EVALUATION OF WORKABILITY PARAMETERS FOR HOOKED-END HIGH STRENGTH STEEL FIBER CONCRETE MIXES

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Discreet discontinuous steel fibers have been found useful in concrete construction. However, their workability present challenges, especially at high volume fraction (V_f). In this study, workability of high strength steel fiber concrete (HSSFC) was evaluated for three hooked-end steel fibers with different aspect ratios of 60, 75 and 83 and at different fiber volume (V_f) of 0.0, 0.5, 1.0, 1.25, 1.5, 1.75 and 2.0 %. The purpose of this study was to establish relationships among the relevant variables through examining their workability test results. Regression models were developed and validated using fiber reinforcement index (FRI). Findings revealed that with an increasing FRI, VeBe time increases exponentially, slump and compacting factor decreases linearly. More so an inverse relationship was observed between yield stress and slump. Regression models were closer to unity, which indicates a strong correlation between FRI and workability parameters with the exception of compacting factor. In order to obtain a valid correlation, it is hereby suggested that a combination of tests should be considered to fully characterize the workability parameters.

Keywords: *Workability; High strength steel fiber concrete; Steel fiber; VeBe time; Slump; Compacting factor; Regression models*

1. Introduction

Workability, a property of freshly mixed concrete or mortar, is defined as the ease in which it can be mixed, placed, consolidated, and finished without segregation [1]. Adequate workability, especially in high-strength concrete (HSC), results in a more uniform concrete mixture that reduces honeycombing, and decreases voids and pores. This becomes important in particularly harsh mixes, such as steel fiber-reinforced concrete (SFRC) which is difficult to achieve. However, it is worthy to note that workability as a term is fairly subjective as it depends on the mixture's intended application. For example, a very dry mix might be noted at the lower end of the workability scale but rather suitable for its intended purpose [2].

Slump, compacting factor, VeBe time have been classified by Tattersall [3] as quantitative measures to be examined when a particular behaviour of concrete is desired under a given condition. Some of these parameters have been heavily criticized due to their inability to fully characterize the behaviour of the fresh concrete. Nevertheless, they are still useful in determining workability especially for a certain category of concrete mixtures i.e. harsh mixes. Most of the tests that have been proposed so far as alternatives to conventional testing which fully describe the rheological properties of fresh concrete as a Bingham fluid (defined in Eq 1) are either too cumbersome, not suitable for field-based application, or require an extensive amount of technical skills and training to be conducted.

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad (1)$$

Where $\tau = shear\ stress\ (Pa)$; $\tau_0 = yield\ stress\ (Pa)$; $\mu = viscosity\ (Pa.s)$; $\dot{\gamma} = shear\ rate\ (s^{-1})$

It has been reported in literature that the addition of steel fibers reduces the workability of fiber-reinforced concretes making it harsh to work with. Early works on the use of steel fibers cited in Mehta and Monteiro [4] report that in mortar, VeBe time increases with an increase in fiber volume (V_f). They also concluded that the slump cone test is not an appropriate test for flowability of steel fiber concrete. This was due to the fact that a 200 mm slump concrete was reduced to a low 25 mm when 1.5 % steel fiber by volume is added. Some researchers [5, 6] observed that with an increase in V_f, VeBe time increased and air content decreased. They also noted that silica fume addition decreased the workability of high strength concrete.

It is noteworthy to state that the most common aspect ratio (length-to-diameter, l/d) used for steel fiber concrete ranges from 50 – 100 at 0.5 - 2.5 % fiber addition level by volume. More so, the probability of balling and heterogeneous distribution increases with an increase in l/d ratio. A decrease in slump becomes significant at 1.5 % V_f, unit weight, on the other hand, increases with aspect ratio and V_f [7]. A study by Atis and Karahan [8] utilizing fly ash also reported an increase in the unit weight with increased fly ash content; as it is expected. At the same time, they observed an

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increase in the VeBe time, which clearly indicates decreasing workability of the concrete. Similar findings have also been reported by [9 – 10].

In Koksal *et al.,* [10], it is explained that due to the combined influence of silica fume and steel fiber, a decrease in the value of the slump cone test and an increase in V_f up to 1.0 % addition of steel fibers with aspect ratio of 65 and 80 is observed. Moreover, Mohammadi *et al.,* [12] carried out an investigation to study the fresh and hardened properties of steel fiber-reinforced concrete (SFRC) containing two corrugated steel fibers of aspect ratio 20 and 40. Their results noted that, for a combination of short and long fibers, the lower aspect ratio fibers resulted in high compacting factor values and a significant reduction in the tendency for balling even at higher V_f. A study by Afroughsabet and Ozbakkaloglu [13] observed a decrease in slump with respect to an increase in fiber addition for a combination of steel and polypropylene fibers. Similarly, Afroughsabet *et al.,* [14] reported a slight increase and decrease of slump on the use of hooked-end steel fibers on high performance recycled aggregate concrete at 1 % V_f. A comprehensive review on high-performance fiber-reinforced concrete by Afroughsabet *et al.,* [15] cautioned on the influence of fiber addition on the workability, indicating that it decreases with an increase in V_f.

