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Mechanical and Microstructural Characteristics of High-Strength Self-Compacting Concrete (HSSCC) with Optimal Silica Fume and Fly Ash Cement Replacement

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Abstract

This paper focuses on high-strength self-compacting concrete (HSSCC) characteristics with the optimal percentages of cement replacers, fly ash, and silica fume. The aim is to analyze the different proportions of HSSCC mixes to evaluate and establish their durability. In the initial part of the study, the maximum proportion of these materials the system should include was calculated with the help of the statistical software Minitab. Then, variable silica fume, fly ash, and W/C ratio functions were investigated using response surface methodology at Minimum, Medium, and Maximum levels. The method of RSM made it possible to identify the composition sets of silica fume, fly ash, and W/C ratio to further assess the possibility of simultaneous optimization. These aspects entailed fresh properties' verification, slump flow, T500, J-ring, segregation resistance, and compressive strength on newly incorporated properties. The research was undertaken with cement replacements by 05% silica fume, 10% and 15%silica fume, and 20 % and 30% fly ash. Mechanical characteristics such as compressive strength, tensile strength, flexural strength, and properties related to durability, such as water absorption and porosity, were also studied. It was also observed that the best-performing mix was obtained with 5% silica fume and 20% fly ash by the quantity of cement with a water-binder ratio of 0.33. This mixture had the best mechanical properties and the maximum compressive strength, which increased by 27% compared to the essential mix containing only OPC. Furthermore, the porosity and water absorption were reduced by 50% and 55%, respectively, compared to the identical standard mix. Therefore, this HSSCC mix can improve the concrete performance to an extent.

1. Introduction

Self-compacting concrete is high-performance concrete, the placement of which does not require external compaction because it is compacted on its weight. The Use of self-compacting concrete (SCC) was first developed in Japan in the 1980s [1]. This makes SCC sustainable since it can use other materials instead of cement to improve its compressive strength [2]. Using SCC also has the following benefits over conventional concrete: no need for vibration, high workability, and good pump ability. This makes it possible to place it in comparatively small spaces with restricted access, particularly in congested steel reinforcement areas. This factor poses some mild challenges when using normal vibrated concrete. On the same note, SCC entails less labor when placing, compacting, and finishing the concrete [3], [4]. Normal vibrated concrete (NVC) comprises ordinary Portland cement, sand, aggregates (stones), water, and, in certain instances, admixtures. Sustainable SCC possesses these attributes, but its constituent features comprise a more significant percentage of chemical admixtures and blending part of the cement with minerals and fillers.

These amendments enhance the properties of fresh and hardened concrete equally. Recent trends towards incorporating SCMs, particularly artificial pozzolans, have surged regarding their environmental aspect and cost efficiency. Superplasticizers such as high-range water reducers are incorporated in SCC to minimize the water-binder ratio and increase flowability while improving the concrete's durability [5]. One technique to enhance the flowing SCC stability is a conventional way where the contents of the reactive or inert fillers are increased, consequently increasing the fines and decreasing the overall aggregates. This, in return, increases the workability of the mix, whereby segregations and bleeding are reduced or minimized. The incorporation of the use of Natural supplements in SCC. Concrete as a partial cement substitute is sustainable and beneficial to the economy. These additives seal pores and help achieve economy [6]. Concrete density, thus reducing bleating, cracking, and permeability [7]. Moreover, using a type of waste product such as fly ash and silica fume in SCC increases its workability. Also, it offers increased strength, improved cohesiveness, and the ability to prevent the material from segregating. Such cementitious materials can enhance the effective properties of the mixture in one way or another without reducing or even increasing the strength of the mix [8].

Earlier work has reviewed the literature regarding the application of supplementary materials in improving the characteristics of HSSCC with specific reference to workability, mechanical properties, and durability [9], identified that concrete containing class F fly ash (FA) in partial replacement of cement enhances the flow ability of HSSCC up to 20% because the increasing fly ash from 10 % to 20 % increases the slump flow value from 555 mm to 595 mm. However, after 20%, there is a clear drop in the rate at which flowability improved, as observed from the study by [10], [11]. Also unveiled that the practical use of up to 20% cement replacement with fly ash enhances workability, while not for SCC's self-compacting nature. However, the concrete containing more than 20% of the replacement made the concrete denser and had poor self-compacting features. Nonetheless, the reports have shown no definite number of fillers in incorporation to HSSCC. Consequently, a clear definition concerning the ideal proportions of some materials, such as fly ash, must be provided through the essential multi-property testing of fresh and hardened concrete materials [12] also, if there is an increase in workability, strength and an decrease in porosity by incorporating cement with other materials, such as silica fume and fly ash, in the concrete.

The fineness and dosage of these substitutes have been shown to impact the early-age strength properties of HSSCC significantly. According to [13], workability and the compressive strength of high-strength self-compacting concrete. Encompassing fly ash as a partial cement replacement shows that SF properly enhanced workability and strength improvement in HSSCC, which was used from 10% to 15%. Toward this end, silica fume substitutions at 0%, 5%, 10%, and 20% of the weight of cement were examined. The findings indicated that the concrete achieved the EFNARC workability; the gain in the compressive strength was 71.52 MPa on average with 5% and 20% silica fume. The most suitable proportions of silica fume were between 5% and 15%, although the exact percentage was not evident. Silica fume (SF) and fly ash (FA) have been tried earlier in concrete mixtures concerning hybrid use [14]. An experimental study of nine specimen series with fly ash content between 10% and 30% and silica fume between 5% and 15% by the weight of cement was conducted. The control mix contained 70% OPC, 20% FA, and 5% SF. In subsequent mixes, OPC content was kept constant while FA and SF content was increased gradually. This work investigated the process, properties, and structure of the high-strength mixtures of OPC, SF, and FA and found that the best mechanical properties were obtained at 75% OPC, 5% SF, and 20% FA. This research thus establishes that FA and SF as cement replacement materials enhance the fresh and hardened characteristics of HSSCC. These additives improve flow ability and prevent an undesirable characteristic known as segregation, which is critical to the fresh state of HSSCC. Incorporating pozzolanic elements also helps to regulate the percentage of cement and the heat of hydration [1]. However, there are also some negative attributes of HSSCC, including the following: first, HSSCC material has lower tensile strength and ductility than the other material. Furthermore, there is no standard mix design strategy [15].

This study also used a control mixture to determine the optimal SF and FA ratio through a preliminary investigation of slump flow, a T500, L-Box, segregation, and compressive strength testing. The goal was to use experimental and theoretical analysis to identify the appropriate combination for producing the best-performing HSSCC combination. As mentioned in Table 1 below, most researchers have employed 5-10% silica fume and 10-50% of fly ash in the experimental and numerical investigation. Yet, limited data is available about the effect of reduced amounts of silica fume and fly ash incorporation on the high-strength properties of concrete used as supplementary cementitious materials. According to prior studies, using these materials to replace ordinary Portland cement is advised. 5% & 10% silica fume (SF) and 10% & 20% fly ash (FA) were chosen unintentionally as replacement levels based on Table 1, finding that these percentages offered the best results. Future research should study durability qualities and their relationship to mechanical performance. This work, therefore, explains how to choose the right HSSCC mix for increased concrete performance.

