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Research Article

Characterizations of high-performance concrete containing mineral additions

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Abstract – This study aims to experimentally investigate the slump, compressive strengths (Cs) at 7 and 28-day of fifteen HPC combinations made from already-existing local materials in Algeria. After that, establish statistical models based on the mix design modeling technique to examine the impact of employing dune sand powder (DSP), as a supplementary cementitious material, both in binary and ternary combinations with cement (PC) and ground blast-furnace slag (GBFS) on the HPCs characteristics. A four-level, three-parameter mixture design was implemented to develop models for the statistical variance of the recorded experimental data and the JMP7 statistical program was employed to perform this analysis. For all responses, models exhibit strong correlation coefficients ($R^2 \geq 0.83$). Replacing cement with GBFS increases the slump. However, slump only remains good when the combinations have a low proportion of DSP. At 7-day, the improvement in Cs can be attributed to the increasing proportion of DSP. In contrast, results suggest the increasing percentage of GBFS in all systems causes a slight decrease of Cs. At 28-day, it is evident that the use of GBFS alone resulted in a slight decrease in Cs, but when combined with PC, GBFS increased Cs. In contrast, Cs is better when a low percentage of DSP is used. Optimal composition (HPC14) with 5%GBFS offers the best compromise between the three studied characteristics.

Keywords – Dune Sand Powder; Ground Blast-Furnace Slag; HPC; Workability; Compressive Strengths

I. INTRODUCTION

To limit the increasing environmental degradation, the researchers considered that the use of supplementary cementitious materials (SCMs) would help reduce this environmental impact and negative emissions of carbon dioxide during the cement manufacturing process; it would also reduce the cost of concrete and further improve their characteristics. Cement can be considered as the most important component in the manufacture of high performance concrete (HPC) [1]. It is important to note that the strength of compressive (Cs) at 28-day of HPC must be above than 50 MPa and the water/binder ratio less than 0.4 [2]. The use of dune sand powder (DSP), as SCM, has recently received increasing attention [3-6], in order to valorize the abundant sand of dunes of Algerian desert. It is used because of its high silica content. Due to its crystalline nature state, the DSP shows a partial pozzolanic reactivity [3-5]. Allout et al. [6] reported that, when the amount of DSP presents in the mix remains low (≤ 15%), the workability improves and the concrete becomes more fluid.This result is also confirmed by results of other studies [4,7]. On the other hand, the ground blast-furnace slag (GBFS) is an addition with several qualities (chemical composition close to that of Portland cement (PC), stability of characteristics for the same source, latent reactivity but activated in the PC presence), which makes it a very interesting addition for the concrete industry. In GBFS cements, clinker is the main activator of GBFS. Wang et al. [8] pointed out that GBFS can increase the compressive strength of HPC and plays an effective role on the workability. Only one research study has been conducted to experimentally evaluate the combined effect of DSP and GBFS [9]. Their results showed that adding DSP and GBFS to cement contributes positively to improving the mechanical strengths and durability of ordinary concrete, when DSP and GBFS were introduced in the proportions of 5% and 15% respectively. Moreover, statistical modeling method of mixture design allows determining the relative importance of the initial parameters of mixture and the effects of their interaction with each other on the studied characteristics [10,11]. This paper examines the effect of using DSP as SCM, both in binary and ternary systems with PC and GBFS on the slump (workability), compressive strengths (Cs_7, Cs_{28}) of HPCs using the method of mixture design modeling. This includes optimizing HPCs formulated with locally available resources.

II. MATERIALS AND METHODS

A. *Identification of materials used*

In this study, a white compound Portland cement (CEM II/A) class 52.5 MPa was employed. Two mineral additives were used. DSP from the region of Biskra and the GBFS from slag of El-hadjar factory in the Annaba region (Algeria). The chemical analysis of cement, DSP and GBFS are shown in Table 1. Table 2 contains the physical properties of sand (0/5 mm) from the region of Djelfa (Algeria). Its granulometric curve is illustrated by Fig. 1. Two gravels (3/8 mm; 8/12.5 mm) from Djelfa region were used. Their physical properties and granulometric curves are presented, respectively, in Table 2 and Fig. 2. A superplasticizer admixture of type “MEDAFLOW 30” was used. It is manufactured by Granitex in Algeria.