Nowadays, regression models are treated as an integral component of engineering application due to their predictive ability that relates the data of the dependent variable to that of the independent variable, up to a certain degree of accuracy. To validate the accuracy of the predicted data, they are compared with a different set of values in other to evaluate the prediction errors, specify the range over which the model can be utilized, and to identify any deviations from the measured set for further improvement [16]. There are multiple ways in which a model's predictive capacity can be validated and those include: checking the coefficient of determination between observed and predicted data, assessing the closeness of intercept and slope to 0 and 1 respectively, using the mean squared deviation between x - y, and comparing the slope and intercept against the 1:1 line [17, 18].

In this study, an attempt has been made to find correlations amongst tests that are used to assess the workability of harsh mixtures with steel fiber addition and to gain a better understanding of the rheological behaviour of the material in its plastic state.

Models capable of predicting workability of harsh concrete mixes to a certain degree of accuracy have been generated using fiber reinforcement index (FRI) which is a product of aspect ratio (l/d) and fiber volume (V_f). Their efficiency was assessed through examination of the coefficient of determination (R^2), standard error of the estimate, and a measured versus predicted values plot and their R^2. Complete regression analysis was also performed and validated.

2. Experimental Procedure

Blast-furnace Slag Cement CEM II/B-S 42.5 N in conformity with EN 197 - 1 [19] was utilized with a specific gravity of 3.15. Silica fume was then added at 10 % of the cement content having 82.2 % content of SiO_2, specific gravity of 2.2, and fineness of 29,000 m^2/kg. Tap water utilized conformed to specification of BS EN 1008 [20]. Lastly, high range water reducer used was GLENIUM 27 conforming to ASTM C 494 [21] ether basis brown in colour with a density of 1,023 – 1,063 kg/lt and alkali content < 3 %.

Aggregates used were crushed limestone rock conforming to the specification of ASTM C 33 [22]. Sieve analysis was then conducted in accordance with ASTM C 136 [23] and the result, is hereby presented in Table 2.

Relative density (SSD) performed for both fine and coarse aggregates were based on ASTM C 127 [24] and ASTM C 128 [25] and were 2.68 and 2.65 respectively. Absorption percentages determined through the same standards were 3.0 % and 0.7 %. Bulk densities based on ASTM C 29 [26] were 2083 kg/m^3 and 1203 kg/m^3, respectively. Voids in aggregates were 25 % and 50 % for fine and coarse aggregates. The percentage of materials finer than 75 μm to ASTM C117 [27] was 3 %. Lastly, the properties of hooked end steel fiber utilized are displayed in Table 3, and the volume fractions and fiber reinforcement index (FRI) given in Table 4.

Table 1

Mix design utilized

Material	Cement 42.5 N (Slag)	Water	Coarse (10 mm D_{max})	Fine	Silica Fume	HRWR	Average Strength (MPa)
Quantity (kg/m^3)	470	165	1050	700	47	14	71

Table 2

Sieve analyses of aggregates

Sieve sizes (mm)	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
% passing coarse	100	100	9.4	0.2	0.2	-	-	-	-
% passing fine	-	-	100	82	48	29	17	7	3

Table 3

Dimensions and tensile strength of steel fibers

Length (mm)	Diameter (mm)	l/d Ratio	Tensile Strength (MPa)
30	0.50	60	1250
50	0.60	83	1200
60	0.80	75	1100

Table 4

Workability test results

Aspect Ratio	Fiber Volume %	FRI	VeBe Time, s	Slump, mm	Compacting Factor	Density, kg/m^3
	0.00	-	4.70	150	0.90	2406
60	0.50	30	6.58	130	0.89	2508
	0.75	45	9.71	110	0.85	2514
	1.00	60	12.18	100	0.88	2511
	1.25	75	14.07	80	0.84	2504
	1.50	90	19.54	70	0.81	2550
	1.75	105	33.45	60	0.75	2534
	2.00	120	39.62	40	0.71	2581
75	0.50	37.5	7.50	95	0.88	2539
	0.75	56.25	9.85	90	0.89	2546
	1.00	75	11.45	85	0.87	2569
	1.25	93.75	16.43	60	0.78	2582
	1.50	112.5	25.85	40	0.77	2573
	1.75	131.25	32.73	20	0.69	2599
	2.00	150	44.64	15	0.70	2565
83	0.50	41.5	9.00	110	0.99	2536
	0.75	62.25	12.77	105	0.87	2516
	1.00	83	15.65	90	0.82	2536
	1.25	103.75	13.05	75	0.83	2585
	1.50	124.5	13.10	40	0.77	2584
	1.75	145.25	20.69	30	0.69	2489
	2.00	166	50.98	20	0.68	2559

