at the later ages of concern (about 140 days), the concrete's strength tends to deteriorate at a specified SF dosage.

Figure 20 further reveals that increasing SCM dosage at early ages (around 50 days) resulted in nearly constant strength responses. As a result, SF content had a small effect on early-age strength under the conditions of the study. It is possible that the above results were caused by the extreme temperatures and arid conditions combined with the lack of proper curing, which minimized the positive impact of the pozzolanic material (SF). The hydrated cement may lose water at an early age due to these circumstances, leading to air voids that hamper the gain in strength. This mechanism can also result in a decline in strength at later ages. The strength of SF–high-strength concrete deteriorated similarly after 28 days of standard curing at high temperatures (100–200 °C), as reported in [31].

Figure 21 shows the chloride permeability isoresponses at various concrete ages, levels of SF content, and hot temperatures. With the aid of Equation (1), chloride permeability isoresponses for different water–binder ratios are plotted. Taking a closer look at the response pattern, it appears that the 6% SF content represents a turning point, as, regardless of the water–binder ratio, a typical trend can be seen. With an SF content of 6% or greater, concrete with water–binder ratios of 0.25, 0.40, and 0.55 had different permeability responses. A further highlight of the figure is how the inclusion of SF notably and favorably enhanced the permeability of the concrete.

In addition, Figure 21 shows that permeability decreases with increasing SF content. However, impermeable concrete would be produced by adding 8–10% SF to concrete with a water–binder ratio of 0.25 (Figure 21a). As a result, increasing silica content by over 8% would not benefit such concrete. By altering larger pores into minuscule ones (i.e., pore refinement), SF caused by the formation of pozzolanic reaction products (e.g., calcium silicates and calcium aluminates) is a possible cause of decreased permeability [10]. This figure also shows that the concrete's permeability property gains continuous improvement over time with a particular SF dosage. These findings suggest that the permeability of SF–concrete is insensitive to hot weather conditions.