Table 1. Chemical composition of cement and mineral additions (%).

Elements	**PC**	**DSP**	**GBFS**
SiO_2	23.50	74.61	39.60
Al_2O_3	3.30	1.35	9.73
Fe_2O_3	0.22	0.86	3.56
CaO	63.70	17.30	41.20
MgO	0.70	0.29	3.38
SO_3	2.20	0.04	0.67
Na_2O	0.40	-	0.01
K_2O	0.50	0.47	0.50
Cl	-	0.005	0.01
LOI	4.70	5.04	1.30

Note: LOI: Loss on ignition

Table 2. Physical properties of sand and gravels.

Property	**S 0/5**	**G 3/8**	**G 8/12.5**
Specific density (kg/m^3)	2620	2660	2640
Coefficient of Los Angeles (%)	-	24.50	24.00
Fines < 80 µm (%)	0.65	-	-
Finesses modulus (FM)	2.79	-	-
Sand equivalent (%)	81.00	-	-

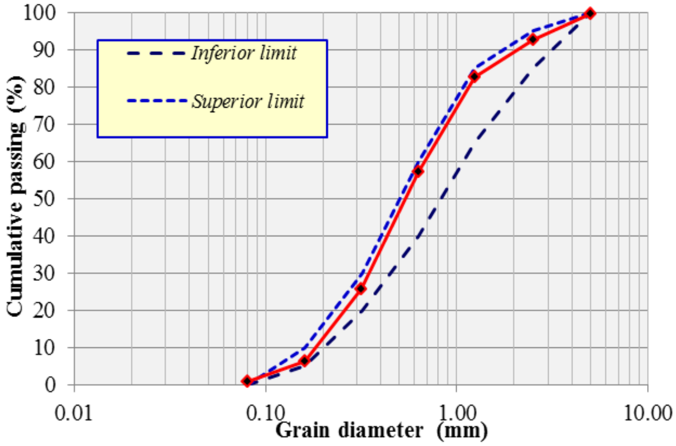

Fig. 1 Granulometric curve of sand.

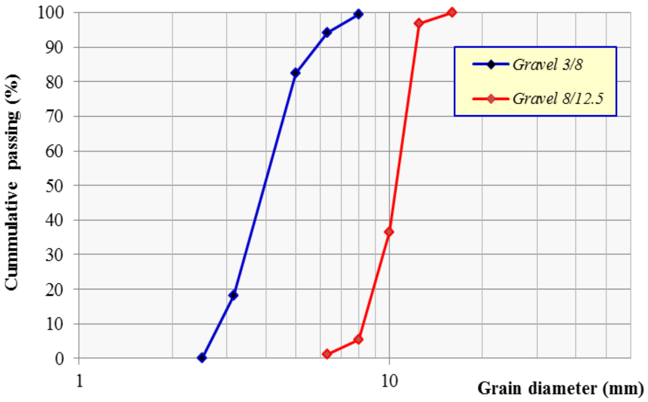

Fig. 2 Granulometric curves of the gravels.

B. *Mixture design method and proportions*

When examining products with multiple components, designs of mixture are used to better organize the tests that go along with scientific research [11]. It is an innovative method which enhances mixes with a very limited number of tests. The mixture parameters (PC, GBFS, and DSP) are the concentrations (x_i) of each component (i) influencing one or more "responses" characteristics (Y) (slump, compressive strengths (Cs_7, Cs_{28}) of HPC). So, it is interesting to employ this method when studying a function of type:

$$Y = f(x_i) \qquad (1)$$

The equation is given by adding the concentrations, when the total is equal to one:

$$\sum_{i=1}^{i=n} x_i = 1 \qquad (2)$$

A three-parameter mixture design (PC, GBFS and DSP) taken in mass proportions has been considered. The total of these ratios must always be 1. The experimental field represents one fifth of the cement amount, replacing 20% of the cement (90 kg). This experimental field was limited by limitations such as:

$$PC + GBFS + DSP = 1 \qquad (3)$$

A statistical model with four levels and three non-independent parameters (PC, GBFS, and DSP), a second-degree polynomial model was employed. The statistical model is presented in the following way:

$$\mathbf{Y} = a_1 \times PC + a_2 \times GBFS + a_3 \times DSP + a_{12} \times (PC.GBFS) + a_{13} \times (PC.DSP) + a_{23} \times (GBFS.DSP) \qquad (4)$$

