Experimental and numerical investigation of the workability and mechanical properties of High-performance fiber-reinforced fluid concrete (HPFRFC)

Laid Guermiti[1*], Dalila Benamara[1] , Mohamed Guendouz[2]

[1]Mechanical and Materials Development Laboratory, University of Djelfa, Djelfa, Algeria
[2]LME Laboratory, University of Medea, Medea, Algeria

*Corresponding authors:
(Guermiti_laid@yahoo.fr ; l.guermiti@univ-djelfa.dz)

Abstract

High workability, strength, durability and considerable ductility are becoming the major serious requirements on construction sites in recent years. High-performance fiber-reinforced fluid concrete (HPFRFC) is one of the modern concretes that can be used in some important and complicated structures with specific requirements. In this study, workability and mechanical properties of fluid High-performance concrete containing metal fibers have been investigated experimentally and numerically. A total of 13 mixtures investigated using a response surface (RSM) method. The input variables in the mixtures are the superplasticizer (SP) and metal fibers (MF) percentages. The percentage in SP takes as extreme levels 1.80% and 2.4%. The metal fibers quantity in the concrete ranging from 23 kg/m^3 to 37 kg/m^3. The slump flow was used to evaluate the rheological properties of mixture at fresh state. For the mechanical characterization, compressive and flexural strength tests were used in the hardened state. The obtained results show that the metal fibers reduce the workability of HPFC mixtures and improve their mechanical properties, especially the ductility. The slump flow (spreading) diameter of all mixtures varied between 400 mm and 580 mm, indicating a good deformability and mobility. Compressive and flexural strength ranged from 82 to 97 MPa and 4.5 to 7.53 MPa, respectively. The ductility was conferred on the HPFRFC composites, while the brittle failure is replaced by a ductile failure. Moreover, the numerical results show that HPFRFC can be produced based on optimized application of superplasticizer and metal fiber content. The optimization results indicate that with 30 Kg/m^3 fibers and 2.4% superplasticizer, the maximum 28-day compressive and flexural strength are obtained, while meeting EFNARC workability indicators. This study proved that it is possible to suitably produce a dense and workable HPFRFC that are much thinner, slenderer, lighter, more durable and low cost-effective for practical application.

Key words: High-performance concrete; metallic fiber; superplasticizer; fluidity; mechanical strength; response surface method.

I. Introduction

High performance concrete is one of the most extensively used materials in all areas of modern construction. This type of concrete is known for its low porosity and a very dense micro-texture [1]. The main characteristics of high performance concretes, namely the compressive strength, modulus of elasticity, creep, permeability, have significantly been improved recently. The use of this type of concrete has considerably increased throughout the entire world, over the past few years [2]. Indeed, high performance concretes tend to progressively replace conventional concretes in many applications.

On the other hand, High performance fluid concrete is a new concrete that met the requirement of actual modern structures. This type of concrete can easily flow to reach all points and corners of the formwork under the effect of its own weight, and without vibration. For this reason, the characteristics of the aggregates used and the proportions of the mixtures for this type of concrete have previously been determined by experimentation in order to provide the mixture with the most appropriate fluidity [3, 4]. The filling capacity can be used to define the workability and fluidity of high performance fluid concrete (HPFC). This characteristic depends on two factors: deformability and resistance to segregation [5, 6]. In this regard, Ozawa and all, proved the existence of a relationship between the filling capacity and the slump of concrete [7]. It is important to know that for low values of slump, the flow would tend to stop due to the increased friction between the particles of concrete. Moreover, for higher values of slump, the aggregates can on the contrary separate more easily from the mortar, and consequently the flow of concrete can be stopped due to the formation of bridges of aggregates resting on obstacles, which can lead to segregation in concrete. Further, in order to achieve maximum filling capacity, it is required to obtain maximum deformability and minimum segregation [5]. To achieve high performance for fluid concrete, it is required to reduce the porosity of the mixture either by acting on the particle size by adding ultrafine particles [8-10], or by including an admixture, such as a super-plasticizer [11, 12], or both at the same time, as is commonly the case.

Currently, Fiber-reinforced concrete constructions have become increasingly widespread throughout the world. Therefore, several technical guidelines have been developed and established to define fiber requirements for structural or non-structural applications in concrete [13]. Therefore, high-performance fiber-reinforced fluid concrete (HPFRFC) is a new generation of high-performance concrete which has multiple benefits when used in areas with high reinforcement density. This new type of concrete is exceptional both in terms of fluidity and mechanical behavior. The workability of this concrete is acceptable for some structures; it is between that of traditional concrete and that of self-compacting concrete. In addition, it was shown that this concrete is easy to implement and can be used for both horizontal (pre-slabs, slabs, and floors) and vertical (walls, and Columns) applications. This type of concrete has a compressive strength greater than 50 MPa for a maturity of 28 days, with a water-to-cement (W/C) ratio less than 0.4

[14]. It is worth emphasizing that the use of this type of concrete in most structures of works of art ought to be accompanied with adequate steel reinforcement. Moreover, it should be noted that the high ductility of this high performance fluid concrete (HPFC) can be achieved by suitably choosing the type and size of the aggregate used [15-17] or by adding fibers [18, 19]. Furthermore, adding fibers to high performance fluid concretes provides significant residual strength after cracking, increases ductility and also improves durability [20]. Note that these properties depend on a number of factors like the aspect ratio (fiber length/equivalent diameter), and the volumetric percentage of fibers; they are also dependent on their physical and mechanical properties. Therefore, this type of concrete can certainly be employed in building structures, such as engineering structures, that are often subjected to high stresses.

In order to reducing the number of experimental tests, and therefore reduce the research expenses, statistical methods are often used to determine the optimum mixture and achieve the optimal value of each variable in the concrete mixtures. In this context, several researchers have adopted the statistical approach for the experimental design and optimization in concrete technology [21, 22]. The Response Surface Method (RSM) is one of the most statistical methods used providing satisfactory results when used to determine the quantity of the variables used in concrete [23, 24]. The evaluation of impact of each variable and the optimization of the mixture by using of this method has been confirmed by several studies [25–27]. Nowadays, this method is used to design experiments in variety of applications [28].

In this study, the RSM method Central Composite Design (CCD), which is one of the RSM methods, was used for the purpose of optimizing and exploring the relationships between various controlled variables (factors), such as the percentage of superplasticizer (SP), and the metal fiber (MF) dosage, as well as their effects on the targeted responses, i.e. spreading, compression, and three-point flexural. Therefore, the analysis of variance (ANOVA), *a* collection of statistical models, was used to assess the significance of the models developed by the *response surface method* (RSM) as well as their correlation coefficients (R^2).

II. Experimental program

II.1. Properties of the materials used

Ordinary Portland Cement CEM I 42.5R that meets the Algerian Standard (NA442-2013) [29] was used in the present study. The physico-mechanical properties and chemical analysis of this cement are summarized in Table 01 and 02 respectively, and its EDX analysis is presented in Figure 01. Silica fume (SF) that satisfies the requirements of the ASTM C1240 Standard [30] was used as a cementitious material. Their chemical and EDX analysis are presented in Table 02 and Figure 02, respectively.