Table 1 *Past research on the peak efficiency of silica fume and fly ash substitutes*

Method and materials	Replacement	Results	Findings	Reference
Probed the possibility of scba-v high volume as a replacement for Portland cement. Discussed the characteristics of concrete in terms of strength and Sound, heat Insulation, and durability.	g 10%,20%, 30%, 40%, and 50% SCBA and 25% SF	The concrete containing SCBA pastes achieved concrete strengths of more than 25MPa at 28 days and a further increase to over 30MPa at 180 days.	The study established that SCBA can replace Portland cement in concrete by a proportion of 10-50%. The results also indicated that the strength of the concrete increases with time; it is well over 30Mpa at 180 days.	[16]
A power-driven rotating pan mixer was used when mixing the concrete ingredients. Cylindrical concrete specimens were prepared after casting and were subjected to determination of their compressive strength.	W/C = 0.35 and 5%, 10%, 15% 20%, and 25%	The binary mix with 20% BA showed the highest compressive strength in the investigation. It also is worthy of note that the ternary mix containing 33 BA, and 7 SF also produced a relatively high strength of 74 MPa in 28 days.	The strength parameters of the blends with 20% BA and 40% BA/SF were higher. The mixes containing additions of BA showed that the microstructure and pore structure became densified.	[17]
Other complementary strength and flow properties studied on cement mortar in the laboratory entailed scanning electron microscopy (SEM), compressive strength, flow, and strength analysis.	15%FA+5%SF and 35%FA+5%SF	At 7 and 28 days, the maximum compressive strength achieved was 68 Mpa.	Ternary mixtures had a lower flow rate than binary mixtures. Moreover, Class F fly ash provided better enhancement in compressive strength than Class C fly ash.	[18]
The synthesis of a ternary blend fly ash-based geopolymer mortar means	In this work, Alccofine and GGBS were substituted in	That is why adding 40% fly ash, 40% GGBS, and 20%	The optimum values of the ternary blend depend on the component ratio of 40	[19]

replacing cement with supplementary cementitious materials.	blends with fly ash, with Alccofine incorporation at 2.5%, 5%, 10%, and 20% and GGBS incorporation at 10%, 20%, 40%, and 80%.	Alccofine achieved the highest compressive strength. The 40% GGBS and 20% Alccofine substitution indicated improved normal consistency and compressive strength. These results show that fly ash, when replaced by 80% GGBS, achieved the highest point of compressive strength quantity of 44.2, 50, and 57.3 MPa at 7, 28, and 56 days, respectively.	percent fly ash, 40 percent GGBS and 20 percent Alccofine. Substitution of materials for specific elements necessary for compressive strength was also shown to increase ratios significantly.	
A study on GGBS and SF was carried out as the cement partial replacement. Evaluated characteristics of grout and PAC through flowability and strength tests.	W/C of 0.50, with GGBS content of 0–40% and SF content of 0–10%.	GGBS and SF improved both the flowability and the strength of the grout. PAC with 40% GGBS and 10% SF was observed to have almost negligible shrinkage. Yet the 28 days were not declared in the given data at all.	GGBS and SF improve the rheological properties of grout and increase its compressive strength. PAC at 40% GGBS and 10% SF shows a smaller shrinkage value.	[20]
Silica fume and fly ash were incorporated as additives. Evaluation was done on the density of the compressive strength as well as the porosity of the concrete.	Silica fume 7.5%, 14.5%, and Fly ash 17%, 35%	The topic of the research work of the paper is the compressive strength and the porosity of concrete. The use of silica fume and fly ash increases the strength of concrete and, at the same time, decreases permeability.	Concrete strength and porosity are improved by silica fume and fly ash. Changes in the proportions of the admixture improve both the strength as well as the lightness of the concrete produced.	[21]

The experiments cover slump, compressive, and splitting tests and carbonation and volumetric electrical resistivity measurements. It also involves TGA, EDS, XRF, and SEM analyzing techniques.		High superplasticizers are deemed necessary to impart workability to LC^3 concrete. In the LC^3 formulations, silica fume, fly ash, and sugarcane bagasse ash perform well.	The flowable LC^3 concretes described in this paper need a high content of superplasticizers. Compared to the rate of other supplementary cementitious materials (SCMs), silica fume showed the best-performing index of LC^3 mixtures.	[22]
Response Surface Methodology (RSM) A	SF 6%, 9%, 12% and FA 20%, 25%, 30%	The optimal mix ratio is OPC: SF = 36-40:12-16:44-48. Such a loss of SF was done without a significant loss in low alkalinity performance. The mixture comprised of 20FA, 6SF, and 30AR had a compressive strength of 20.17 N/mm^2 While the second trial of 20FA-12SF-30AR gave a compressive strength of 21.27 N / mm^2 or an increment of 5.45% of the former one.	Optimal Mix: OPC: SF= 36-40:12-16:44-48. Minimizing SF allows for maintaining low alkalinity rates and results in cost benefits.	[23][24]
Fresh Properties Tested: Slump flow, T50 cm, V-funnel, L–box. Mechanical Properties Evaluated: These are the compressive strength test, the split tensile strength test as well as the flexural strength test.	The fluidity of the paste was investigated with a water-to-cement (W/C) ratio of 0.45 and replacement levels of fly ash (FA) and ground granulated blast-furnace	50% partial replacement of GGBS and FA has sound effects on enhancing the properties of hardening of SCGC. Also, SCGC is cheaper for precast concrete and cast-in-it concrete systems	The hardening properties of SCGC are improved by a 50:50 mix of GGBS and FA. Besides, SCGC is economical for precast and cast-in-situ construction projects.	[25]

	slag (GGBS) as 0%, 25%, 50%, 75%, and 100% respectively.	to be adopted for construction.		
The concrete mixture's workability, compressive, and flexural strengths were also determined, and scanning electron microscopic examination of the concrete specimens was also done.	replacements of BFAE or BFAP in 0%, 10% and 20%	At any specific time, BFAE reduced the slump of fresh concrete that was ready for use as opposed to BFAP, which boosted the slump. As the results indicated, both BFAE and BFAP can be appropriately used to replace less than 10% of the cement content.	BFAE reduced the slump of fresh concrete, while BFAP increased the slump. BFAE and BFAP programs are fit to replace at least 10 percent of cement players.	[26]