With: response is (Y); coefficients of model are (a_1, a_2, a_3, a_{12}, a_{13}, a_{23}).

These coefficients show how each parameter and each interaction between parameters have an impact on the property "response". Table 3 displays the parameter percentages in the examined compositions, which are supplied by the software. The JMP7 statistical program is then used to analyze the results of the responses that were obtained.

Table 3. Parameter proportions in the studied compositions.

N°	**PC**	**GBFS**	**DSP**
1	0	0	1
2	0	0.25	0.75
3	0	0.50	0.50
4	0	0.75	0.25
5	0	1	0
6	0.25	0	0.75
7	0.25	0.25	0.50
8	0.25	0.50	0.25
9	0.25	0.75	0
10	0.50	0	0.50
11	0.50	0.25	0.25
12	0.50	0.50	0
13	0.75	0	0.25
14	0.75	0.25	0
15	1	0	0

C. *HPC fundamental composition and specimens preparation*

The approach developed by the Sherbrooke University was used to determine the fundamental composition of HPC without entrained air [1]. The Dreux-Gorisse approach was employed to optimize the aggregates granular skeleton [12]. HPC analyzed compositions are listed in Table 4.

Table 4. Studied compositions.

HPC n°	PC (kg/m^3)	GBFS (kg/m^3)	DSP (kg/m^3)	Water (L/m^3)	W/L	Sp (kg/m^3)	G (3/8 mm) (kg/m^3)	G (8/12.5 mm) (kg/m^3)	Sand (kg/m^3)
HPC 1	360	0	90	148.5	0.33	6.75	242.31	807.69	781.90
HPC 2	360	22.5	67.5						783.92
HPC 3	360	45	45						785.93
HPC 4	360	67.5	22.5						787.95
HPC 5	360	90	0						789.97
HPC 6	382.5	0	67.5						785.42
HPC 7	382.5	22.5	45						787.44
HPC 8	382.5	45	22.5						789.45
HPC 9	382.5	67.5	0						791.47
HPC 10	405	0	45						788.94
HPC 11	405	22.5	22.5						790.96
HPC 12	405	45	0						792.97
HPC 13	427.5	0	22.5						792.46
HPC 14	427.5	22.5	0						794.48
HPC 15	450	0	0						795.98

III. RESULTS AND DISCUSSIONS

Findings of characterization tests of the fifteen HPCs are listed in Table 5. These findings are utilized to create mathematical models which can show the impacts of PC, GBFS, DSP and any potential combinations on each response variation. Estimates of the model parameters for the studied responses are shown in Table 6. Based on Table 6, the developed models have respectable correlation coefficients ($R^2 \geq 0.83$) for all responses and probabilities are suitable.

Table 5. Findings of characterization tests

HPC n°	Slump (cm)	Compressive strength Cs (MPa)	
		Cs at 7-day	Cs at 28-day
HPC 1	16.5	49.70	64.54
HPC 2	18	46.99	66.12
HPC 3	19	48.34	66.46
HPC 4	21	44.17	70.04
HPC 5	24	42.58	68.70
HPC 6	17	53.40	66.28
HPC 7	19	51.50	67.61
HPC 8	22.5	50.00	70.75
HPC 9	23	48.50	71.42
HPC 10	18	54.00	67.20
HPC 11	20	49.50	71.88
HPC 12	22	48.00	75.80
HPC 13	19	50.00	75.53
HPC 14	21	49.33	79.70
HPC 15	21	50.43	72.75