Siliceous dune sand with a maximum size of 5 mm was used as fine aggregate. The specific density, absorption rate and fineness modulus of this sand calculated according to the ASTM C128 and ASTM C136 Standards [31, 32], are equal to 2.64, 0.46% and 2.34, respectively. The EDX analysis of this sand is presented in Figure 03.

Two crushed stone fractions (G3/8 and G8/15) were used as coarse aggregates. The specific density and absorption rate of these aggregates were calculated according to the ASTM C127 standard [33] and were found equal to 2.67 and 2.12%, respectively. Figure 4 shows the particle size distributions of the sand and gravel used in this study. A polymer-based super-plasticizer named MEDAFLOW Re25 with a specific density of 1.08 was used in this study for improving the workability of the mixes. Double Hooked end Steel Fibers have been used for all mix designs (Fig. 5).

Table 1. Physical and mechanical properties of the used cement

Characteristics	CEM I 42.5 R
Specific density (kg/m^3)	3140
Normal consistency (%)	25.8 – 26.4
Hot expansion (mm)	0.25 – 1.0
Initial set	150 – 190
Final set	220 – 250
Compressive strength (MPa)	
2 days	20 – 29
28 days	42.5 – 52.5

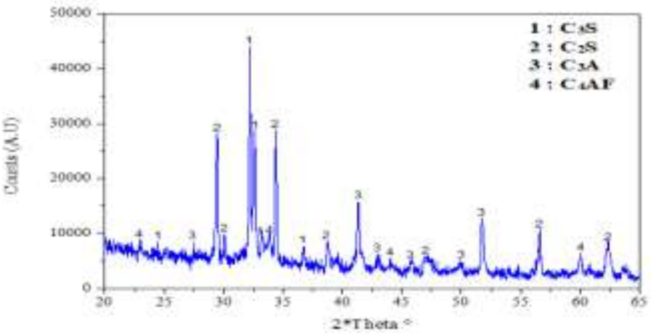


Figure 1. EDX analysis of cement used.

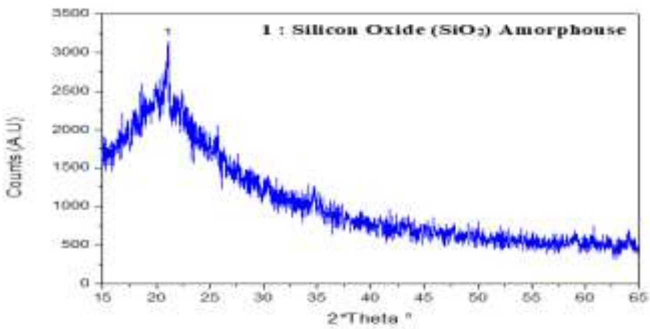


Figure 2. EDX analysis of silica fume used.

Table 2. Chemical analysis of cement and silica fume used

Chemical Constituent (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SrO	TiO_2	P_2O_5	Cl	SO_3	Loss
Cement	20.54	4.45	3.41	64.10	3.01	0.67	0.18	0.06	0.25	0.15	0.02	2.22	1.2
Silica fume	90.45	1.25	0.19	0.15	0.29	0.68	0.16	-	0.04	0.26	0.01	0.29	0.04

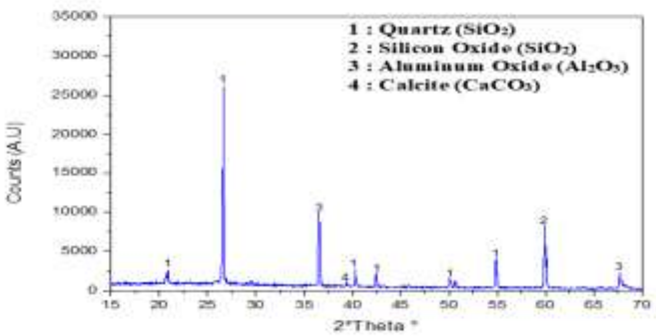


Figure 3. EDX analysis of sand (0/5) used .

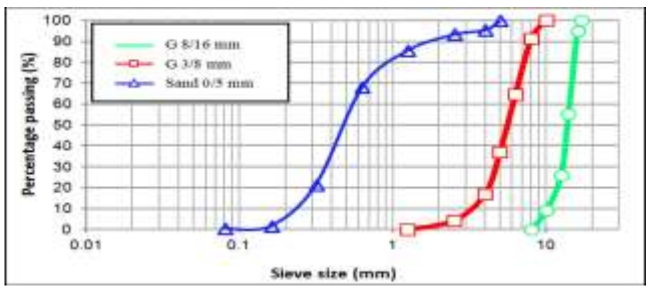


Figure 4. Grading curves of sand and

gravels used.

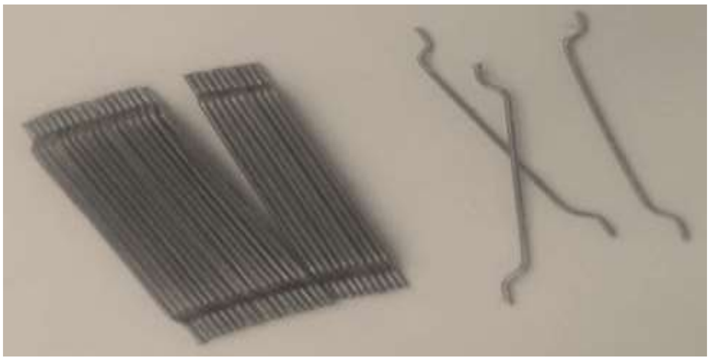


Figure 5. Double Hooked end Steel Fibers used.

Table 3. Properties of double Hooked end Steel Fibers used

Characteristics	
Tensile Strength (MPa)	> 1100
Density (kg/m^3)	7800
Fiber Length (L), (mm)	30
Diameter (d), (mm)	0.55
Aspect Ratio (L/d)	54.55

II.2. Mix proportions of HPFRFC

The adopted reference formulation in this study to determine the different constituents of reference mixture is that of base formulation for high performance concrete [34], with a fixed water-to-binder (W/B) ratio equal to 0.30 (Table 4). The dosages of superplasticizer was optimizing after to achieving an appropriate initial workability.

In the rest of this work, the formulation of the proposed HPFRFC mixtures was then developed based on the reference formulation. In order to assess the effect of the two factors to be controlled, namely the percentage of superplasticizer (SP) and the dosage of metallic fibers (MF), The cement and water quantities were kept constant in all the studied mixes., and the dosage of superplasticizers and metallic fiber were changed compared to the levels provided by the CCD method. In this study, the superplasticizer is in the range of 1.8–2.4 % of the total weight of the powder material and metallic fibers is in the range of 23 kg/m^3 to 37 kg/m^3 of concrete are selected and varied, as presented in Table 5.