To avoid balling, the mixing operation was done as prescribed by the manufacturer which specifies that fibers (stacked in a fibrillated bundle of water soluble glue) be placed last by distribution in small amounts. Immediately upon contact with moisture, the fibers dispersed; however, the mixing time was notably longer for volume percentages from 1.25 % and above. VeBe time test was conducted in accordance with BS EN 12350 – 3 [28] and Compacting factor to BS EN 12350 – 4 [29]. Slump determination and unit weight of concrete was tested to ASTM C143 [30] and ASTM C 138 [31] respectively. Each of the tests were an average of 3.

Fig. 1 - Typical mix with 0.50 % steel fiber addition.

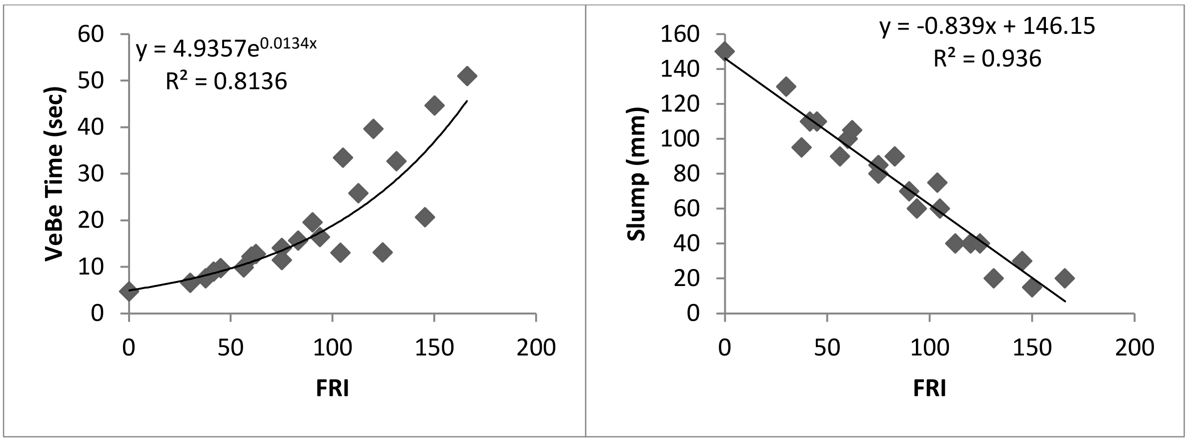

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Fig. 2 - Relationships between FRI and (a) VeBe time (b) Slump.

3. Results and Discussion

3.1. Workability Test Results

3.1.1 VeBe Time

This test intended for concrete that cannot be properly evaluated using the slump test was conducted for all the three aspect ratios, and the test results presented in Table 4. In general, It is seen that the addition of steel fiber in the mix resulted in an increase in the VeBe time for all mixes. The mixes with aspect ratio of 60 seem to have a higher workability than 75 and 83. The minimum values for VeBe time with fiber addition for the three aspect ratios 60, 75 and 83 were 6.58, 7.50 and 9.00 seconds and the maximum values were 39.62, 44.64 and 50.98 seconds respectively.

Fig. 2(a) shows VeBe time and slump values plotted against FRI. It is apparent that VeBe time increases exponentially with FRI, fiber volume and length due to interparticle friction. The test results in this study are in agreement with the results of [8].

3.1.2 Slump

This widely applicable test was conducted and test results are presented in Table 4. It is evident from the test results that slump decreases with an increase in V_f and FRI. This decrement is due to the shape of the hooked-end fiber and its surface area. Fig. 2(b) depicting a plot of slump versus FRI shows a reduction in the flow as FRI values increases. On the other hand, Fig. 3 shows the correlation between yield stress, VeBe time and slump indicating an inverse relationship exists between yield stress and slump as well as VeBe time with slump.

Yield stress which is the magnitude or limit before the onset of the flow is defined in Eq 2 developed by [32] has been used in this study to estimate the values.

$$\tau_0 = \frac{\rho}{270}(300 - s) \qquad (2)$$

Where:
τ_0= yield stress in Pa; s = slump in mm;
ρ = density in kg/m^3

The maximum and minimum values for yield stress obtained were 2867.81 Pa and 2524.22 Pa respectively.