A. *HPC slump modeling*

The workability (slump) is a key aspect of HPC that enables assessing how simple it will be to implement. Table 6 displays estimates for the model parameters of slump. The slump mathematical model is as listed below:

$$\textbf{Slump}\text{ (cm)} = 20.54 * \textbf{PC} + 23.79 * \textbf{GBFS} + 16.40 * \textbf{DSP} + 0.71 * \textbf{PC} * \textbf{GBFS} - 1.43 * \textbf{PC} * \textbf{DSP} - 2.14 * \textbf{GBFS} * \textbf{DSP} \qquad (5)$$

The impacts of PC, GBFS, and DSP proportions on slump are shown by iso-response curves in Fig. 3. The findings demonstrate how the three parameters types and combinations impact the workability of the HPCs.

According to the statistical model of workability, each parameter coefficient clearly shows that it has an impact on the slump value. The HPCs also offer good workability values, which ranges from 16.5 cm to 24 cm. Using the slump prediction profiler (see Fig. 4), it is obvious that the existence of GBFS enhances the workability of HPC. According to the model and Table 6, slump is influenced first by an increase in the dose of GBFS, then by an increase in the dosage of PC and DSP, and finally by the different associated effects. The correlation coefficient for the slump model is relatively high ($R^2 = 0.94$). Fig. 3 shows that the improvement of the HPCs slump can be attributed to the increasing proportion of GBFS in binary and ternary systems. As opposed, the findings suggest the rising percentage of DSP in binary and ternary systems causes the decrease of slump. A good slump value (23 cm) for the binary system (25% PC + 75% GBFS) was attained. Additionally, a ternary system with proportions of 0.25 PC, 0.50 GBFS and 0.25 DSP was able to achieve an appropriate slump value (22.5 cm). The associated effects (GBFS*DSP) and (PC*DSP) have a negative impact on workability, as shown by the negative coefficients (-2.14) and (-1.43), respectively; a rise in these associated parameters reduces slump. Because of this, the slump only remains good when the combinations have a low proportion of DSP (≤ 0.25). In other words, the addition of a small proportion of DSP has an effective effect.

Table 6. Model parameter estimates of studied responses.

Term	**Slump**		**Cs_7**		**Cs_{28}**	
R^2	0.94		0.83		0.83	
P	< 0.0001		< 0.0001		< 0.0001	
Coeff. / P-Value	Coeff.	P-Value	Coeff.	P-Value	Coeff.	P-Value
a_1 : (PC)	20.542	<0.0001*	48.989	<0.0001*	75.647	<0.0001*
a_2 : (GBFS)	23.792	<0.0001*	43.191	<0.0001*	68.615	<0.0001*
a_3 : (DSP)	16.400	<0.0001*	49.918	<0.0001*	64.128	<0.0001*
a_{12} : (PC*GBFS)	0.714	0.7806	11.452	0.0787	14.914	0.0980
a_{13} : (PC*DSP)	-1.428	0.5800	14.602	0.0323	-4.245	0.6119
a_{23} : (GBFS*DSP)	-2.142	0.4116	1.615	0.7860	3.011	0.7180

Notes: *: significant contribution of parameter in the response variation; R^2: correlation parameter; P: probability; Coeff.: estimated coefficient in the linear model; P-Value: probability that the parameter is negligible (null hypothesis H_0). P-Value < 0.05 indicates that the parameter should be in the prediction model.