Response Surface Methodology (RSM), which presents a variety of response surface designs [35], was used in this study for the purpose of analyzing and optimizing the responses that are influenced by the variables under consideration. The Central Composite Design (CCD) was also used in this study to determine the number of the studied experiments. The CCD is an augmented version of the factorial plane, with central and axial points [36].

Furthermore, the Design-Expert version-7 software was used in the experimental design, statistical analysis, mathematical modeling and optimization of process variables for the studied High-performance fiber-reinforced fluid concrete (HPFRFC). Firstly, the critical variables are determined in this method. For modeling and analyzing these impacts variables, mathematical and statistical techniques are used afterwards [37].

The relationship and interaction between the input factors (percentage of superplasticizer and metallic fiber content), and responses for the properties of concrete in the fresh and hardened state were obtained using the analysis of variance (ANOVA) [38, 39]. Figure 6 shows the classic CCD process for the variables.

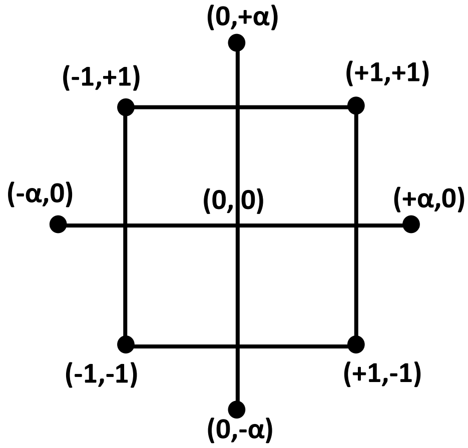


Figure 6. Central Composite Design (CCD) for two variables [40].

Table 4. Mix proportions of reference HPFC mixture

Mixture	W/B Ratio	MF (Kg/m^3)	SP (%)	Constituent (Kg/m^3)					
				Water	Cement	SF	Sand	G (3/8)	G (8/16)
HPFC	0.30	-	1.50	145	439.39	43.94	816.02	347.97	646.17

$$y=\beta_0+\sum_{j=1}^{k}\beta_j X_j+\sum_{i\pi j}\sum_{i\pi j}\beta_{ji}X_iX_j+\sum_{j=1}^{k}\beta_{jj}X_j^2+\varepsilon. \quad (1)$$

The factorial plane points (±) are represented by the four corner points. These points define the boundaries of the operability zone inside which the optimum is supposed to exist. The previous points are generally outside the boundary line. Regarding, the axial design points (±α), they are denoted by the four central points. The axial points define the operability zone, and the zone of interest is inside the operability zone [40].

It is worth pointing out that the response models used in this study were chosen in accordance with the fresh and hardened properties of the HPFRFC, with variable factors such as the superplasticizer percentage and metal fiber dosage. By choosing the most appropriate model, and determining the best fitting conditions, the response surface model (RSM) can then easily be described. Moreover, the quadratic equations were selected for the model that is also described by Equation (1).

Where y represents the response function;

$$\sum_{j=1}^{k}\beta_{jj}X_j^2+\varepsilon$$

is the quadratic effect of one single variable; $\Sigma_{i<j}$ $\Sigma_{i<j}$ $\beta_{ji}.x_i.x_j$ refers to the interaction effect between two variables; β_0, β_i, β_{ii}, and β_{ij} are the regression coefficients; X_i and X_j are the factors under study; k represents the number of factors; and finally ε is the observed noise error.

In this work, 13 experimental trials were carried out, for the two variables SP and FM, using the central composite design (CCD) method. It should also be noted that the percentage of SP takes as extreme levels 1.80% and 2.40%, with a dosage of metallic fibers (FM) ranging from 23 kg/m^3 to 37 kg/m^3, and a fixed amount of fumed silica (SF) that is equal to 10% of cement weight. However, the percentages of the other components in the concrete mixture remain unchanged. Moreover, the binder dosage is considered an invariable factor; it was set at 483.33 kg/m^3 of concrete (Table 5).

Table 5. Mix proportions of HPFRFC mixtures

Mixture No	SP (%)	MF (Kg/m^3)	Water (L/m^3)	Cement (Kg/m^3)	SF (Kg/m^3)	Ratio W/B	Sand (Kg/m^3)	G(3/8) (Kg/m^3)	G(8/16) (Kg/m^3)
HPFRFC1	1.90 (-1)	25 (-1)	145	439.39	43.94	0.30	761,33	367.5	682.5
HPFRFC2	1.90 (-1)	35 (+1)	145	439.39	43.94	0.30	761,33	367.5	682.5
HPFRFC3	2.30 (+1)	25 (-1)	145	439.39	43.94	0.30	757,47	367.5	682.5
HPFRFC4	2.30 (+1)	35 (+1)	145	439.39	43.94	0.30	757,47	367.5	682.5
HPFRFC5	1.80 (-1.414)	30 (0)	145	439.39	43.94	0.30	762,29	367.5	682.5
HPFRFC6	2.40 (+1.414)	30 (0)	145	439.39	43.94	0.30	756,79	367.5	682.5
HPFRFC7	2.10 (0)	23 (-1.414)	145	439.39	43.94	0.30	759,40	367.5	682.5
HPFRFC8	2.10 (0)	37 (+1.414)	145	439.39	43.94	0.30	759,40	367.5	682.5
HPFRFC9	2.10 (0)	30 (0)	145	439.39	43.94	0.30	759,40	367.5	682.5
HPFRFC10	2.10 (0)	30 (0)	145	439.39	43.94	0.30	759,40	367.5	682.5
HPFRFC11	2.10 (0)	30 (0)	145	439.39	43.94	0.30	759,40	367.5	682.5
HPFRFC12	2.10 (0)	30 (0)	145	439.39	43.94	0.30	759,40	367.5	682.5
HPFRFC13	2.10 (0)	30 (0)	145	439.39	43.94	0.30	759,40	367.5	682.5

II.3. Manufacturing and tests

To obtain the fluidity and mobility of mixture in an unconfined environment, after the mixing process was completed, the slump flow of the mixtures was measured immediately on the fresh concretes, by using the concrete slump cone test (Fig. 7), according to the requirements and recommendations of ASTM C143 standard for slump test [41], These two quantities can be determined by measuring the Slump or the spread. The slump flow shows the spread of fluid concrete in the horizontal direction without the presence of any obstacles and the final diameter was measured in the slump flow test (D1+D2)/2.

Figure 7. Slump flow test for fresh HPFRFC mixes.

After testing HPFRFC mixes in fresh state, a number of specimens were then cast in lubricated molds without any vibration and compaction in order to determine the mechanical properties of different mixtures at hardened state.

To determine the compressive strength of mixtures (Cs) at 28 days, three cube samples with dimensions of 10×10×10 cm^3 were used for each mixture according to BS EN 12390-3 standard [42]. The flexural strength (Fs) at 28 days was assessed on three prismatic specimens of dimensions 7x7x28 cm^3, according to BS EN 12390-5 standard [43] (Fig. 8 and 9).