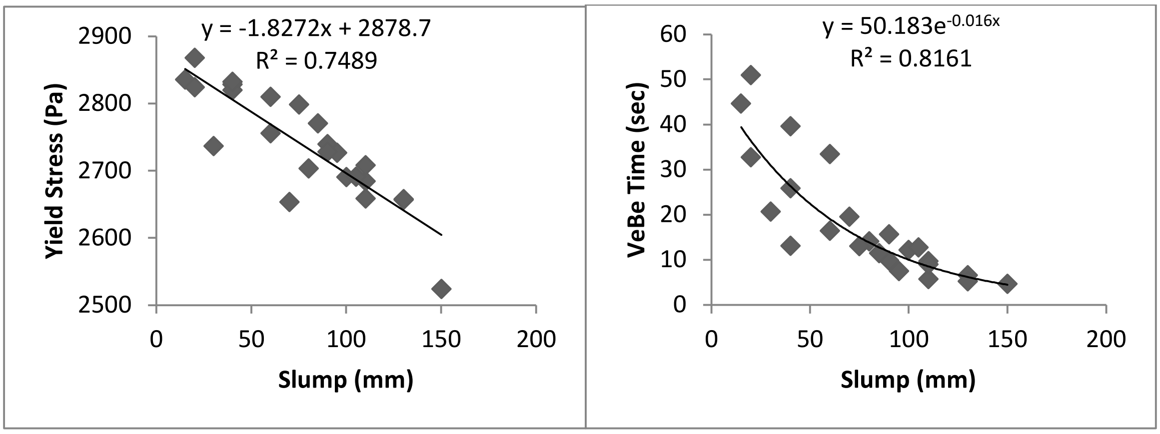

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Fig. 3 - Relationships between (a) Yield stress versus slump (b) VeBe time versus slump.

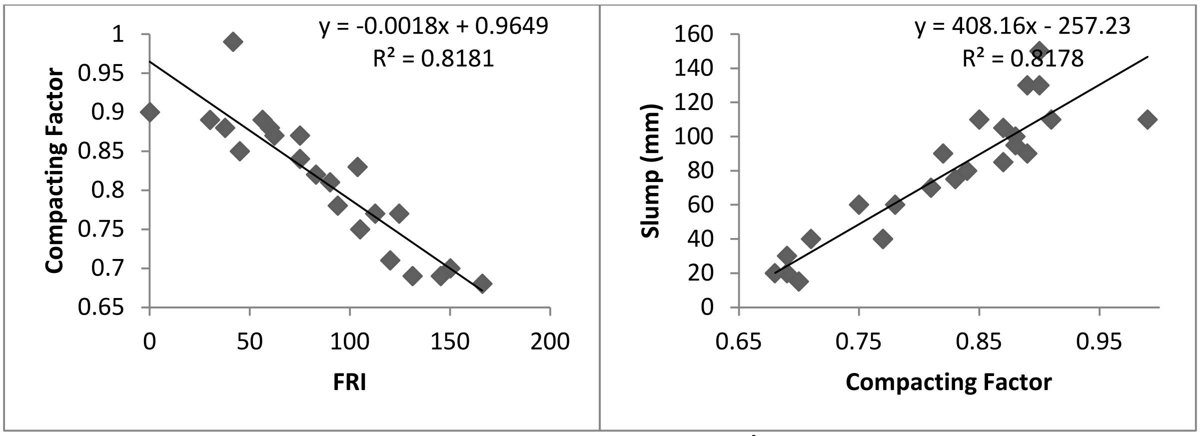

Fig. 4 - Correlation factor between (a) Compacting factor versus FRI (b) Slump versus compacting factor.

3.1.3 Compacting Factor

This is a density ratio that measures the degree of compactibility between partially compacted to fully compacted concrete. It is affected by entrapped air, shape and surface texture of the aggregates. In this study, compacting factor test was conducted for all aspect ratios and the test results are shown in Table 4, Fig. 4 and Fig. 5. The maximum compacting factor value was 0.99 at aspect ratio of 83 while the minimum was 0.68 also at aspect ratio 83. As can be seen from the results of slump, here the value of the compacting factor also decreases with aspect ratio and fiber addition. This occurs due to the reduced interparticle friction, which affects the mobility of the concrete mixture.

Further, the results showed the development of cohesive forces increases shear stresses; this changes the concrete mixture's condition from flowable to stiff. According to reference [33], a good measure of workability correlation can be obtained by combining VeBe test and Compacting Factor test. This is presented in Fig. 5, which shows a good correlation exists for mixtures having a compacting factor above 0.8. This indicates that within this region, the effect of fiber length is more pronounced, as it can be seen in mixtures incorporating fibers with aspect ratio 60 and 75. Moreover, beyond 1.25 % fiber addition by volume a good correlation cannot be obtained.