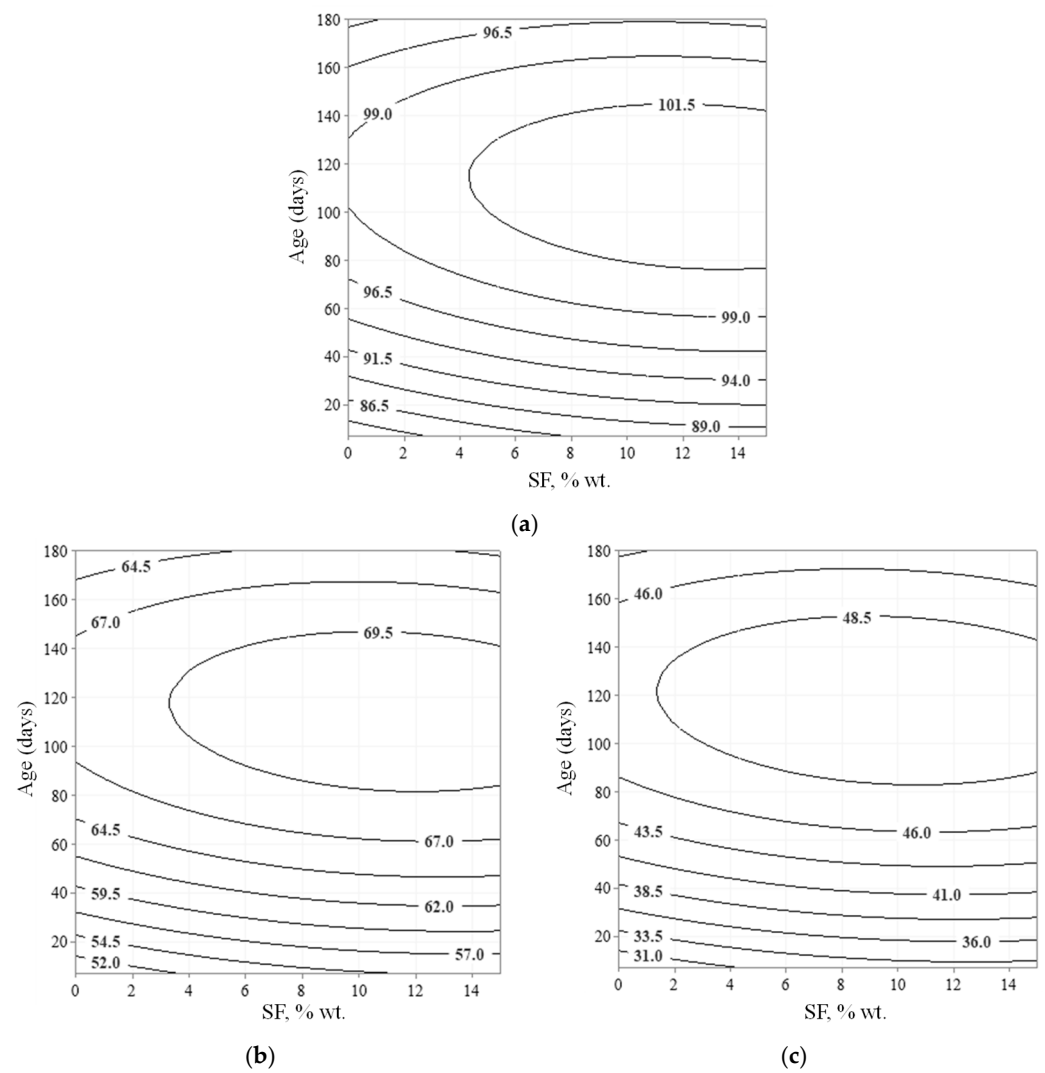


Figure 20. Isoresponse contour plots for the compressive strength (MPa) with w/b of (a) 0.25, (b) 0.40, and (c) 0.55.

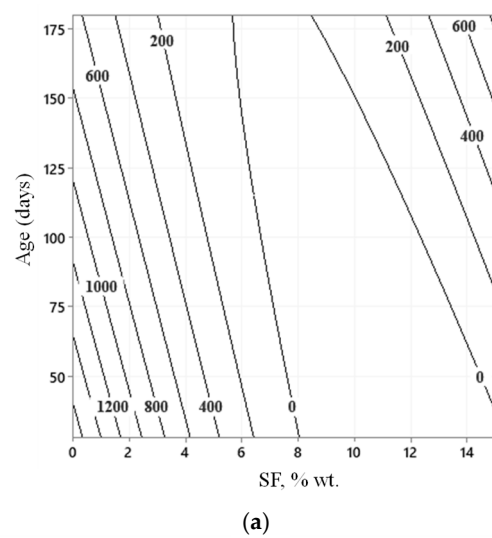


Figure 21. Cont.

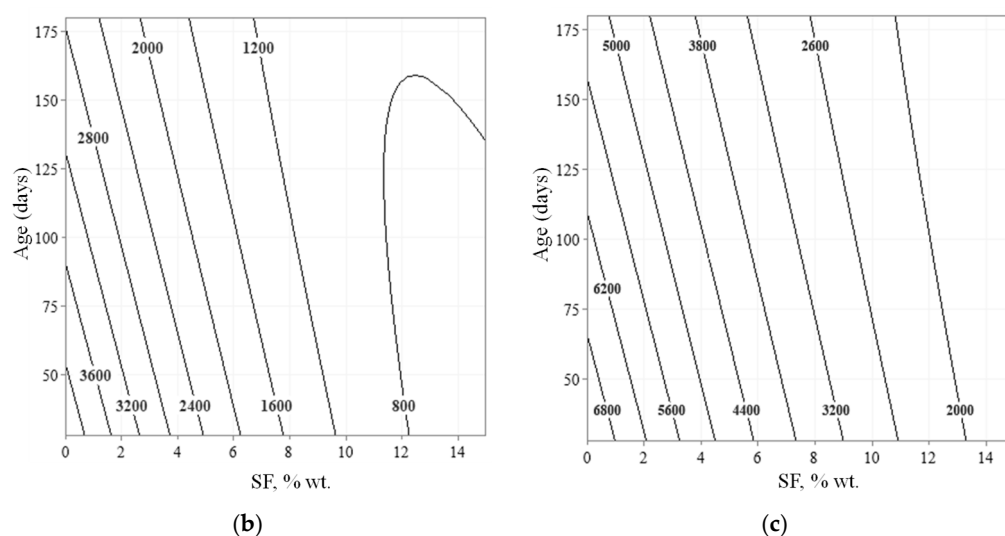


Figure 21. Isoresponse contour plots for the chloride permeability (coulombs) with w/b of (a) 0.25, (b) 0.40, and (c) 0.55.

5. Parametric Investigation

In this study, an analysis of parametrization was conducted to provide a deeper understanding of the relationship between strength and chloride permeability to various influential parameters. The developed RSM-based model (Equation (1)) was used for this analysis. This parametric analysis also aimed to assess the objectivity of the results in order to further validate the developed model. By setting constant values for these parameters and evaluating the response for different ages, the impact of various influential parameters on the strength and durability properties of concrete under hot weather conditions was investigated. To plot the strength response, for example, the SF content and water–binder were kept constant (e.g., 0.3 and 5%, respectively) and, by varying the age, the strength is calculated by using Equation (1).