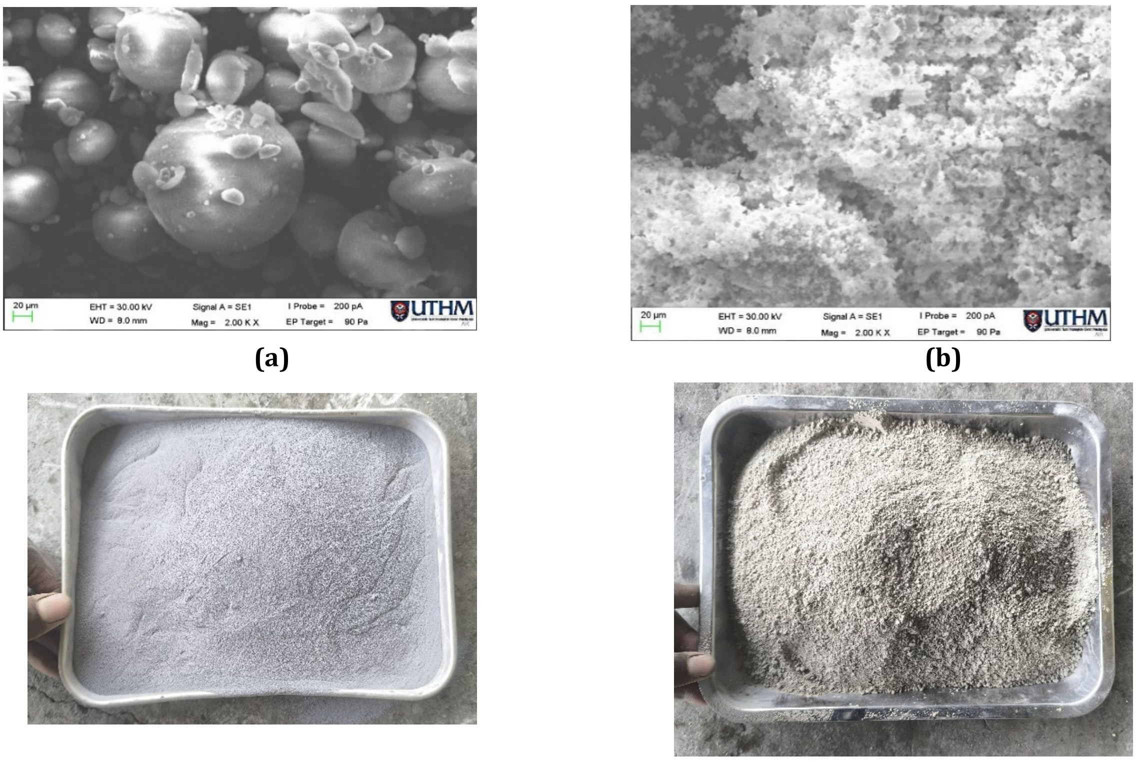
1.1 Experimental Program

1.2 Materials Properties

The cement used in this research was Ordinary Portland Cement (OPC) from the Tasek brand, compliant with ASTM Standard Type I (MS EN 197-1:2014). These replacement materials conformed to the (ASTM C618 2014) classification requirements when the mineral filler was Class F fly ash. The fly ash utilized in the study had a fineness of 3990, 3450 cm^2/g, a specific gravity of 3.15 and 2.45, and a soundness value of 1.0 mm. Fly ash was sourced from the power station in Tanjung bin Johor, and the SF was supplied. By Elkem Microsilica SF-Type. The following values presented on this material's Material Safety Data Sheet complied with (ASTM C1240 (2015) standards for silica fume: Table 2 provides the chemical compositions of the materials. Fig. 1(a) and (b) represent SEM images of SF and FA particles, which are irregular, sharp, spherical, and porous in shape and possess different surface properties. Photographs of the replacement material are in Fig. 1(c) and (d). Workability is another factor that influences OPC, silica fume, and fly ash. It makes concrete stronger in terms of direct and bending stress, decreasing its porosity, decreasing the number of cracks, and increasing its resistance to chemical attacks and freeze-thaw cycles. The superplasticizer employed in this study was Fosroc Conplast AP, a polycarboxylate-based water-reducing plasticizer, and a set accelerator obtained from Fosroc Sdn. Bhd. It was proved to have a density of 1.126 g/ml at 25-°C and a viscosity of 1.39 cP at the same temperature. This superplasticizer was required to ensure the concrete was workable and met ASTM C494 Type G and F (ASTM C494/C494M-08) standards. Additional tests, such as HSSCC and normal concrete, were not performed for several reasons. Others include the dossier of this superplasticizer, which might not afford many prospective results when further tested; lack of time and finance for conducting more tests that might not be very productive; change of paradigm in materials that are exploited in constructions like a shift to sustainable ones, better mechanical properties among others; lack of resources in terms of finance, personnel, and equipment that define the possibility of study to be carried out. The small aggregate was sand originating from the area, with a grain size of 4.75 mm and a specific gravity of 2.62. The coarse material was spherical natural gravel that passed through a 20 mm IS sieve with a specific gravity of 2.6. This study did not do any additional testing on the superplasticizer because it was purchased directly from the manufacturer.

Table 2 *Past portland cement, fly ash, and silica fume chemical properties*

Chemical Composition	OPC	SF	FA
Silica (SiO_2)	20.82%	93.67%	62.11%
Calcium Oxide (CaO)	66.60%	0.31%	17.13%
Aluminum Oxide (Al_2O_3)	5.7%	0.83%	18.58%
Magnesium Oxide (MgO)	2.2%	0.84%	0.24%
Iron Oxide (Fe_2O_3)	4.4%	1.30%	-
Sodium Oxide (Na_2O)	-	0.40%	0.29%
Potassium Oxide (K2O)	0.8%	1.10%	0.84%
Loss Of Ignition (L.O.I)	-	2.10%	1.55



(a) (b)

(c) (d)

Fig. 1 *(a) SEM images of SF; (b) SEM images of FA; (c) raw SF; (d) raw FA*

1.3 Mix Proportions

The preparation of the HSSCC mixtures in this study was done in two phases in the first stage, the blends of HSSCC mixtures were prepared. In the first stage, it was necessary to design a control mix corresponding to the HSSCC, referencing the EFNARC guidelines (EFNARC, 2005). Several samples were prepared at the laboratory, and an experimental approach was adopted to get the required characteristics. The control mixture was used only to prepare three different mixes in the second stage and assess them without relation to the control mix. The percentages of the ingredients by mass for stage 2 and per cubic meter for the three HSSCC mixtures are shown in Table 2. Different replacement materials were used in these blends, including SF and FA, at their respective proportion of use. In stage 2 of the study, the best mix design was selected using a theoretical statistical program. The composition of the HSSCC mixtures with the best replacement proportions is shown below in Table 3.

