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Non Linear Regression Model for Compressive Strength of Silica Fume Concrete

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Abstract **In the present research work, investigations were carried out to improve the performance of concrete in terms of strength by incorporating silica fume (SF) as mineral admixture in concrete. Parametric study was carried out by considering w/cm ratio, various percentage of SF and age of concrete as parameters to understand the effect of each parameter. The study was conducted for different water-to-cement (w/cm) ratios of 0.32, 0.35, 0.4 and 0.5. The SF proportion was varied from 0 to 15% with an increment of 5% and ages of concrete from 3 to 90 days were considered and experiments performed accordingly. The effects of above said parameters on the various properties of concrete such as workability, compressive strength and pH of concrete were investigated and the results of SF concrete were compared with the conventional concrete. From the results, it was observed that SF concrete showed consistent performance in all w/cm ratios, and maximum strength was achieved at 0.32 w/c . Longer curing period is found to be more beneficial for higher w/cm ratios, and the optimal amount of SF reduced the pH values, but the reduction is insignificant. A Multiple non-linear regression analysis was used to develop a statistical model to predict the strength and found to have good correlation between the observed and predicted values. From the model, It was observed that the maximum strength of 57.75 N/mm2 was obtained with 3.6% SF at 0.32w/c. High R^2 value of 0.961 indicated a strong association between the pairs of variables and the model explained the variations in the predictor variables satisfactorily. These readily available models are very much useful to the practicing engineers and researchers with simple input data. It was concluded that the concrete and the model developed in this study have significant potential for use on real time projects.**

Keywords — compressive strength, pH, Silica fume, w/cm ratio

I. INTRODUCTION

Reinforced concrete has come to stay as the most accepted construction material in world wide. It is a composite consisting of steel and concrete, which, in itself, is another heterogeneous material consisting of cement and aggregates with varied shapes, sizes, configurations and orientations. During service, the reinforcement almost invariably undergoes rusting and hence deterioration has been observed in concrete structures well within their service life especially in some aggressive environments, leading to premature failure (Hassan, 2000). The economic loss due to premature failure and the cost of rebuilding runs up to several percentage of national income. In this context it is of paramount importance to produce durable concrete structures with longer life and less damage due to unforeseen factors. One of the main causes for damages is due to corrosion of reinforcing steel and therefore of late, there has been major interest in developing technology for corrosion control by developing a durable concrete with mineral admixtures. It is understandable from the reported literature that addition of mineral admixtures like fly ash (FA), silica fume (SF), metakaolin (MK) etc in concrete improves strength and durability characteristics of concrete. The strength of concrete depends on several factors like chemical composition of cement, water-to- cement ratio, types and amounts of mineral admixtures etc. Therefore, in order to improve the strength, the mix proportions of concrete should be carefully selected considering the above parameters. Many studies have been carried out on the use of admixtures, however search for efficient alternative admixture is still continuing. Thus in the present work, studies were carried out on the compressive strength of concrete, thereby to develop a model by adding silica fume as a partial re- placement of cement. Poon *et al.* (2006) and Mazloom *et al* (2004) related the mechanical and durability properties of high performance metakaolin and silica fume concretes to their microstructure characteristics. The particle size of SF was studied by selvaraj *et al.* (2003) and found that the specific surface area of SF is very high about 2000 m^2/kg whereas for ordinary Portland cement it's about 300 m^2/kg. Due to the larger surface area of SF it reacts rapidly with calcium

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hydroxide leads to decrease in alkalinity of pore solution thereby increasing the chloride binding (Ozyildirim et al 1994).

Many investigations were carried out to study the strength development of silica fume concrete. Kazuyuki Torii *et al.* (1994) reported that the replacement of silica fume beyond 10% is not very effective with respect to mortar. Different studies carried out by Hooton *et al.* (1997) found that optimum replacement level of SF was 7%. However, most research studies agree on the replacement level ranging between 5% and 10% depending on the type of concrete properties desired (Abdullah A. Almusallam et al 2004).The compressive strength of silica fume concrete did not increase after 90 days and its drying shrinkage decreased with the increase of SF content(Mazloom et al 2004). But Maher A. Bader (2003) reported that if concrete is not sufficiently cured, the permeability of the surface layer may be increased by 5 to 10 times. The strength of silica fume concrete exposed to elevated temperature was investigated by Emre Sancak et al(2008) and found that concrete containing higher amount of SF reduces the strength.Hanumesh et al(2015) studied the compressive strength and split tensile strength of M_{20} grade concrete and found that addition of silicafume beyond 10% reduced the strength. Ashhad Imam et al(2018) studied the hardened properties and durability parameters of concrete and found that compressive strength and split tensile strength decreases with increasing w/cm ratio.