After filling all the molds, the studied samples were kept at environmental laboratory with a temperature of approximately 21°C, and after 24 h, were taken out of the molds and placed in water saturated lime at a temperature of 21° C until the age of testing.

Figure 8. Compressive strength test for hardened HPFRFC mixes.

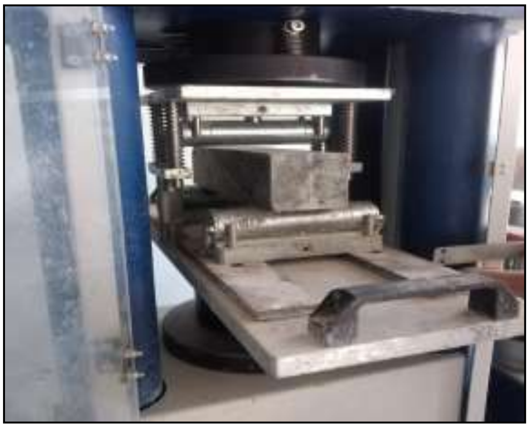


Figure 9. Flexural strength test for hardened HPFRFC mixes.

III. Results and discussion

III.1. Experimental results

The rheological (slump flow and spreading) assessing by the slump flow test, and mechanical (28 days compressive and flexural strengths) results of the control high-performance fluid concrete (HPFC) as well as those of the high-performance fiber-reinforced fluid concrete (HPFRFC) are summarized in table 6. From this table it is clearly shown that the spreading values in the studied mixtures are in the range of 40–58 cm. On the other hand, the 28-day compressive and flexural strength values are in the range of 77 – 97 and 4.50 – 7.53 MPa, respectively.

Table 6. Rheological and 28 day's mechanical test results of HPFRFC.

Mixtures	Slump flow (cm)	Sp reading (cm)	Cs (MPa)	Fs (MPa)
HPFC	15	-	82	4.50
HPFRFC1	-	49	93	6.54
HPFRFC2	-	40	77	7.21
HPFRFC3	-	51	89	7.30
HPFRFC4	-	44	85	7.53
HPFRFC5	-	46	84	6.80
HPFRFC6	-	58	92	7.45
HPFRFC7	-	55	97	7.05
HPFRFC8	-	43	81	7.37
HPFRFC9	-	50	87	7.00
HPFRFC10	-	50	87	7.00
HPFRFC11	-	50	87	7.00
HPFRFC12	-	50	87	7.00
HPFRFC13	-	50	87	7.00

III.2. Mathematical models

The affectation of the independent studied variables on the response values for each experimental test is provided by the ANOVA analysis and its statistical parameters (CCD method) are shown in Tables 7 and 8, respectively. The effect level of the variables on the experimental results is determined by the F-value and p-value. The effect of the variables on the response is considered higher with higher F-value and lower p-value.

The p-value indicates the significance of the tested defined parameters in the results values. If a variable's p-value is<5 %, it is considered as a significant variable and has a significant effect on the test response. However, the variables with p-value greater than 0.05 do not have significant effect on the response and are neglected to improve the accuracy of the proposed model. In this study, the experimental results modeling and ANOVA analysis are performed with an error level of 4 %.

Table 7. Variance analysis (ANOVA) for the regression models

Response	Source	Sum of squares	Degrees of freedom	Mean square	F-value	Probability error	
Spreading	Model	244.34	5	48.87	6.15	0.0169	Significant
	Residual	55.66	7	7.95			
	Lack of Fit	55.66	3	18.55			
	Pure Error	0.00	4	0.00			
	Total	300.00	12				
Cs	Model	293.64	5	58.73	20.50	0.0005	Significant
	Residual	20.05	7	2.86			
	Lack of Fit	20.05	3	6.68			
	Pure Error	0.00	4	0.00			
	Total	313.69	12				
Fs	Model	0.86	5	0.17	41.09	< 0.0001	Significant
	Residual	0.03	7	4.18E-003			
	Lack of Fit	0.03	3	9.76E-003			
	Pure Error	0.00	4	0.00			
	Total	0.89	12				

Table 8. Statistical parameters from the analysis of variance for the regression models

Response	R^2	Adjusted R^2	Coefficient of variation. %	Standard of deviation	Adequate Precision	PRESS
Spreading	0.81	0.68	6.00	2.82	7.30	395.82
Cs	0.94	0.89	1.94	1.69	15.90	142.57
Fs	0.97	0.94	0.91	0.07	19.12	0.21

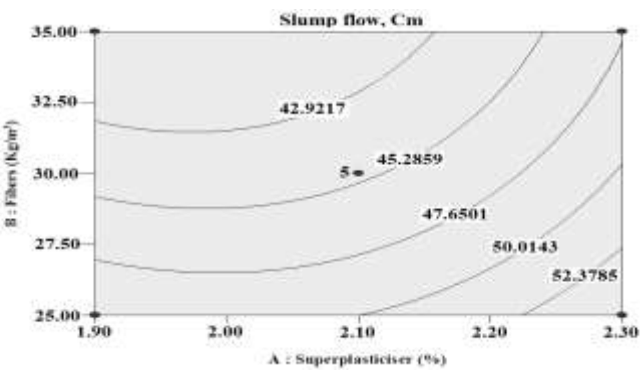
PRESS: predicted residual error sum of squares.

The determination coefficient (R^2) for all tests, confirms the correlation between the experimental data and the predicted responses. Where, the closer the value of this coefficient to the number one, the more accurate the proposed model [44]. In this study, the correlation coefficients, of all test results, were relatively high (Table 8), which testifies to a good correlation between the obtained experimental results and the values provided by the model under consideration. Note also that all these coefficients were obtained by a regression method that is based on the least squares optimization criteria.

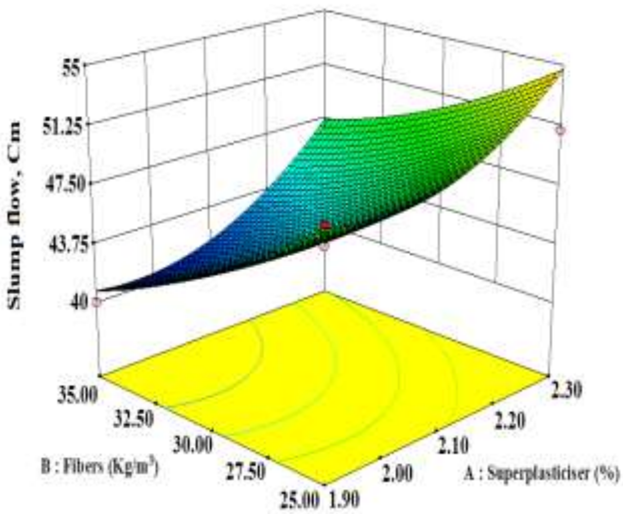
III.3. Analysis of modelling results

III.3.1. Spreading (cm)

Figures 10 (a) and (b) respectively illustrate the iso-response curves (2D and 3D) for the superplasticizer and fiber content on the spreading value of HPFRFC mixtures.



a) 2D Contour diagram.



b) 3D surface diagram.