Table 3 *Ingredients weight per cubic meter binder*

Total binder kg/m³	Coarse Aggregate	Fine Aggregate kg/m³	Water/Binder kg/m³	Superplasticizer kg/m³
530	1200	900	0.33	2.0

1.4 Mixing and Casting Procedures

The target proportions of coarse and fine aggregates for the fresh SCC mixtures were first mixed in a rotary drum mixer with a $0.1m^3$ for one minute. This was done mechanically in a non-conductive mixer for two minutes to ensure that cement replacement particles were uniformly distributed throughout the cement.

1.5 Properties of Optimal HSSCC Mixes

Fresh concrete characteristics were also investigated after mixing, and the rheological characteristics of the mixtures were tested. All new property measurements of the high-strength self-compacting concrete (HSSCC) were assessed regarding EFNARC provisions (EFNARC, EFCA, 2005) [28][29]. In the preparation of the optimum mixtures, the material conditions used in the laboratory and the exact quantities as calculated from the theoretical values were accomplished, and the results were tested in practice. These experimental values obeyed the theoretical predictions with reasonably good accuracy. Each optimum mix is tabulated in Table 3 using the properties identified for the evaluation; the images of the slump flow test for the three ideal HSSCC mixes are shown in Fig. 2.

Properties for optimal combinations was shown in Table 4.

Table 4 *Properties for the optimal combinations*

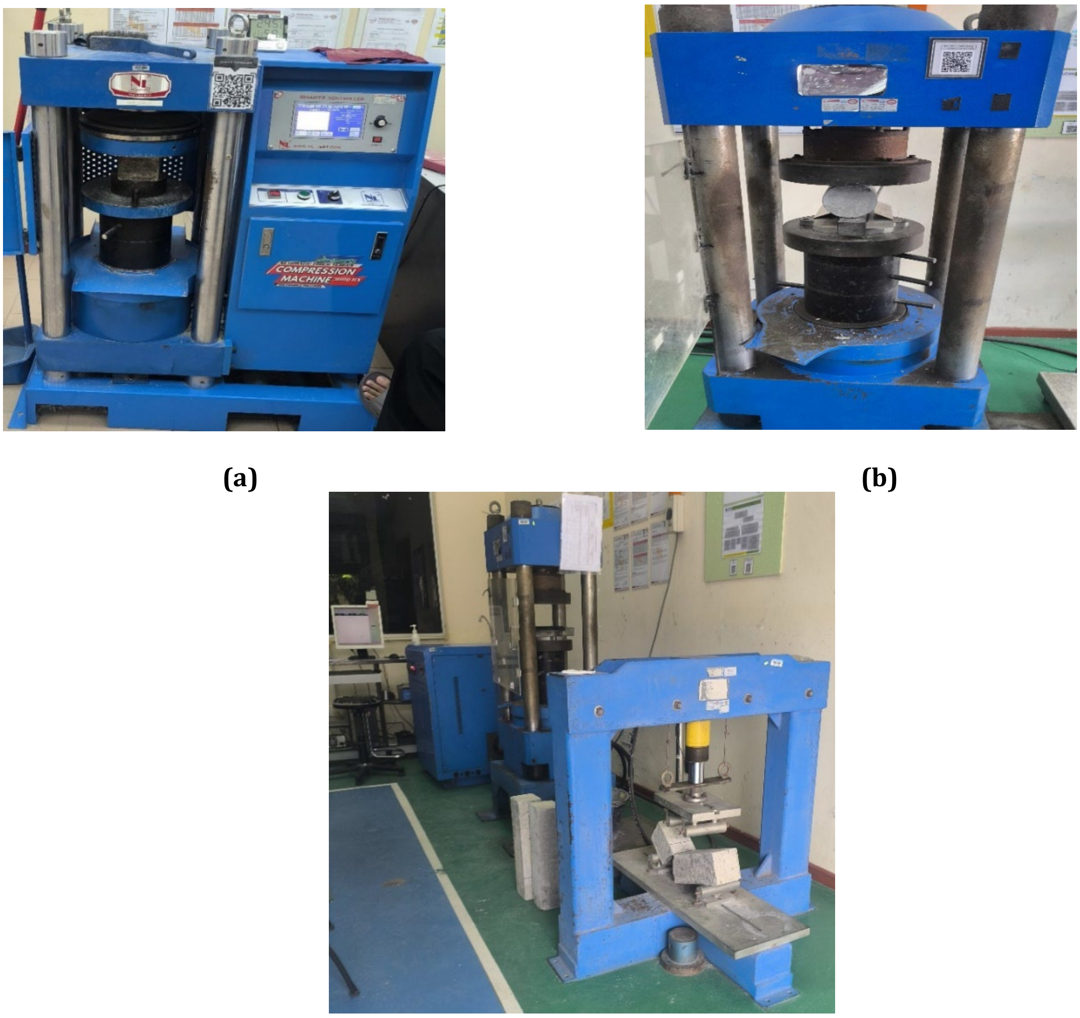
Combinations	Slump Flow Test (mm)	T_{500} Test(s)	J-Ring Test	J-Ring Test (s)
CONTROL	700	6.6	680	8
15% SF & 20% FA	630	6.0	615	7
10% SF & 20% FA	625	6.5	610	8
5% SF & 30% FA	600	6.2	585	7

(a) **(b)**

Fig. 2 *(a) Slump flow test; (b) Slump flow test*

1.6 Properties of Optimal HSSCC Mixes

The quantitative measurement of the three 100 mm cubic specimens' average compressive strength employed the Digital compression testing Machine having a maximum load speed of 7.0 kN/s, as stipulated by BS 12390-3 (2009). The same machine was used with a loading rate of 0.94 kN/s for the splitting tensile strength using three cylinders of 100 × 200 mm conforming to GT/B 50081-2002 While three prisms with a dimension of 100 × 100 × 400 mm were tested to determine the modulus of rupture, refer to ASTM C78-15 (2015). Other tests were also carried out as durability-related tests because they influenced the durability of concrete. Besides, three 100 mm cubic samples had porosity and water absorption tests after a 28-day curing period. The test referred According to ASTM C642 (2013), the outcomes were averaged to obtain the best values. The mechanical and related durability characteristics testing is presented in Fig 3.