3.1.4 Density

In high strength concretes, it is expected that the unit weight would be higher than that of normal concrete due to both higher cement content and very low water-cement ratio. The unit weight difference could be as much as 100 kg/m^3 which were observed by [34].

This clearly indicates the important role that mixture proportioning plays and highlights the increased amount of fine aggregate content.

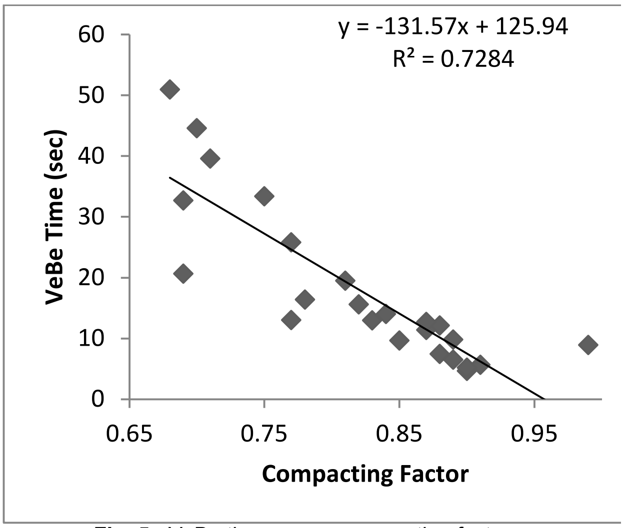

Fig. 5 - VeBe time versus compacting factor.

3.2 Regression Analysis

The most widely used regression models are of the form in Eqs 3 – 5,

$$y = a + bx \quad (3)$$

$$y = a + bx + cx^2 \quad (4)$$

$$y = a + bx + cx^2 + dx^3 \quad (5)$$

Where a, b, c, and d represents regression coefficients and x is an explanatory item or the independent variable. This study holds FRI as the independent variable, and VeBe time, slump, compacting factor and density or unit weight, as the dependent variables. For every FRI (independent variable) increment presented in Table 5, there is a corresponding change in the dependent variables. It became apparent that an increase in FRI resulted in an increase in the VeBe time, however, a decrease in both slump and compacting factor values was also observed. This could be possible due to the harshness of the mixture resulting from fiber addition which makes it difficult for interaction among the mixture's constituents.

Table 5

Modelling of each response

Responses	Aspect Ratio L/d	Coefficients				R^2	Standard error of estimate
		a	b	c	d		
VeBe Time	60	6.85	-0.0206	0.00062	0.000016	97.6	2.73581
	75	11.34	-0.2007	0.002813	-	99.6	1.0882
	83	34.82	-0.6866	0.004464	-	80.5	7.7858
Slump	60	185.70	-2.3700	0.01958	-0.000082	99.4	3.45033
	75	30.00	3.129	-0.04368	0.000147	99.4	3.53553
	83	53.57	2.607	-0.03498	0.000109	99.0	5.17549
Compacting Factor	60	0.8807	0.000225	-0.000004	-0.000000	95.4	0.020295
	75	0.98	-0.0020	-	-	90.4	0.0287
	83	1.05	-0.0023	-	-	92.5	0.0323
Density	60	2328.00	10.6200	-0.183800	0.000945	78.4	25.5913
	75	2551.00	-1.1950	0.027930	-0.000128	83.0	11.9035
	83	2476.00	1.4170	-0.006280	-	10.3	40.9855

Table 6

Ratio of Prediction versus Experimental Results

Aspect Ratio	Fiber Volume, %	FRI	VeBe Time, s (P/E)	Slump, mm (P/E)	Compacting Factor (P/E)	Density, kg/m^3 (P/E)
60	0	0	0	0	0	0
	0.5	30	1.1	1.01	1	1
	0.75	45	0.89	1.02	1.04	1
	1	60	0.93	0.97	1	1
	1.25	75	1.11	1.05	1.05	1
	1.5	90	1.11	1.02	1.08	0.97
	1.75	105	0.9	0.97	1.15	1
	2	120	1.04	1.04	1.2	1
75	0		0	0	0	0
	0.5	37.5	1.04	0.99	1.04	1
	0.75	56.25	0.91	1.05	0.98	1
	1	75	1.06	0.96	0.96	1
	1.25	93.75	1.05	1.01	1.03	1
	1.5	112.5	0.95	0.97	0.99	1
	1.75	131.25	1.03	1.03	1.05	1
	2	150	1	0.85	0.98	1
83	0		0	0	0	0
	0.5	41.5	1.56	1	0.96	1
	0.75	62.25	0.74	1.02	1.04	1
	1	83	0.55	1.02	1.05	1
	1.25	103.75	0.9	0.93	0.98	0.99
	1.5	124.5	1.42	1.16	0.99	0.99
	1.75	145.25	1.42	0.95	1.04	1.03
	2	166	0.87	1.06	0.98	1

P = Predicted results (model) E = Experimental results

Regression equations presented in Table 5 were used to obtain predicted values for dependent variables. Furthermore, the prediction error was measured using the ratio of predicted values versus the observed values presented in Table 6.