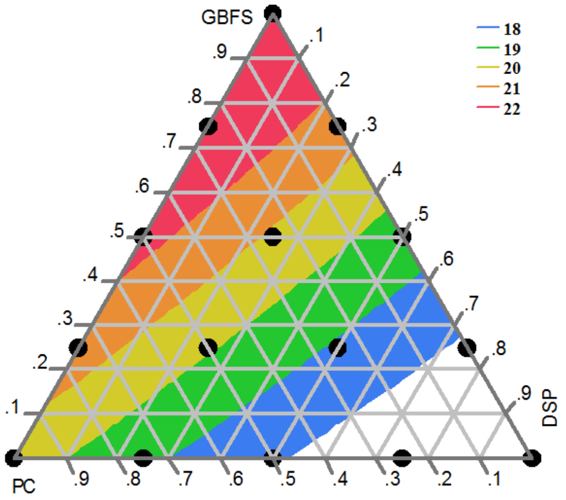

Fig. 3 Iso-response curves of slump (cm) as function of additions

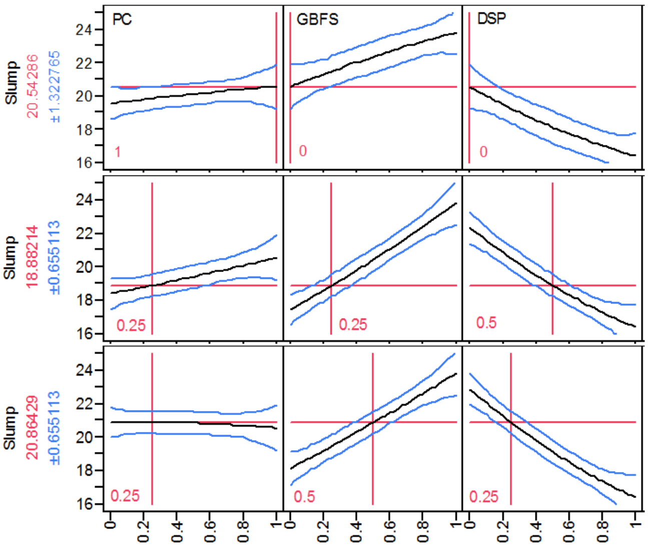

Fig. 4 Profiler of slump prediction.

B. *Modeling of HPC compressive strengths*

The most essential test is the compressive strength test as it provides information about the main concrete characteristics. Besides, the construction industry frequently considers a 28-day compressive strength as the only requirement for approval of a concrete mix. The compressive strength prediction models at 7-day and 28-day are summarized below:

$$\textbf{Cs}\text{ at 7-day (MPa)} = 48.99*\textbf{PC} + 43.19*\textbf{GBFS} + 49.92*\textbf{DSP} + 11.45*\textbf{PC*GBFS} + 14.60*\textbf{PC*DSP} + 1.61*\textbf{GBFS*DSP} \quad (6)$$

$$\mathbf{Cs}\text{ at 28-day (MPa)} = 75.65*\mathbf{PC} + 68.61*\mathbf{GBFS} + 64.13*\mathbf{DSP} + 14.91*\mathbf{PC*GBFS} - 4.24*\mathbf{PC*DSP} + 3.01*\mathbf{GBFS*DSP} \qquad (7)$$