(a) (b)

(c)

Fig. 3 *(a) Compressive strength; (b) Split tensile strength; (c) Flexural strength tests*

2. Results and Discussions

2.1 Mechanical Properties

The average test results observed at 28 days for compressive strength, tensile strength, and flexural strength are plotted in Fig. 4, 5, and 6. The same trend of results was observed in this investigation, where the highest strengths were obtained with 5% silica fume and 20% fly ash partial replacement for cement on a weight basis. This was followed by a similar effect with 10% silica fume and 20% fly ash; however, the mixture containing 15% and 30% (SF and FA) had a lower strength value. There is robust evidence that concrete is improved by incorporating silica fume and fly ash and that the most beneficial gain is compressive strength achieved in ternary blends with OPC [30]. Therefore, the superior tensile strength observed in this study could be attributed to the silica fume particle characteristics of fine particle size and high surface area, the filling power of fly ash, and the pozzolanic activity of the silica fume [31]. The obtained results can be statistically processed using the mean and standard deviation; the mean value can denote the quality of compaction, while the standard deviation can point to the repeatability of the process. Further compaction should ideally be achieved to provide enhanced properties such as freeze-thaw action and cost-effective ease of compaction. Significantly, the obtained mean and the standard deviation do not mirror the concrete's compressive strength. The study also established the rational level of cement replacement of these materials. The hydration product of cement, also identified as calcium hydroxide, combines with pozzolans by forming a new hydration product, calcium silicate hydrate (CSH), which contributes to concrete strength gain. When the correct quantity of pozzolans is available, this reaction minimizes calcium hydroxide formation, forming an interfacial transition zone surrounding particles. Which generally hinders interaction between aggregates and cement paste. Consequently, increased the amount of binder, brought by the reduction of excess calcium hydroxide and the formation of more CSH, increases compressive strength.

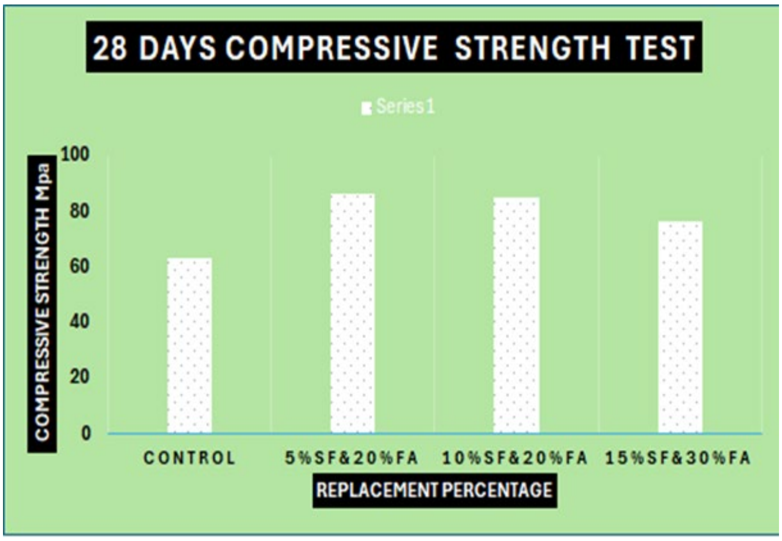


Fig. 4 *Compressive strength test results at age 28 days*

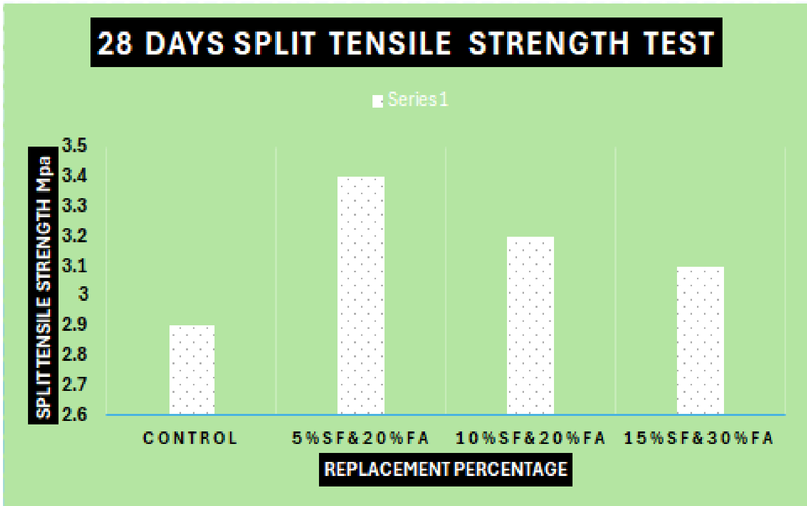


Fig. 5 *Splitting tensile strength test results at age 28 days*

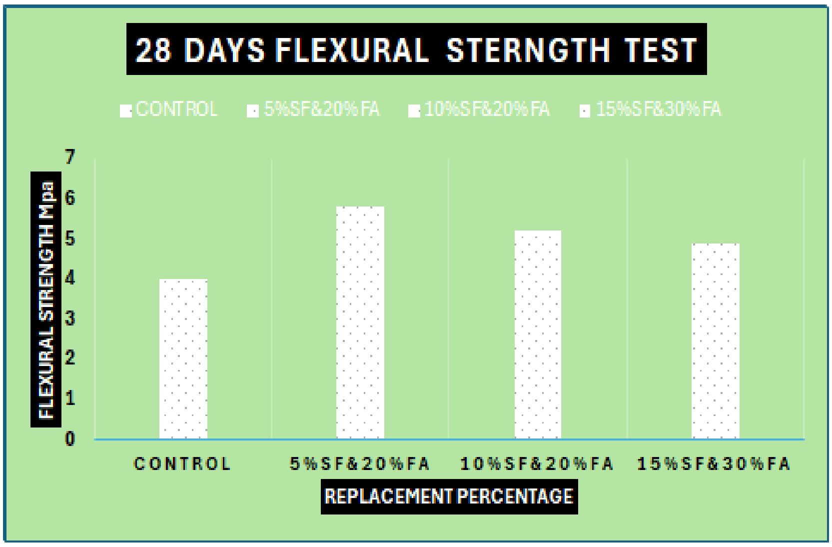


Fig. 6 *Flexural strength test results at age 28 days*

2.2 Related Durability Properties Test

Fig. 7 and Fig. 8 present the test's findings on water absorption and porosity at 28 days. Porosity and water absorption represent the most important characteristics of concrete concerning durability. The figures showed that the control mix had the highest water absorption and porosity compared to the mixes containing silica fume and fly ash. There is also a marked reduction of water absorption and porosity when a ternary blend of silica fume and fly ash is utilized as an alternative material. In particular, optimum concentrations of these materials improved the performance of the composites in the following aspects. This improvement could be attributed to the increased packing density of the microstructure in the high-strength self-compacting concrete (HSSCC) due to better particle size distribution control. Due to the filling nature of fine particles of silica fume and their pozzolanic activity, the structure of SCC becomes more homogeneous. This usually implies reduced water absorption and porosity of the floor. These findings parallel the view presented by [32].