The experimental program was planned to study the effect of various parameters like, mineral admixture, w/cm ratio, and age of concrete on the mechanical properties of concrete. Further, an attempt has been made to develop correlation between the above said factors on the strength of concrete. A Multi variate non-linear regression model was established to predict the strength of silica fume concrete. A non-linear regression analysis was used to develop a statistical relationship between compressive strength, w/cm ratio, SF percentage and age of concrete. In a multivariate experiment, there are several important problems with the conventional approach of changing only one or two variables in a run, because the variables often interact with each other. For example, the amount of admixture optimized for one w/cm ratio, may not be applicable for other w/ cm ratios. These limitations of a classical method can be eliminated by considering the relative importance of all the influencing variables simultaneously by statistical methods. The functional relationships between the independent process variables such as w/cm ratio, amount of admixture, age of concrete and the dependent variable strength of the concrete were investigated. The analysis was done by response surface methodology with coded values of the variables. Common statistical tools, such as analysis of variance, F-test, the student's t-test, and lack of fit were used to define the most important process variables affecting the strength.

II. EXPERIMENTAL PROGRAM

Four series of concrete mixes were prepared at the w/cm ratios of 0.32, 0.35, 0.4 and 0.5. In each series, cement was partially replaced by SF with different proportions and a control mix without any admixture to assess their influence on strength for various curing periods. The percentage of SF varies from 5 to 15% by weight of cement with an increment of 5%. Detailed experimental investigations for various properties of concrete such as workability, compressive strength and pH of concrete have been done for various mixes.

The compressive strength was determined at various ages (3, 7, 14, 28 and 90 days). The results were compared to the same properties of a control concrete mixture. pH of each concrete mixture was measured to know the alkalinity of concrete. Specimens of 100 mm size cubes were cast for control and SF concrete for testing the compressive strength. The entire study has been limited to normal curing conditions and ambient temperature.

MATERIALS USED

Ordinary Portland Cement (OPC) of 53 grade of Indian Standard was used in this study and SF was obtained from Elkemmaterials.

The chemical composition and physical properties of the cement determined as per IS: 12269-1987, Indian Standard Specifications for 53 Grade Ordinary Portland cement are shown in Table 1. Table 2 presents the physical and chemical properties of silicafume.

TABLE 1 Physical and Chemical properties of Cement

Physical properties			Chemical composition		
01	Consistency	37%	01	Lime (CaO)	62.72 %
02	Specific gravity	3.2	02	Silica (SiO_2)	31.38 %
03	Initial setting time	55 min	03	Fe_2O_3 and Al_2O_3	6.89%
04	Final setting time	355 min	04	Magnesia (MgO)	2.02%
05	Fineness by sieving	1% residue	05	SulphurTrioxide(SO_3)	3.14%
06	Soundness	1.5 mm	06	Loss on Ignition	2.76%
			07	Insoluble residue	1.25%

TABLE 2 Physical and Chemical Properties of S F

Physical properties			Chemical composition		
01	Colour	Dark grey	01	Lime (CaO)	0.50 %
02	Specific gravity	2.2	02	Silica (SiO_2)	89.00 %
03	Bulk density	180 kg/m^3	03	Fe_2O_3 and Al_2O_3	1.10 %
04	Average particle size	0.35 □	04	Magnesia (MgO)	1.30 %
05	Fineness	1300 m^2/kg	05	Sulphur Trioxide (SO_3)	-
			06	Loss on Ignition	1.40
			07	Insoluble residue	1.94 %

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A. Aggregates

Locally available river sand lesser than 4.75 mm sieve size conforming to grading Zone III of IS 383 – 1970 was used as fine aggregate and crushed granite stones of 12.5 mm maximum size were used as coarse aggregates. The physical properties of fine and coarse aggregates were determined as per IS: 2386-1963 and are listed in Table3.

TABLE 3. Physical Properties of Aggregates

Sl. No	Physical properties	Fine aggregate	Coarse aggregate
01	Fineness modulus	2.60	7.93
02	Specific gravity	2.65	2.78
03	Bulk density	1.66 g/cc	1.61 g/cc
04	Void ratio	37.59%	45.61%
05	Bulking of sand	58%	-
06	Water absorption	1.01%	0.84%

B. Super Plasticizer

Super plasticizer was used to obtain sufficient workability for the mixes of low w/cm ratios. The super plasticizer used was high range water reducer. It was a brown colour solution of sulphonate naphthalene formaldehyde type of super plasticizer. The specific gravity is about 1.20.