Most of the predicted values were closer to unity with some small overestimation in some cases. Plots of observed versus predicted (OP) values can be seen in graphic format through Figs. 6 – 8; they were done to evaluate the accuracy of the prediction with regression parameters.

Observed versus predicted (OP) was

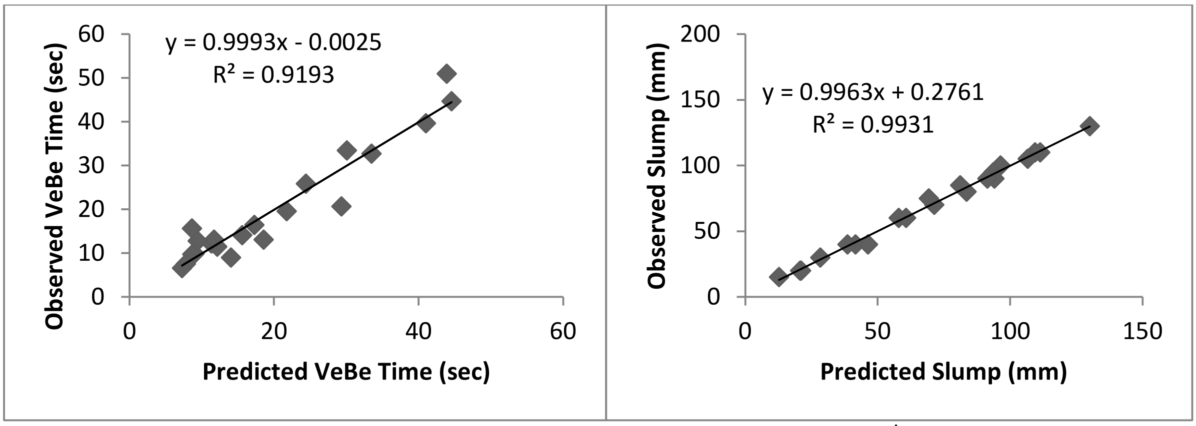

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Fig. 6 - Observed versus Predicted fitted values (a) VeBe time (b) Slump

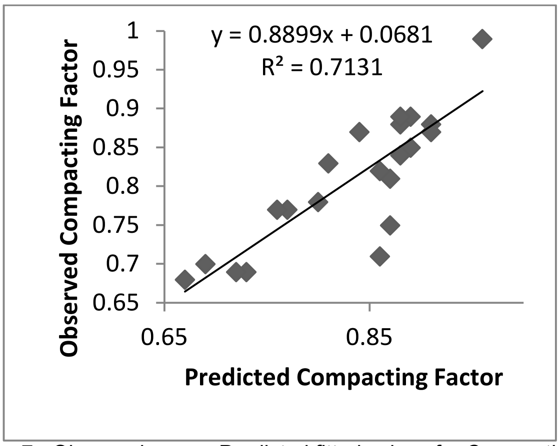

Fig. 7 - Observed versus Predicted fitted values for Compacting factor.