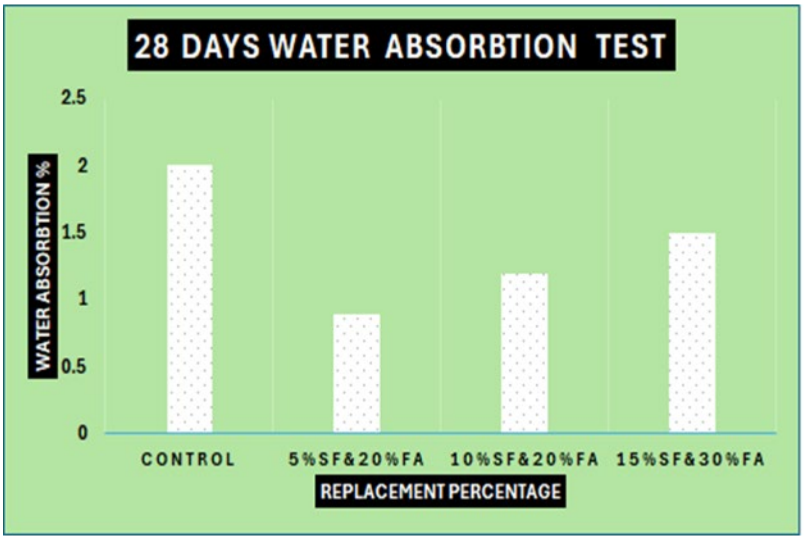


Fig. 7 *Water absorption test results at age 28 days*

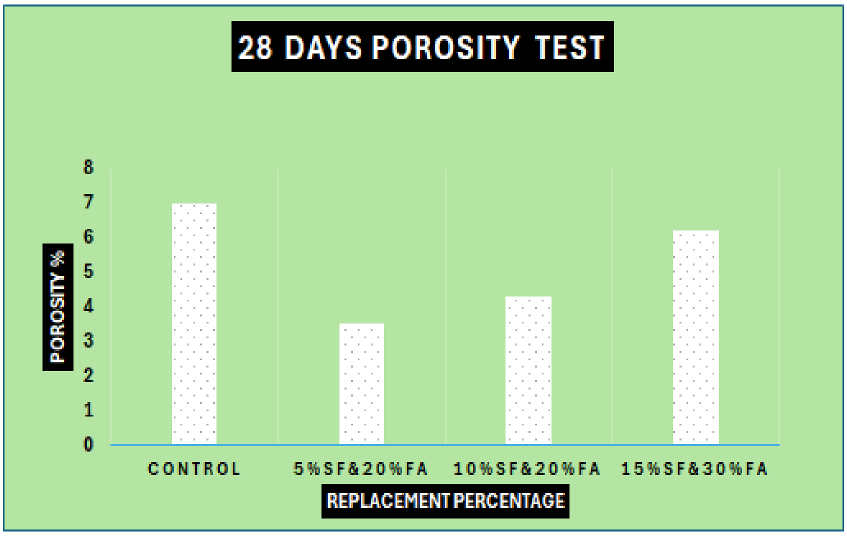


Fig. 8 *Porosity test results at age 28 days*

2.3 Selection of Optimal Proportions

Thus, the best combination of each defined factor, including 28-day compressive strength, was determined with the help of the received values. First, the Response Optimization feature of Minitab® Statistical Software Minitab 2019 was used, and then Derringer & Su's Special cubic model and Desirability functions were used in Excel. Minitab is a statistical tool that provides a tool for mixture optimization.

2.4 Minitab Method

RSM is preferred to other optimization methods because it identifies the best solution in the design space for a set of experiments through the sequential approach. It can perfectly handle nonlinear relativity between variables, thus making it ideal for complex problems, and it is cheaper than some methods, such as factorial design, since it minimizes the computational cost and time. RSM enhances accuracy because the mathematical model offers an accurate estimation of the response surface, and RSM is flexible and less sensitive to multiple responses, constraints, and noise. Moreover, using a graphic display makes it easier to make sense of variable interactions and optimization outcomes. Thus, With the help of response optimization, the content of silica fume, fly ash, and water cement ratio in concrete was adjusted in the maximum and minimum tested range shown in Table 5. The predicted responses were the slump test, the J-ring test, and compressive strength at 28 days.

Table 5 *Constraints used (% cementitious material)*

Constituent	SF	FA	W/C
lower limit	0	0	0.30
upper limit	15	30	0.36

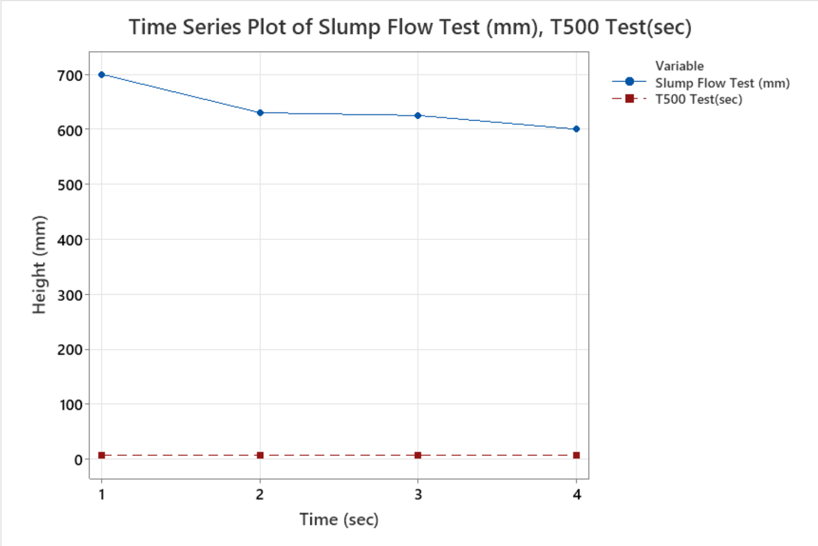


Fig. 9 *Illustrates the predicted slump flow (%)*

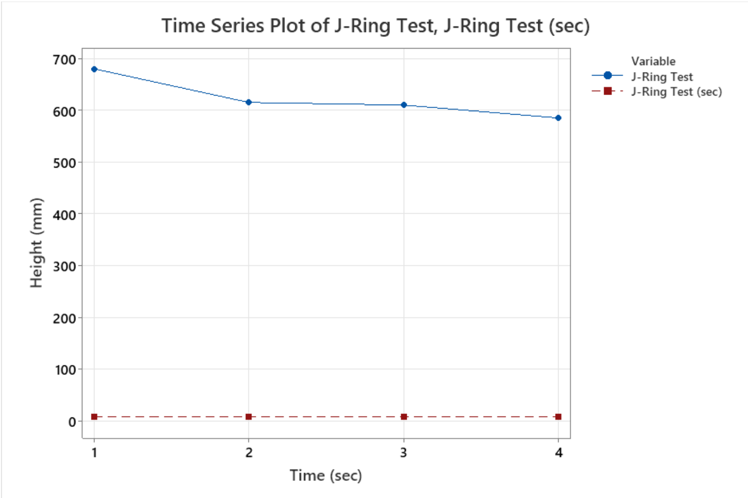


Fig. 10 *Illustrates the predicted J-ring flow (%)*

2.5 Response Optimization: J-Ring Test (sec), J-Ring Test, T500 Test (sec), Slump Flow Test (mm), 28 days Compressive Strength (Mpa)