C. Water

Locally available potable water was used for mixing and curing of concrete.

MIX PROPORTIONS

The mix proportions were arrived as per IS 10262 – 1982. The mix designation and the mix ratios for the control mix are given in Tables 4 and 5. The slump values were maintained between 50 and 100 for all the mixtures by adding suitable dosage of high range water reducer.

TABLE 4. Mix Designation

Sl.No	Composition of mix	Mix designation
	w/cm = 0.32	
01	100 % OPC	C_1
02	95 % OPC + 5 %SF	S1
03	90 % OPC + 10 %SF	S_2
04	85 % OPC + 15 % SF	S_3
	w/cm = 0.35	
05	100 % OPC	C_2
06	95 % OPC + 5 % SF	S_4
07	90 % OPC + 10 % SF	S_5
08	85 % OPC + 15 % SF	S_6
	w/cm = 0.40	
09	100 % OPC	C_3
10	95 % OPC + 5 % SF	S_7
11	90 % OPC + 10 % SF	S_8
12	85 % OPC + 15 % SF	S_9
	w/cm = 0.50	
13	100 % OPC	C_4
14	95 % OPC + 5 % SF	S_{10}
15	90 % OPC + 10 % SF	S_{11}
16	85 % OPC + 15 % SF	S_{12}

TABLE 5 Mix Ratio for Different w/cm Ratio

S. No	Mix	Slump (mm)	Mix Ratio
1	C_1	65	1: 0.69: 1.61
2	C_2	70	1: 0.90: 2.10
3	C_3	70	1: 0.99: 2.31
4	C_4	90	1: 1.20: 2.80

Component materials in Mix ratio – Cement: Sand: Coarse aggregate

C_1: Control concrete with w/cm = 0.32

C_2: Control concrete with w/cm = 0.35

C_3: Control concrete with w/cm = 0.40

C_4: Control concrete with w/cm = 0.50

TESTS ON FRESH AND HARDENED CONCRETE

A. Compressive Strength

Slump test was conducted for measuring the workability of concrete and the results are tabulated in Table 6. The compressive strength of the plain and admixed concrete were determined by conducting compression test as per IS specification (IS 516, 1959). 100 mm concrete cubes were cast as per mix proportion for different water cement ratios and for the various percentage of replacement of cement with the mineral admixture (SF). These specimens were cast in steel moulds and compacted on a table vibrator. After 24 hours of casting, the cubes were de- moulded and cured in water for 3, 7, 14, 28 and 90 days. Three samples each were cast for various water cement ratio, percentage of replacement level and period of curing respectively. The curing is done with normal temperature conditions to suit the practical conditions. All the specimens were cast and cured in prevailing temperature and humidity conditions. Effects of various curing and temperature conditions are not considered in the present study. After the required curing period, the cubes were tested in the computerised compression-testing machine of capacity 3000 kN. The strength variations are shown in Fig. 1 and Fig 2.0.

B. pH of concrete

Various concrete samples were crushed mechanically and powdered samples passed through 75 microns sieve were collected for both control specimen and SF admixed concrete. The powdered sample thus collected was mixed with the distilled water in the ratio of 1:10 (Khatib and Wild, 1996). After 2 hours, the solution was filtrated and its pH was measured using a portable pH meter (Elico Ltd -Model 120, type: 003). The pH values are shown in Fig. 6

III. RESULTS AND DISCUSSION

A. Workability

From the results of slump test, shown in Table 6, it has been observed that the SF concrete gives improved workability than the control mix especially at lower w/cm ratios, in which little bit higher amount of super plasticizer was used to get the desired workability. The higher demand of super plasticizer is

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due to the fact that, fineness and glassy surface of the SF adsorbs some of the superplasticiser on its surface. However, there was a substantial reduction in workability when the SF replacement level was increased from 5% especially at higher w/cm ratios and is attributed to its high chemical activity and high specific surface leads to increased water requirement. From the literature it is evident that, further adjustments in the fineness results in retaining cohesiveness and reducing the loss in workability (Tiwari *et al.*, 2003).