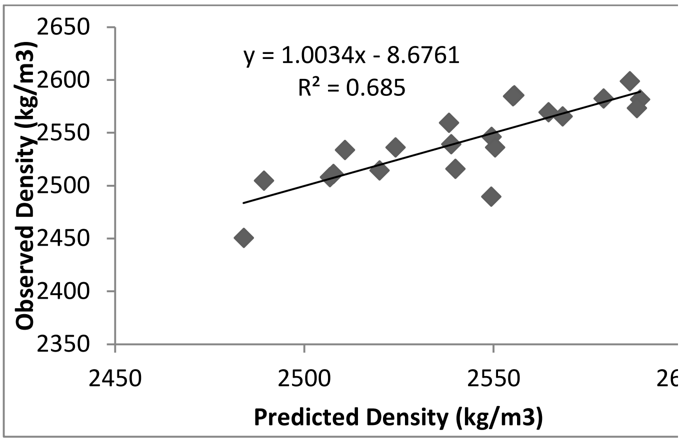

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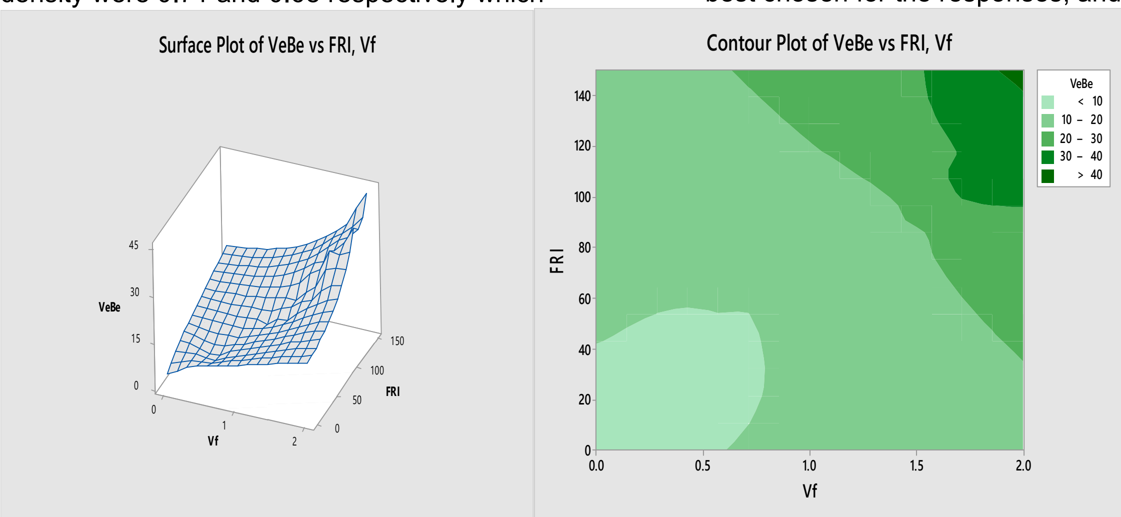
Fig. 8 - Observed versus Predicted fitted values for Density

chosen rather than predicted versus observed (PO), because it gave the best indicator of model parameters performance. Although both gave the same value of R^2, the 1:1 regression line changed. Results for VeBe time and Slump showed a *perfect equality* which can be defined as Y = X since the correlation were 0.92 and 0.99 respectively. On the other hand, the correlation for compacting factor and density were 0.71 and 0.68 respectively which is very low. This is best described as a *translation* with Y = 1 + X. Further, this indicates that with fiber addition in HPC, the values of density and compacting factor do not give a valid depiction of the model.

Table 5 shows the correlation established between the dependent and independent variables fitted to polynomials. Quadratic models were the best chosen for the responses, and the



a Fig. 9 - VeBe vs FRI and Volume Fraction (a) 3D Mesh Surface Plot (b) Contour Plot b

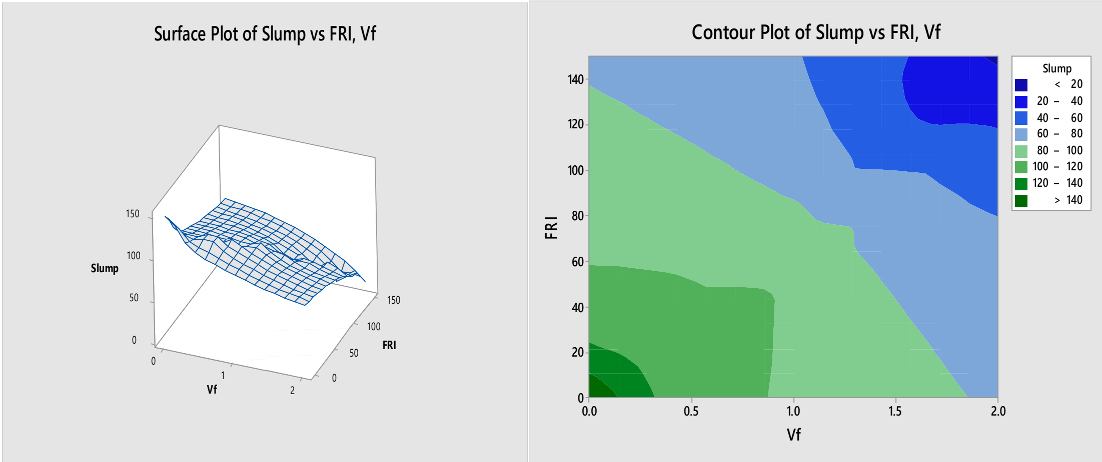


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Fig. 10 - Slump vs FRI and Volume Fraction (a) 3D Mesh Surface Plot (b) Contour Plot