According to Table 6, the prediction models for compressive strengths exhibit good correlation coefficients ($R^2 = 0.83$). The impacts of PC, GBFS, and DSP proportions on compressive strengths at 7 and 28-day are illustrated by iso-response curves in Fig. 5. It has been observed that the curves have different shapes. At 7-day, using the profiler of compressive strength prediction (see Fig. 6), it is obvious that the existence of DSP enhances the Cs of HPC, particularly for the proportion of 50% DSP with very good Cs, in comparison with the reference (HPC 15), Cs was improved by the addition of PC and DSP. Fig. 5 shows that the improvement of the Cs at 7-day can be attributed to the increasing proportion of DSP in binary and ternary systems. Cement hydration is chemically activated through a physical process that depends on the fineness and quality of DSP, and which influence the evolution of Cs at early-age. Therefore, the cement hydration process is accelerated by the DSP. In the short-term, better Cs can result from both the acceleration effect and the filler mechanism of DSP. This is consistent with what has been reported by other researchers [3,4]. The maximum compressive strength at 7-day is approximately 54 MPa, which has been recorded for the binary system (50% PC + 50% DSP); for ternary system with proportions of 0.25 PC, 0.25 GBFS and 0.50 of DSP, the compressive strength could reach about 51.50 MPa. In contrast, the results suggest the increasing percentage of GBFS in binary and ternary systems causes a slight decrease of the Cs at 7-day. This is mainly due to the slow hydration rate of GBFS and because the GBFS contributes to hydration after 28-day, thus improving long-term strength, thanks to its pozzolanic reaction [14]. At 28-day, employing the profiler of compressive strength prediction (see Fig. 7), it is obvious that the existence of PC enhances the Cs of HPC, particularly for the proportion of 75% PC with very good Cs in comparison with the reference (HPC 15), Cs was improved by the addition of PC and GBFS. It is evident that the use of GBFS alone resulted in a slight decrease in Cs, but when combined with PC, GBFS increased Cs compared to the reference. That is to say, replacing cement with 25% of GBFS contributes to this increase of the Cs at 28-day. This contribution was likely attributable to the filler function of GBFS, the initial phase of the GBFS pozzolanic reaction and to the correct and appropriate combination of cementitious materials used. Fig. 5 shows that the improvement of the Cs at 28-day can be attributed by the increasing proportion of PC in binary and ternary systems. The maximum compressive strength at 28-day, which is about 79.70 MPa, was reached for the binary system (75% PC + 25% GBFS); for ternary system with proportions of 0.50 PC, 0.25 GBFS and 0.25 of DSP is about 71.88 MPa. In contrast, the results suggest the increasing percentage of DSP in binary and ternary systems causes a slight decrease of the Cs at 28-day. For this reason, the Cs at 28-day is better when the combinations have a low percentage of DSP (≤ 25%), this enhancement was due to DSP partial pozzolanic reaction.

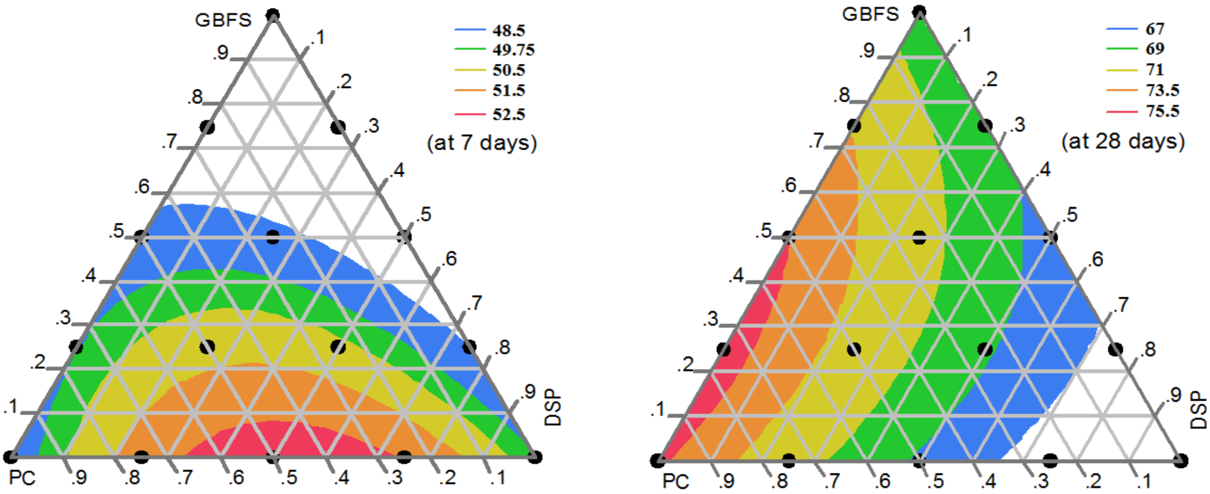

Fig. 5 Iso-response curves of compressive strengths (MPa) as function of PC, GBFS and DSP proportions.