Figure 10. RSM Analysis diagrams for representing slump flow (spreading).

It is clearly shown from Figure 7 that the spreading increases as the superplasticizer (SP) dosage goes up, and decreases with the increase in the metallic fibers (MF) content ; this was done while keeping the values of the water-to-binder (W/B) ratio constant in the domain of the studied plane.

The improvement in the spreading is certainly due to the presence of the super-plasticizer which plays the role of plasticizer; it can also be attributed to the compatibility of the polymer contained in the superplasticizer with the cement used. This would then have a positive effect on the rheology of concrete. In this study, the spread may vary between 40 and 58 cm.

On the other hand, it was revealed that the incorporation of metallic fibers leads to a reduction in the workability of concrete. This workability decline was found to be proportional to the amount of fibers added. Moreover, it was also found that the inclusion of metallic fibers in concrete causes blocking problems. This phenomenon is probably due to the shape and rigid nature of metal fibers, which is not the case for synthetic fibers which are more flexible, as previously mentioned by Grunewald [45].
As reported by Güneyisi and Grabois et al. [46, 47], increasing fibres in percentages have a significant negative effect on the fresh properties of concrete as fibres act as a threedimensional web negating flow. And therefore, act as a barrier to flow thus dosage must be optimized so as to provide optimal performance for both fresh and mechanical properties. These results are in accordance with the results obtained by other researchers [28,46,48-50], confirming that increasing metallic fiber content negatively effects the concrete workability. Aslani and Kelin [51] observed the same results and confirmed that increasing superplasticizer content can help overcome the flowability reduce.

It should be pointed out that the studied HPFRFC mixes are characterized by a spread varying between 40 and 58 cm, indicating that this type of concrete has a consistency that varies between that of concrete S3 which is quite compact and elastic, and that of concrete S5 which is very fluid which can make it more manageable and easier to place [52]. In addition, these concretes are characterized for their very high deformability; they are also known for their ease of implementation under the effect of their own weight, without vibrations, even in the case of dense reinforcement, as previously reported by the French Association of Civil Engineering (AFGC, 2000) and other authors [52, 53].As presented in Table 8, the modeling used made it possible to write a model that was used to predict the responses in the entire field of study and presented by the quadratic equation (Eq. 2). This equation has been derived to predict the amount of spreading as function to the superplasticizer and metallic fiber content. The value of R^2 and adjusted R^2 coefficients for this experiment are 81% and 68%, respectively.

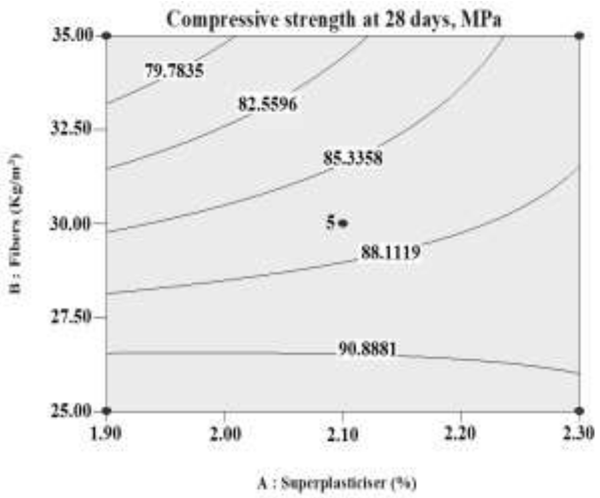
$$Spreading,\ Cm = +45.00 + 2.87A - 4.12B + 0.50AB + 2.37A^2 + 0.88B^2. \quad (2)$$

$$Compressive\ strength,\ MPa = +87.00 + 1.91A - 5.33B + 3.00AB + 0.12A^2 + 0.38B^2. \quad (3)$$

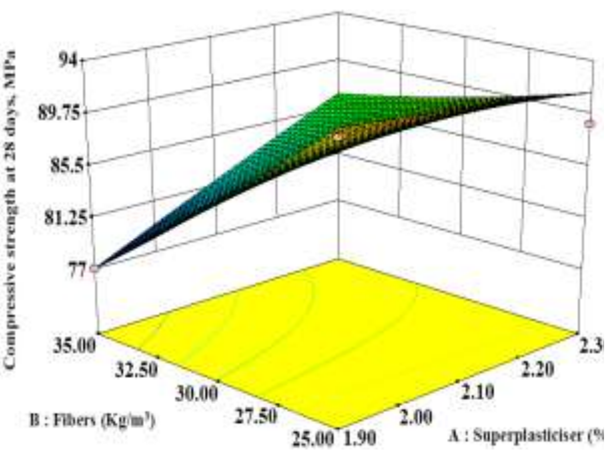
III.3.2. Compressive strength

Figures 11 (a) and (b) present respectively the iso-response curves (2D and 3D) for the superplasticizer and fiber content effect on the compressive strength value of HPFRFC mixtures.

As presented in Table 8, the modeling used made it possible to write a model that was used to predict the responses in the entire field of study and presented by the quadratic equation (Eq. 3). This equation has been derived to predict the amount of compressive strength as function to the superplasticizer and metallic fiber content. The value of R^2 and adjusted R^2 coefficients for this experiment are 94% and 89%, respectively. According to Cheng Yuan et al. [54], the compressive strength of metal fiber-reinforced concretes is always higher than that of non-fiber reinforced concrete, as is clearly confirmed by the results obtained and presented in Table 6. In addition, it was noticed that the mechanical behavior of high-performance fiber-reinforced fluid concretes (HPFRFC) evolved with the percentage of superplasticizer (SP) and the proportion of metallic fibers (MF) used, except for the HPFRFC2 and HPFRFC8 mixes where a slight decrease in the compressive strength values was noticed in comparison with the reference mixture (HPFC); this decrease was respectively about 7% and 1% for these two mixes.



a) 2D Contour diagram



b) 3D surface diagram.

Figure 11. RSM Analysis diagrams for representing compressive strength.

Regarding the other mixtures, their compressive strength increased by around 18%, which proved that there was good compatibility between the super-plasticizer (Medaflow Re 25), the type of cement, the slenderness of the metallic fibers ($\phi < 0.02$), and the quantity incorporated. It is important to emphasize that short fibers, when used in low dosage, do not pose the problem of entanglement and the formation of pilot “sea urchins”, which is not the case when fine fibers are used even in large quantities. Therefore, the presence of fibers in the matrix slightly increases the porosity, but does not cause any drop in the compressive strength.

This means that the incorporation of metal fibers, with a good orientation and a homogeneous distribution within the matrix, significantly improves the ductility of the material and also enhances the cracking threshold (Figure 12.b). These findings are in good agreement with those reported by other authors [20, 28, 55].