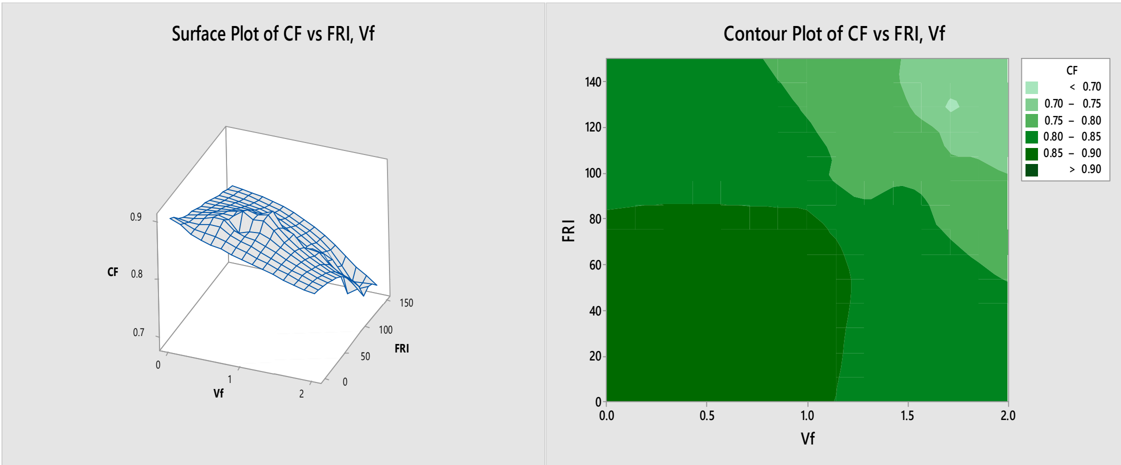

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Fig. 11 - Compacting Factor vs FRI and Volume Fraction (a) 3D Mesh Surface Plot (b) Contour Plot

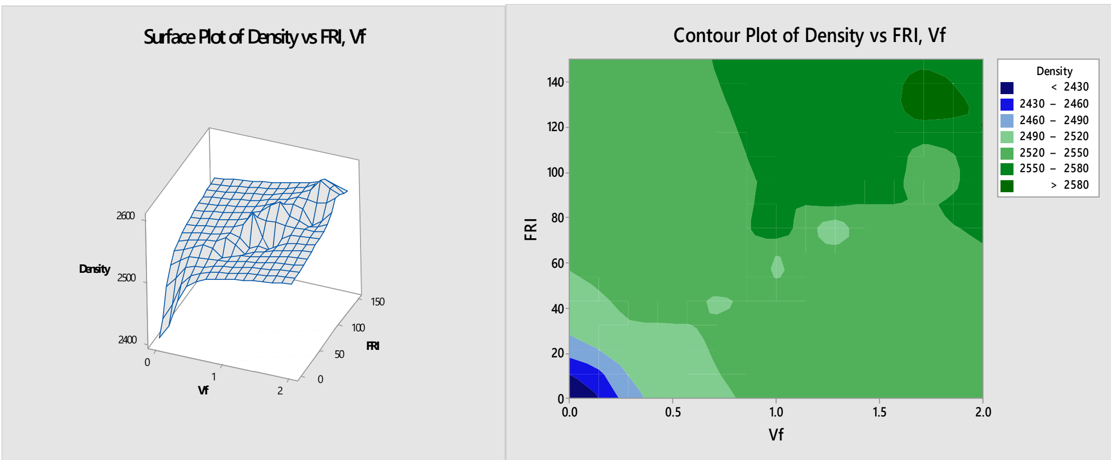

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Fig. 12 - Density vs FRI and Volume Fraction (a) 3D Mesh Surface Plot (b) Contour Plot

quality assessed by R^2. With the exception of Density, the R^2 values were very good and close to unity.

The effect of FRI and volume fraction on the workability parameters were analysed using response surface methodology. The effect of FRI and V_f on VeBe, slump, compacting factor and density are presented graphically in Fig. 9 – 12. Optimal values for aspect ratios and V_f can be extracted when needed.

4 Conclusions

Based on this investigation, the following conclusions can be made:

Steel fiber addition at higher V_f results in an increase in the viscosity of the mix, decreasing the flowability, and increasing the unit weight.

An Increase in FRI values results in an increase in the VeBe time, decrease in the compacting factor and slump, and an increase in the tendency for balling to occur, while significantly decreasing the workability.

A good correlation exists between FRI and the workability parameters in question (0.81, 0.82 and 0.94 for VeBe, compacting factor and slump respectively).

Model fitting, based on the regression equations developed with FRI indicates a strong correlation with the exception of VeBe time for aspect ratio of 83. This was classified as a poor predictor of the response in both under and overestimate measures.

Increased fiber addition resulted in low correlation in model accuracy performance indicators (compacting factor and density compared with VeBe time and slump) using observed versus predicted values.

Regression models selected were satisfactory based on fittings and surface plots.

In general, models can only predict the behaviour and range of responses. Therefore, emphasis on a single validation parameter is not advised. A combination of two or more parameters should be used to evaluate the efficiency of the system.

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