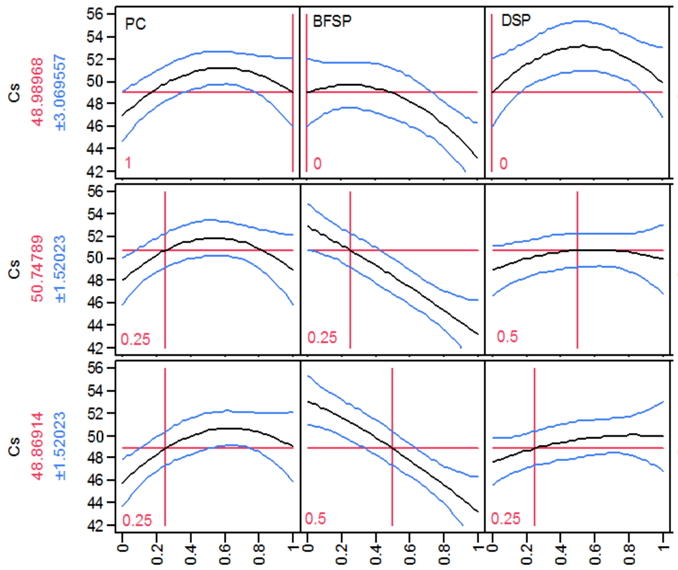

Fig. 6 Profiler of compressive strength prediction at 7-day.

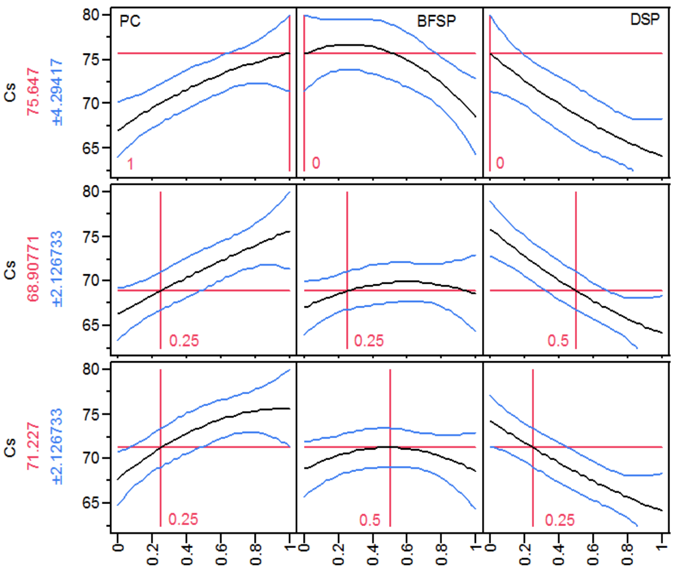

Fig.7 Profiler of compressive strength prediction at 28-day.

IV. CONCLUSION

The key findings of the study are presented below:

- The statistical models and the prediction curves for slump, compressive strengths at 7 and 28-day of HPCs were achieved with high accuracy, using the method of mix design modeling.
- For all responses, models exhibit strong correlation coefficients (R2 ≥ 0.83).
- Replacing cement with GBFS increases the slump of binary and ternary mix because the GBFS particles have a smooth, glassy surface texture and are less permeable to water. However, slump only remains good when the combinations have a low proportion of DSP (≤ 0.25).
- At early-age, the improvement of Cs can be attributed by the increasing proportion of DSP in binary and ternary systems. This is due to both the accelerating effect of the cement hydration process and their fill mechanism. In contrast, results suggest the increasing percentage of GBFS causes a slight decrease of Cs, in all systems.
- At 28-day, it is evident that the use of GBFS alone resulted in a slight decrease in Cs, but when combined with PC, GBFS increased Cs, compared to the reference composition, and contributed to the porosity reduction. This enhancement was likely attributable to the filler function of GBFS, the hydration of cement and the initial phase of the GBFS pozzolanic reaction. In contrast, Cs is better, with low porosity, when a low percentage of DSP is used. This decrease in porosity was due to both the filler mechanism and the DSP partial pozzolanic reaction.
- The optimal composition (HPC14 with 5%GBFS) offers the best compromise between the three characteristics, less cement can also be used because the HPC4 (15%GBFS-5%DSP) displayed characteristics roughly comparable to the reference HPC15. The results of this study confirm that DSP and GBFS can be used as alternatives to cement in the manufacture of affordable and environmentally friendly HPC.

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