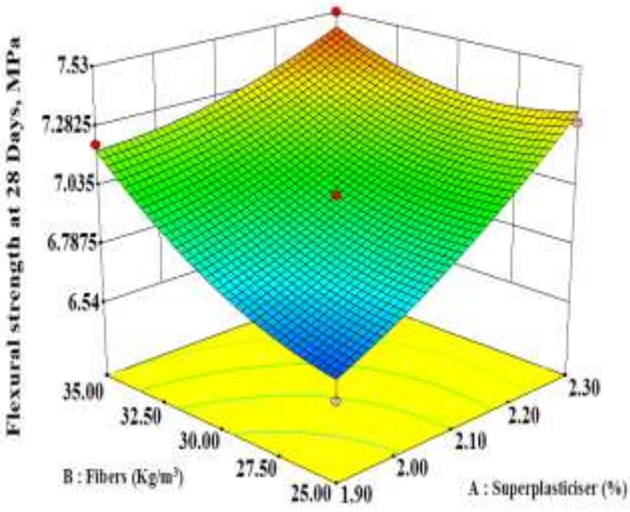
Through the visual examination of crashed specimens, it can be seen also that most of the cubic specimens showed cracking along a line at roughly 45° to the axis, near the ends (Figure 12.a).

a) HPFC.

b) HPFRFC.

Figure 12. Failure modes of cube specimens at 28 days compressive test.

Therefore, it can be said that incorporating fibers in the cimentitious matrix slows down the development of microcracks, which induces a significant increase in the compressive strength; this is in agreement with the findings of other researchers [28, 56].



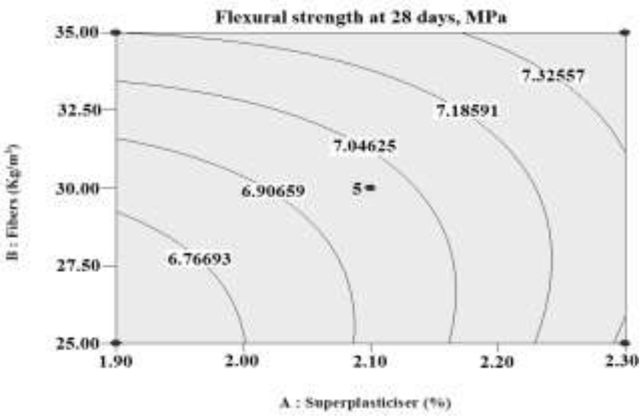
b) 3D surface diagram

Figure 13. RSM Analysis diagrams for representing Flexural strength.

$$Flexural\ strength,\ MPa = +7.00 + 0.25A + 0.17B - 0.11AB + 0.057A^2 + 0.099B^2. \quad (4)$$

III.3.3. Flexural strength

Figures 13 (a) and (b) present respectively the iso-response curves (2D and 3D) for the superplasticizer and fiber content effect on the flexural strength value of HPFRFC mixtures.



a) 2D Contour diagram

As presented in Table 8, the modeling used made it possible to write a model that was used to predict the responses in the entire field of study and presented by the quadratic equation (Eq. 4). This equation has been derived to predict the amount of flexural strength as function to the superplasticizer and metallic fiber content. The value of R^2 and adjusted R^2 coefficients for this experiment are 97% and 94%, respectively.

The results illustrated in figures 13.a and 13.b suggest that the flexural strength is quite high for all the concrete mixtures under study, and are in good agreement with those found in the literature [55-57]. Indeed, a clear flexural strength increase was observed for all the mixtures under study.

It can be clearly seen from figure 10, that the flexural strength increases as the superplasticizer (SP) amounts and metal fiber (MF) dosages went up. This increase, which is between 45 and 67%, can certainly be attributed to the presence of metallic fibers in the matrix which play a triple role. First of all, they allow the mobilization of a greater part of the elastic energy within the material; then, they increase the energy consumed in the vicinity of cracks (high tenacity); finally, they serve as stitching elements on the lips of the cracks. Note also that after the formation of the cracks, the lips remain connected by the fibers (dowel action).

During the flexural tests (figure 14), the high performance fluid concrete (HPFC) cured specimens showed a brittle type of failure (sudden failure); this was certainly due to its low tensile strength. However, for all the composite concretes, including different fiber contents, a ductile fracture was observed with a densification of microcracks. This may probably be attributed to the addition of metal fibers which contribute to stop the rapid propagation of cracks. The same results were found by Majain et al. [28, 57-61].

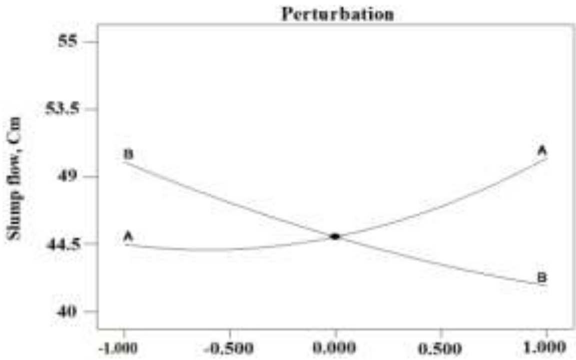
a) HPFC.

b) HPFRFC.

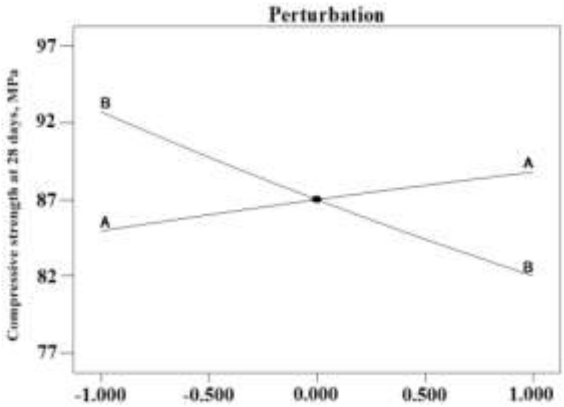
Figure 14. Typical fracture patterns of specimen in flexural strength.

III.4. Perturbation graphs

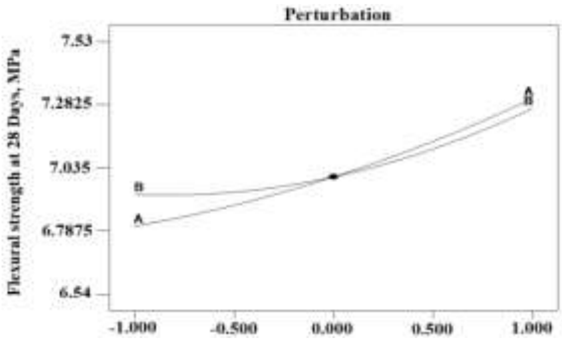
The perturbation diagrams illustrated in figures 15.a, 15.b and 15.c indicate that B has a negative effect, which means that when the proportion of metal fibers increases, the flow and compressive strength decrease, as was previously mentioned when the effect of fibers on these parameters was studied. On the other hand the effect of A and B for the case of bending (flexural) are positive in parallel.



a) Slump flow (spreading).



b) Compressive strength.



c) Flexural strength.

Figure 15. Perturbation plot.