2.5.1 Optimization Plots for Compressive Strength

The optimization plot shows how the different experimental conditions affect the simulated compressive strength, slump test, and J-ring test for the examined levels of silica fume (SF), fly ash (FA), and water-to-cement ratio (W/C). As shown in Fig. 11, the single desirability (d) and response (y) values are as follows: For J-ring time 9204 and 1.0000, for J-ring test 585.1990 and 0.99791, for T500 6.1503 and 0.74956, for slump test 600.0995 and 0.99901, and for compressive strength 77.5609 and 0.38201 respectively. The solid red lines show the range of factor settings where optimal performance values for the J-ring test, water content, and compressive strength values were obtained. The dotted blue lines correspond to the forecasted results for these tests depending on changes in the ratio of such components as SF, FA, and W/C. The predicted values for FA and SF can be summarized as follows: Compressive strength promoted by higher FA and lower SF levels at 30% or less. [31]. The maximum predicted compressive strength is achieved when the W/C ratio equals 0.30, the silica fume content is 10%, and the fly ash content is 30%. Tables 6 and 7 illustrate the Response Optimization for J-Ring Test (sec), J-Ring Test, T500 Test(sec), Slump Flow Test (mm), 28 days Compressive.

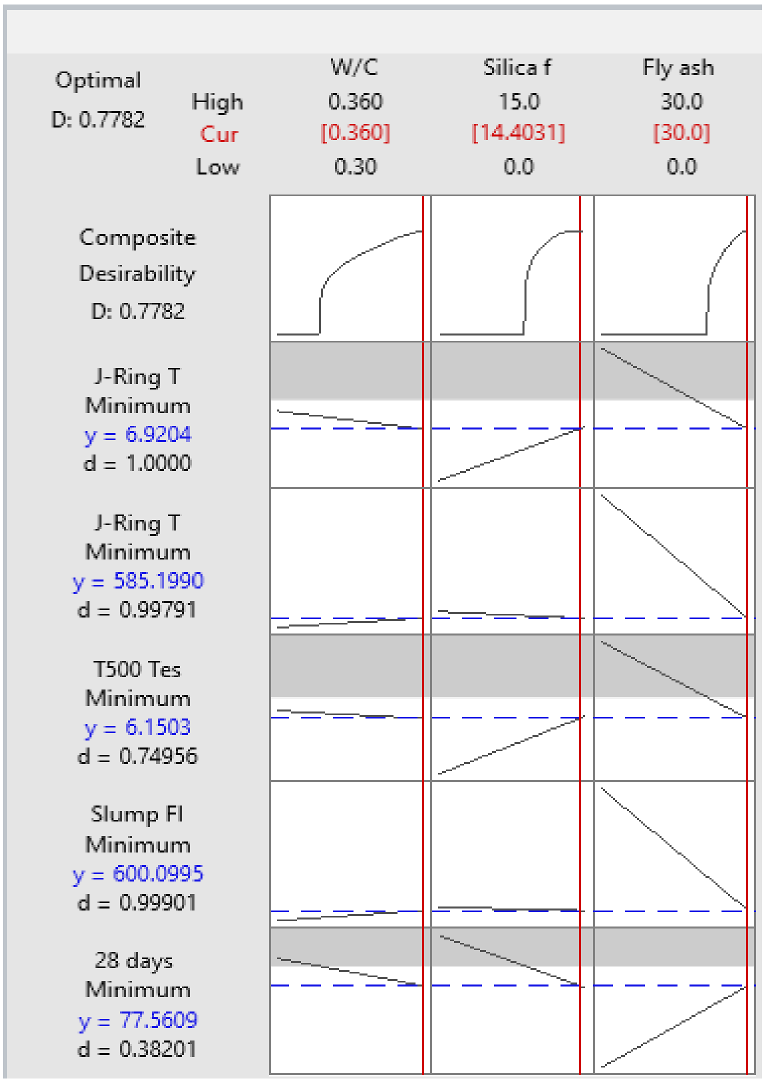


Fig. 11 *Optimization plot of the slump, J-ring, and compressive strength against W/C, SF, and FA*

Table 6 *Response optimization parameters*

Response	Goal	Lower	Target	Upper	Weight	Importance
J-Ring Test (sec)	Minimum		7.0	8.0	1	1
J-Ring Test	Minimum		585.0	680.0	1	1
T500 Test(sec)	Minimum		6.0	6.6	1	1
Slump Flow Test (mm)	Minimum		600.0	700.0	1	1
28 days Compressive strength (M	Minimum		63.1	86.5	1	1

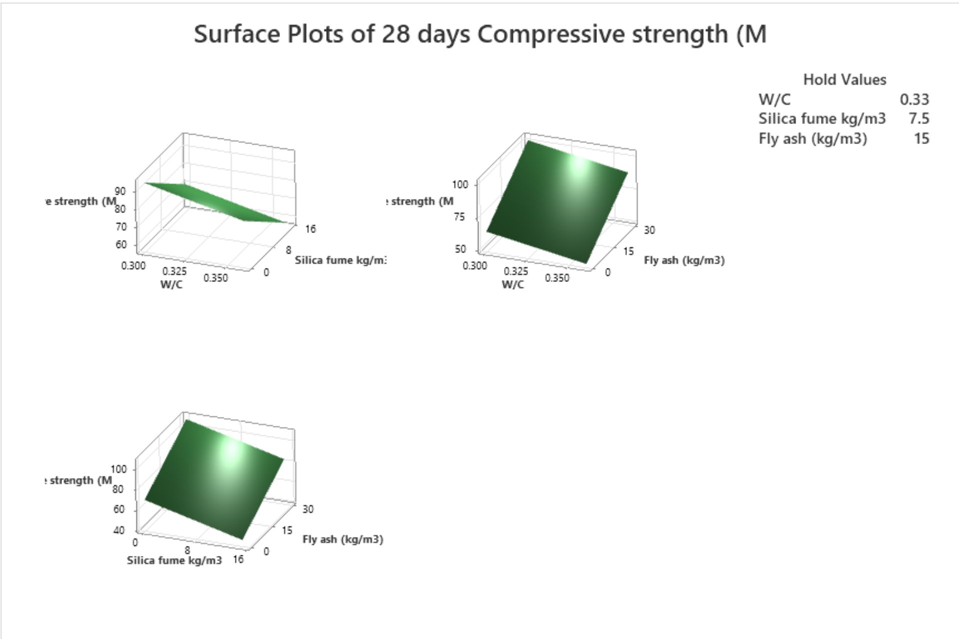
Table 7 *Response optimization solution*

Solution	W/C	Silica fume kg/m3	Fly ash (kg/m3)	J-Ring Test (sec) Fit	J-Ring Test Fit	T500 Test(sec) Fit	Slump Flow Test (mm) Fit
1	0.36	14.4031	30	6.92042	585.199	6.15026	600.099