Figure 22 illustrates the combined influence of SF and the ratio of water–binder on the compressive strength development (for 180 days). This figure shows that including 5% SF (Figure 22a) contributed to increasing the compressive strength. The enhancement will likely become more pronounced as the water–binder ratio decreases. As illustrated in Figure 22b, however, using 10 and 15% SF did not provide significant benefits. This finding of the parametric study supported the conclusions drawn in Section 3.1. A general trend was observed for all water–binder ratios, namely that strength development started slowly at an early age and declined over 120 days. The hot weather conditions are thought to have had a direct negative impact on the strength. In addition, this finding reinforces the discussion presented in Section 4.3.

Figure 23 shows the influence of the water–binder ratio (0.3, 0.4, and 0.5) and SF content (5, 10, and 15%) on the chloride permeability of concrete in hot weather over time (up to 180 days). Note that the figure does not include water–binder ratios below 0.3 due to the anticipated inaccuracy of the model (Equation (1)) at low ratios (refer to Section 4.2). Figure 22a demonstrates the positive impact of the introduction of 5% SF on the permeability, as a considerable reduction was achieved for all cases of water–binder ratios. Additionally, the permeability of concrete continues to decrease as it ages, as shown in this figure.

The concrete becomes more impermeable when the SF content increasing (10 and 15%, Figure 23b). It is unlikely that concrete with a 10% SF and 0.3 water–binder ratio will continue to improve in permeability over time. At this ratio, further increases in SF would result in less permeability over time. The results here contradict what was discussed in Section 3.2 with regard to an increase in permeability due to increased SF

content. The proposed permeability model (Equation (1)) may only be applicable to low SF concentrations (up to 5%).

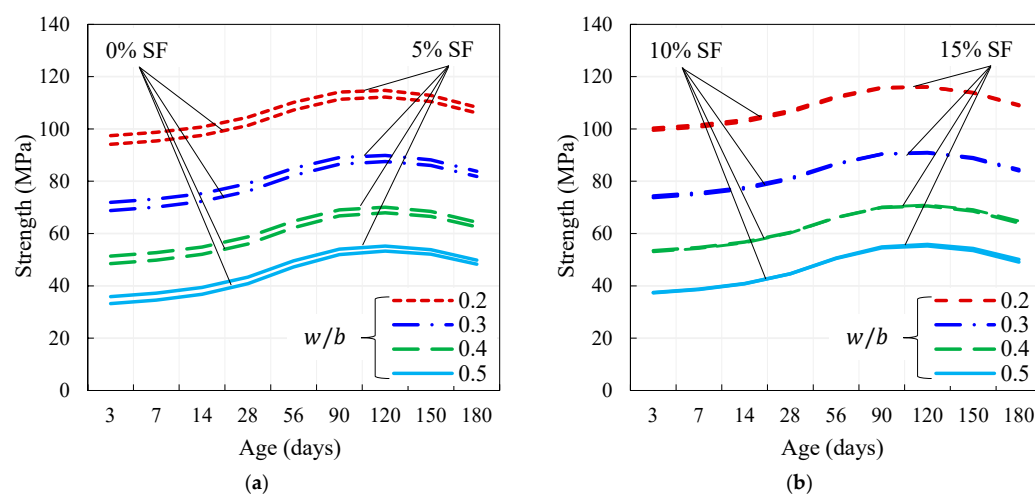


Figure 22. Effect of w/b on the compressive strength of concrete under hot weathering: (a) 0–5 and (b) 10–15% SF.