IV. Conclusions

This study was conducted with the aim of answering some questions relating to the evolution of the rheological and mechanical properties of high performance fiber-reinforced fluid concrete. The main conclusions drawn from this work are:

- The workability of the studied HPFRFC mixtures is with a spread varying between 40 and 58 cm. Indicating that this type of concrete has a consistency that varies between that of S3 concrete and that of S5 concrete which can make the HPFRFC more manageable and easier to place.
- The incorporation of metallic fibers leads to reduce the workability of concrete and the decline in this workability was found to be proportional to the amount of fibers added.
- The amounts of superplasticizer (SP) and metallic fibers (FM) used have a significant effect on the mechanical properties of HPFRFC. The flexural and compressive strengths of HPFRFC are significantly greater than those of control high performance fluid concrete (HPFC).
- An improvement in the failure mode was observed, with a certain ductility conferred on the composite concretes during the mechanical tests. Indicating a replacement of the brittle failure by the ductile failure.
- Based on the data obtained from the response surface methods, a high correlation between the flexural strength and the amounts of components incorporated in concrete could be developed using the generalization capabilities. Some equations were developed and the results found were validated by means of ANOVA; the significance level of the model developed was greater than 95%.
- According to the models established, it was shown that our experimental results were well correlated with those obtained with the theoretical models; this was true for all the selected responses.
- The study proved that it is possible to suitably produce a dense and workable HPFRFC that are much thinner, slenderer, lighter, more durable and low cost-effective for practical application. It was revealed that the considerable reduction in the thickness of the structures allows for a significant economic gain.

Références

[1] Neville, A-M. Properties of Concrete, Eyrolles Editions, 2000, Paris, France.
[2] Shi C, Wu Z, Xiao J, Wang D, Huang Z, Fang Z. A review on ultra-high performance concrete: part I. Raw materials and mixture design. Construction and Building Materials,. 2015 ; 101(1) :741-751.
[3] Guendouz, M., Boukhelkhal, Dj. Properties of flowable sand concrete containing ceramic wastes, Journal of Adhesion Science and Technology, 2019, 33(24), 2661-2683.
[4] Hajime Okamura, Self-Compacting High-Performance Concrete, Concrete International, Volume: 19, Issue: 7, 1997.pp. 50-54.
[5] Joumana Yammine, Rhéologie des bétons fluides à hautes performances : relations entre formulations, propriétés rhéologiques, physico-chimie et propriétés mécaniques, Thesis, University of Higher Normal School in Kashan, 2007.
[6] Guendouz, M.; Boukhelkhal, Dj.; Bourdot, A. Recycling of floor tile waste as fine aggregate in flowable sand concrete. Advances in Green Energies and Materials Technology. Springer Proceedings in Energy. Springer, Singapore, 2021.
[7] Ozawa K., Kunishima M., Maekawa K., Okamura H., Challenge for high performance concrete, Proceedings conference on High performance concrete, University of Tokyo, September, 1991, pp. 5-17.
[8] Khalifa S. Al-Jabri, Makoto Hisada, Salem K. Al-Oraimi, Abdullah H. Al-Saidy, Copper

slag as sand replacement for high performance concrete, Cement & Concrete Composites 31 (2009) 483–488.

[9] Xinpeng Wang, Rui Yu, Qiulei Song, Zhonghe Shui, Zhen Liu, Shuo Wu, Dongshuai Hou, Optimized design of ultra-high performance concrete (UHPC) with a high wet packing density, Cement and Concrete Research, Volume 126, December 2019, 105921.

[10] Boukhelkhal, Dj.; Boukendakdji, O.; Kenai, S.; Kadri, E.H. Combined effect of mineral admixture and curing temperature on mechanical behavior and porosity of SCC. Adv. Conc. Const. 6 (1) (2018) 69-85.

[11] A.Rasheed , M. Usman H. Farooq, A Hanif, Effect of Super-plasticizer Dosages on Fresh State Properties and Early-Age Strength of Concrete, Materials Science and Engineering 431 (2018) 062010.

[12] Muhsen Salem, Salahaldein Alsadey, Megat Johari, Effect of Superplasticizer Dosage on Workability and Strength Characteristics of Concrete, Journal of Mechanical and Civil Engineering (IOSR-JMCE), (Jul. - Aug. 2016), PP 153-158.

[13] Piotr Smarzewski, Influence of basalt-polypropylene fibres on fracture properties of high performance concrete, Composite Structures, Volume 209, 1 February 2019, Pages 23-33.

[14] Forster SW. High-performance concrete – stretching the paradigm. Concr Int Oct 1994;16(10):33–4.

[15] Zhou, F.P., Barr, B.I.G., Lydon, F.D., 1995. Fracture properties of high-strength concrete with varying silica fume content and aggregates. Cement and Concrete Research 25, 543–552.

[16] Tasdemir, C., Tasdemir, M.A., Lydon, F.D., Ban, B.I.G., 1996. Effects of silica fume and aggregate size on the brittleness of concrete. Cement and Concrete Research 26, 63–68.

[17] Nasir Kabir, Sani Aliyu, Mohammad Abdu Nasara, Adamu Umar Chinade, Aminu Shehu, Characteristics of Different Type of Coarse Aggregate on Properties of High Performance Concrete, Sustainable Structure and Materials, Vol. 2, No .1, (2019) 88-96.

[18] Köksal, F., Altun, F., Yiğit, Î., Şahin, Y., Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes. Construction and Building Materials,.2008, 22, 1874–1880.

[19] Smarzewski, P., Influence of basalt-polypropylene fibers on fracture properties of high performance concrete. Composite Structures, 2019, 209, 23– 33.

[20] Osama Zaid, Faisal M. Mukhtar, Rebeca M-García, Mohammad Galal El Sherbiny and Abdeliazim M. Mohamed, Characteristics of High-Performance Steel Fiber Reinforced Recycled Aggregate Concrete Utilizing Mineral Filler, Case Studies in Construction Materials,2021, 16, e00939.

[21] M. Khashaa Mohammed, A. Ismail Al-Hadithi, M. Mohammed, Production and optimization of eco-efficient self-compacting concrete SCC with limestone and PET, Construction and Building Materials,.2019, 197, 734–746.

[22] M. Aziminezhad, M. Mahdikhani, M, Memarpour, RSM-based modeling and optimization of self-consolidating mortar to predict acceptable ranges of rheological properties, Construction and Building Materials,.2018, 189, 1200–1213.

[23] N. Sultana, S. Zakir Hossein, M. Shah Alam, M. Hashish, M., Islam, An experimental investigation and modeling approach of response surface methodology coupled with crow search algorithm for optimizing the properties of jute fiber reinforced concrete, Construction and Building Materials,.2020, 243, 118216.

[24] I. Ferdosian, A. Camoes, Eco-efficient ultra-high performance concrete development by means of response surface methodology, Cem. Concr. Compos. 2017, 84, 146–156.

[25] Megan Weyers, Optimised mix composition and structural behaviour of ultra-high-performance fibre reinforced concrete, master of engineering (structural engineering), university of pretoria, Afrique du Sud, 2020.