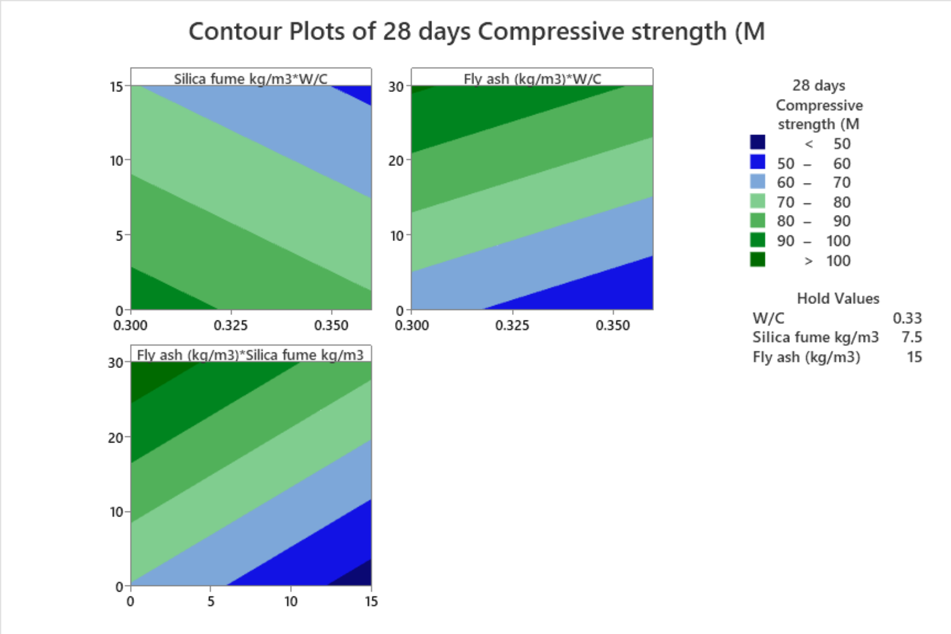
Solution	28 days Compressive strength (M Fit	Composite Desirability
1	77.5609	0.778231

2.5.2 Three-dimensional Response Surface and Two-dimensional Contour Plots of W/C, Silica Fume (SF), and Fly Ash (FA) on 28-day Compressive Strength

Fig. 12 shows the response surface and contour plot of W/C, SF, and FA. The degree of interaction between SF and FA on W/C at the central point is depicted through surface and contour plots of Fig. 12 (a) and (b). These findings show that the best W/C is attained when the concentration of SF is low while FA is high.



(a)



(b)

Fig. 12 *W/C * SF and W/C * FA (a) response surface plot (b) response contour plot*

3. Recommendations

1. The recommendation for future research is to undertake long-term exposure testing (10-20 years) of High-Strength Self-Compacting Concrete (HSSCC) to establish its durability in adverse environments, including marine, coastal, and industrial environments. Numerical models for concrete composition, exposure conditions, and cracking should enhance insights into chloride and sulfate ion transport mechanisms. Further research has to be carried out to check how the presence of seawater, tidal, and marine organisms influence HSSCC and its stability at high and low temperatures of desert and arctic conditions. Furthermore, work should begin on a more long-term and environmentally friendly HSSCC blend containing SCMs, recycled aggregates, and other materials.
2. The benefits of using high-strength self-compacting concrete include the following practical consequences:

- service life of structures in hostile climates and minor maintenance and repair. From this study,
- design and construction recommendations can be made to increase the safety and efficiency of HSSCCs during operation under stress conditions.
- The research focuses on formulating sustainable and durable HSSCC mixtures that contribute to environmental conservation by reducing the effects of the concrete construction industry on the environment, thus incredibly beneficial to the world's sustainability.
- Furthermore, it can deepen the knowledge of the impact of extreme environments and improve the stability of structures in the face of natural disasters and extreme weather conditions.

Overall, it can be concluded that the optimum features of HSSCC, combined with durability and breakthrough capabilities, would yield distinctive economic advantages, including lower maintenance costs, longer service life, and enhanced property values.

Based on the findings, the future areas, which are the topics with little concern that require extra evaluation from the recognized current study field, were discovered to have all the substitutions and combinations met their target strength, and it studied the obstacles of durability. More research is needed on the problems of some chemicals that affect concrete in a challenging environment.

4. Conclusions

HSSCC mixes with cement replacement materials such as Silica Fume (SF) and fly ash (FA) were cast in the present study, and a series of tests were carried out on them. The results allow us to make the following conclusions:

Optimum Combination: theoretically justified optimum values of adding silica fume and fly ash (5% SF and 20% FA), (10% SF and 20% FA) showed the highest mechanical characteristics and durability of HSSCC. Compressive strength results: The mix incorporating 5%-10% SF and 20% FA as cement replacement materials gave the maximum compressive strength of 86.5 MPa, and the minimum compressive strength of 63.1 MPa belongs to the control mix. This was achieved using 15% SF and 30% SF replacements, which yielded a compressive strength of 78.5MPa. Splitting Tensile Strength: The results revealed here indicate that SF and FA incorporated HSSCC mixes possessed greater splitting tensile strength than the control mix. The maximum splitting tensile strength of 3.4 MPa was obtained for 15% and 30% replacement of both SF and FA. Flexural Strength: The work presented in this study revealed that HSSCC mixes with SF and FA provided better flexibility than the control mixture. The greatest flexural strength of 5.8 MPa was achieved at the 15% and 30% SF and FA substitution. Water Absorption and Porosity: This research has found that adding the optimum level of FA at 5% - 10% SF and 10% - 20% FA in the HSSCC mix contributed help to reducing water absorption and porosity compared to other HSSCC mixes. The above combination was better than applying SF or FA only, particularly at optimal concentrations. Effect of Superplasticizer: As seen from the above study, the right amount of silica fume and fly ash (5% SF + 20% FA) coupled with 2% superplasticizer (based on cement content) increases the water content in the mix, which caused nonhomogeneous HSSCC mix. Therefore, the present set of scenarios failed to report a discernible enhancement in the mechanical properties and endurance of the produced composites.

Overall Performance: Adding FA and SF at optimum content on the HSSCC mix generally showed improved mechanical and durability characteristics. This mix was, therefore, chosen for further investigation of the durability of HSSCC.

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Conflict of Interest

The authors declare no conflict of interest regarding the paper's publication.

Author Contribution

Ahmed Aliyu Azare: I have first-handwriting responsibility for the manuscript, which includes contributions to the ***initial writing and research content****. Wan Ibrahim M.H.:* ***Oversee the project management and supervision during the study****. Abdullah Faisal Alshalif, Ramadhansyah Putra Jaya:* ***Conducted writing of the review section, edited the manuscript, and significantly contributed to the final document****. All authors: Interacts on the situation where am allowed to edit the final manuscript to be submitted.*

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