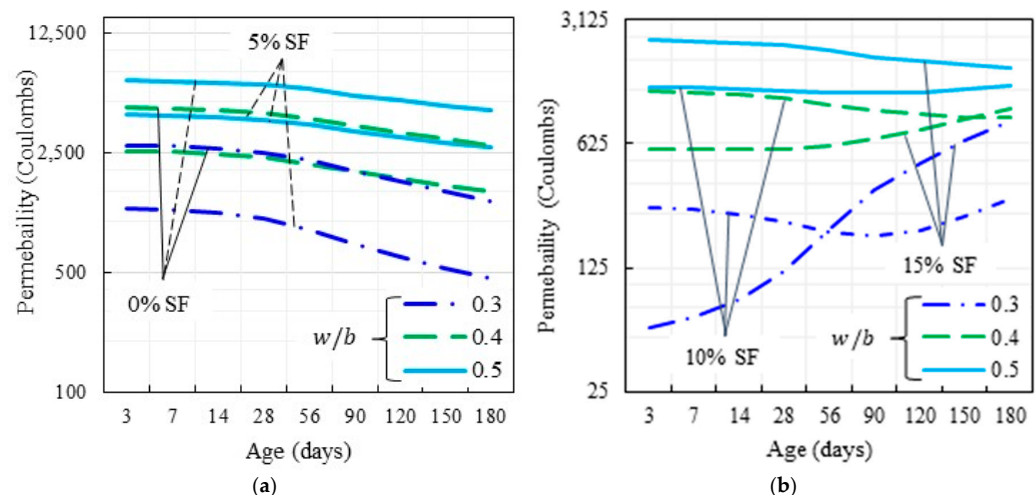


Figure 23. Effect of w/b on the chloride permeability of concrete under hot weathering: (a) 0–5 and (b) 10–15% SF.

6. Conclusions, Limitations, and Prospects

In this study, various dosages of SF, i.e., 0 (control mix), 5, 10, and 15%, in N, H, and U mixes and up to 24% in UH mixes, were investigated in concrete with different water–binder ratios (0.18, 0.25, 0.40, and 0.55) cured under hot weather conditions. The compressive strength and durability (chloride permeability) properties of the SF–concrete were tested (by following the BS 1881 and ASTM C 1202 recommendations) and analyzed at various ages. Moreover, an RSM-based model that demonstrated its objective capability to predict the properties of SF–concrete has been developed, validated, and used in a parametric study. By using the validated predictive model and p -value hypothesis test, the present study developed isoresponsive strength and permeability curves. In addition to providing insight into a specific response, these curves may also be useful in predicting the properties of materials and optimizing these properties. A parametric analysis was also carried out in this study to examine the relationship between strength and chloride permeability depending on several influential parameters.

The conclusions below may apply to the strength and permeability of SF-concrete in Saudi Arabia's central region. As a further limitation, the developed prediction model provided a lack of precision when evaluating the permeability of concrete in most cases with a water–binder ratio of less than 0.3 and an SF content of more than 5%. In comparison with the control mixes, the SF-concrete mixes showed significant increases in compressive strength after 28 days. The strength enhancement rate in SF-concrete was higher than that in plain cement HPC. Strength was improved at 28 days after incorporating 5% of SF, while 10% and 15% had no significant benefits. A higher content of SF did not affect strength, but the effect was associated with curing. It is unlikely that SF-concrete will perform well after 28 days without any curing. This phenomenon was attributed to the thermal stress cycles that occurred during the day and night, ranging from 30 to 45 °C, as well as the extremely low humidity. It is well known that an interstitial transition zone of varying qualities forms around coarser aggregates, which are also responsible for this phenomenon, which dissipates with decreasing aggregate size, as is the case with UH mixes, and optimizing curing systems requires more comprehensive and in-depth research on this finding.

There were almost no differences in strength development patterns for SF-concrete with various water–binder ratios as well. The strength gains were slightly higher for concrete with a water–binder ratio of 0.55 after 28 days compared to 0.18, 0.25, and 0.40. The permeability was reduced by about 70% when adding 5% SF to a water–binder ratio of 0.25; however, adding 10% and 15% had little effect. In contrast, the permeability of concrete with a water–binder ratio of 0.40 and 0.55 decreased with increasing SF content. The higher the water–binder ratio (i.e., 0.40–0.5), the less effect hot weathering would have on concrete permeability. The developed model for predicting the strength and permeability showed its low variance and efficient use with an average of 1.009 and 0.96 for the predicted–tested ratios, respectively, while these data points fell within the $\pm 90\%$ accuracy range. The developed model was effective in predicting the strength and permeability of SF-concrete, with averages and standard deviations of 0.96–1.01 and 9.4–15.5 for the predicted–tested ratios, respectively, while these data points fell within the $\pm 90\%$ accuracy range.

It appears that regardless of the water–binder ratio, the strength contour shows the same pattern; however, at late ages of concern (around 140 days), concrete's strength degrades at the SF dosages specified. At 6% SF content, the isoresponse pattern of permeability typically changed, and the addition of SF significantly increased permeability. In the parametric analysis, it was determined that adding 5% SF increased compressive strength. In the case of decreasing water–binder ratios, the enhancement could become more apparent. In general, strength development began slowly at an early age and slowed over 120 days. Moreover, by increasing the SF content to 10 and 15%, concrete becomes more impermeable.

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