[26] S. Alsanusi, L. Bentaher, Prediction of Compressive Strength of Concrete from Early Age Test Result Using Design of Experiments (RSM), Int. J. Civil, Environ., Struct., Constr. Archit. Eng., 9 (12) (2015), p. 2015.

[27] T.F. Awolusia, O.L. Okea , O.O. Akinkurolerea , A.O. Sojobib, Application of response surface methodology: Predicting and optimizing the properties of concrete containing steel fibre extracted from waste tires with limestone powder as filler, Case Studies in Construction Materials Volume 10, June 2019, e00212.

[28] H. Basser, T. M. Shaghaghi, H. Afshin, R. S. Ahari, S. S. Mirrezaei, An experimental investigation and response surface methodology-based modeling for predicting and optimizing the rheological and mechanical properties of self-compacting concrete containing steel fiber and PET, Construction and Building Materials,. 315 (2022) 125370.

[29] NA 442. Algerian Standards, hydraulic binders – common Cements, Composition, Specification, IANOR, Algiers; 2003 [in French].

[30] ASTM C1240: Silica Fume Used in Cementitious Mixtures, ASTM, West Conshohocken, Pennsylvania, 2015.

[31] ASTM C 128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, ASTM, West Conshohocken, PA, 2015.

[32] ASTM C136: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM, West Conshohocken, PA, 2014.

[33] ASTM C127: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate, ASTM, West Conshohocken, PA, 2015.

[34] Aitcin CP. High performances concrete. Paris: Edition Eyrolles; 2001.

[35] Deniz Bas, Ismail H Boyaci, Modelling and optimization. I. Usability of response surface methodology, Journal of Food Engineering., 78 (2007), 836–845.

[**36**] Montgomery, D.C.: Design and Analysis of Experiments, 5th edn. Wiley, New York (2001).

[**37**] R.C. Soares, A. Mohamed, W.S. Venturini, M. Lemaire, Reliability analysis of non-linear reinforced concrete frames using the response surface method, Reliab. Eng. Syst. Saf. 75 (1) (2002) 1–16.

[38] O. Rezaifar, M. Hasanzadeh, M. Gholhaki, Concrete made with hybrid blends of crumb rubber and metakaolin: optimization using response surface method, Construction and Building Materials,.123 (2016) 59–68.

[39] V.C. Khed et al., Experimental investigation on pull-out strength of hybrid reinforcement of fibre in rubberized cementitious composites, Int. J. Civil Eng. Technol. (IJCIET) 9 (7) (2018) 1612–1622.

[40] Megan Weyers, Elsabe P. Kearsley. Effect of High Plasticiser Dosage on Ultra High-Performance Fibre Reinforced Concrete (UHPFRC), International Union of Laboratories and Experts in Construction Materials, Systems and Structures,2020.

[41] ASTM C143. Standard test method for slump of hydraulic-cement concrete; 2012.

[42] BS EN 12390-3. Testing harden concrete. Compressive strength of test specimens. France ; 2012 April.

[43] BS EN 12390-5, Béton-Essai de flexion, Éditions AFNOR, Paris 1981.

[44] C. Klockner, A comprehensive model of the psychology of environmental behavior—A meta-analysis, Global Environ. Change 23 (2013) 1028–1038.

[45] Grunewald S., Performance-based design of Self-Compacting Fiber Reinforced Concrete, Ph D thesis, 2004, 165 p.

[46] E. Güneyisi, Fresh properties of self-compacting rubberized concrete incorporated with fly ash. Mater. Struct. 2010, 43 (8), 1037e1048.

[47] T.M. Grabois, G.C. Cordeiro, R.D. Toledo Filho, R.D., Fresh and hardened state properties of self-compacting lightweight concrete reinforced with steel fibers. Construction and Building Materials,. 2016, 104, 284e292.

[48] R. Deeb, A. Ghanbari, B.L. Karihaloo, Development of self-compacting high and ultra-high performance concretes with and without steel fibres; Cement & Concrete Composites 34 (2012) 185–190.

[49] P. Jeganmurugan, A.S. Rameswari, N. Anuja, Experimental behaviour of fibre reinforced Self compacting concreteunder cyclic loading, Materials Today: Proceedings 52 (2022) 1488–1493.

[50] K. . Akça , M. Ipek, Effect of different fiber combinations and optimisation of an ultra-high performance concrete (UHPC) mix applicable in structural elements, Construction and Building Materials,. 315 (2022) 125777.

[51] F. Aslani, J. Kelin, Assessment and development of high-performance fibre-reinforced lightweight self-compacting concrete including recycled crumb rubber aggregates exposed to elevated temperatures, Journal of Cleaner Production 200 (2018) 1009e1025.

[52] Association Française de Génie Civil Bétons autoplaçants – "Recommandations provisoires " Annales du bâtiment et des travaux publics, juin 2000.

[53] Guendouz, M.; Boukhelkhal, Dj.; Bourdot, A.; Babachikh, O.; Hamadouche, A. The effect of ceramic wastes on physical and mechanical properties of eco-friendly fowable sand concrete Ceramic Materials. IntechOpen. 10, 2 (2020).

[54] Cheng Yuan, WensuChen, Thong M.Pham, HongHao, Bond behavior between basalt fibres reinforced polymer sheets and steel fibres reinforced concrete, Engineering Structures, Volume 176, 1 December 2018, Pages 812-824.

[55] E. Rahmani, M. Dehestani, M.H.A. Beygi, H. Allahyari, I.M. Nikbin, On the mechanical properties of concrete containing waste PET particles, Construction and Building Materials,.47 (2013) 1302–1308.

[56] Nelly Majain, Ahmad Baharuddin Abd. Rahman, Azlan Adnan, Roslli Noor Mohamed, Bond behaviour of deformed steel bars in steel fibre high-strength self-compacting concrete, Construction and Building Materials,. 318 (2022) 125906

[57] Ingrid Lande Larsen, Rein Terje Thorstensen, The influence of steel fibres on compressive and tensile strength of ultra-high performance concrete, Construction and Building Materials,. 256 (2020) 119459.

[58] Ibrahim I.S, Che Bakar,M.B, Effects on mechanical properties of industrialised steel fibres addition to normal weight concrete, science direct, procedia engineering 14 (2011) 2616-2626.

[59] Wasim Abbass M. Iqbal Khan. Shehab Mourad. Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete. Construction and Building Materials,.168 (2018) 556-569.

[60] K. A. Ostrowski, K. Furtak, The influence of concrete surface preparation on the effectiveness of reinforcement using carbon fibre-reinforced polymer in high-performance, self-compacting, fibre-reinforced concrete, Composite Structures 276 (2021) 114522.

[61] D. Zhang, H. Tu, Y. Li, Y. Weng, Effect of fiber content and fiber length on the dynamic compressive properties of strain-hardening ultra-high performance concrete, Construction and Building Materials,. 328 (2022) 127024.