TABLE 6. Slump Values

Mix	Super plasticizer in % by weight of cement-silica fume				Slump value in mm			
	w/cm = 0.32	w/cm = 0.35	w/cm = 0.40	w/cm = 0.50	w/cm = 0.32	w/cm = 0.35	w/cm = 0.40	w/cm = 0.50
C	1	1	0.8	-	65	70	70	90
SF5	1.6	1.6	0.4	-	70	70	90	89
SF10	2.6	2.2	0.8	-	80	80	75	85
SF15	3.4	2.8	1.0	-	80	85	70	80

B. Compressive strength

From the test results, it has been observed that there is a general trend of increasing strength with age for all the concrete mixtures with and without admixtures. Fig 1.0 shows the variation of compressive strength between control concrete and silica fume concrete for various w/c ratios. It was found from the results shown in Fig1.0, that concrete added with SF showed in general, little improvement in compressive strength than control concrete especially at later stages. This may be attributed to non-availability of sufficient calcium hydroxide at early ages (usually up to seven days) for pozzolanic reaction to take place. From Fig 1, it was observed that maximum compressive strength was achieved at 0.32 w/c ratio. At 0.4 & 0.5 w/c ratios, it can be seen that there is an appreciable increase in compressive strength during the later stage of curing (28 & 90 days). From Fig 2.0, it is seen that, At the age of 28 days, the strength of concrete containing 5% silica fume varies from 8 % to 20 % more than that of control concrete at higher w/c ratios whereas at lower w/c ratios it was found to be less than 5 %. However, the strength increases marginally at 90 days more particularly at 0.5 w/c. Therefore longer curing period is found to be advantageous for improving the compressive strength especially at higher w/c ratios (0.4 & 0.5). Also it was observed that at 0.5 w/c ratio, the increase in compressive strength was more or less uniform and consistent throughout the test period .Among different replacement levels, SF with 5% found to be performing well for all w/c ratios expect at 0.32. Whereas addition of 10% SF yields the maximum strength at 0.32 w/c ratio. However there is no appreciable increase in compressive strength between SF5 and SF10 and hence 5% SF can be used for all practical purposes due to economic considerations. The important findings are given in Table 7 and among all w/cm ratios, the optimum percentage of SF recommended is 5% and the maximum compressive strength was obtained at 0.32 w/c .

Table 7. Important Findings

Admixture	Optimum % of admixture	Influence of	
		w/cm ratio	Curing period
SF	5% SF – for all w/c	Behaviour of SF is more or less consistent for all w/c	Longer curing period is more beneficial especially for higher w/c ratios.

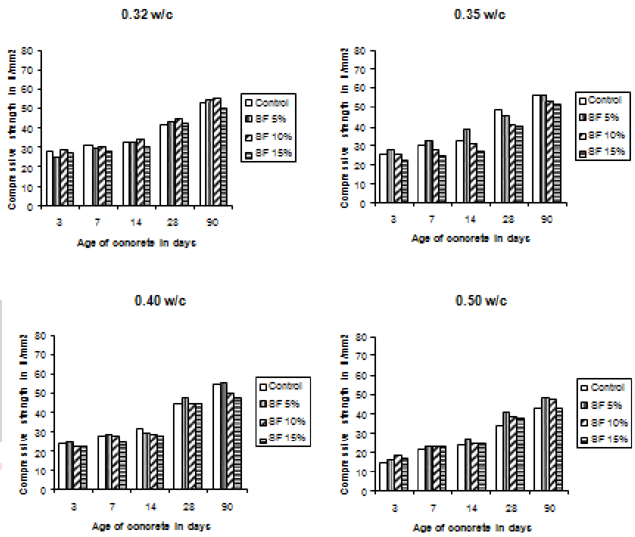

Fig.1. Compressive Strength versus SF replacement level with ages

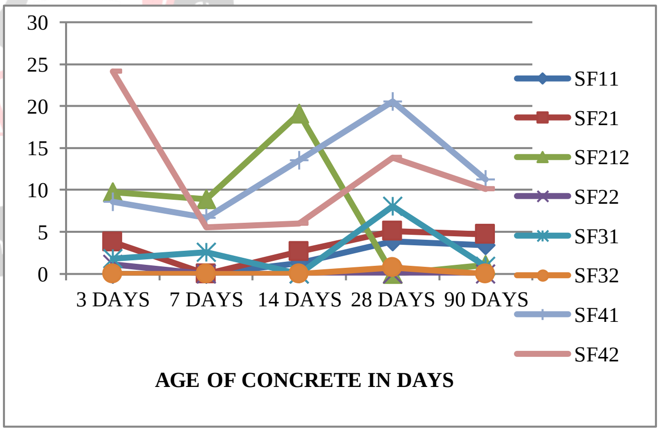

Fig2.0: Improvement of compressive strength of SF concrete compared with control specimen for different w/c ratios.

C. NON-LINEAR REGRESSION MODEL

The following quadratic equation was used to describe the behaviour of the system:

$$f_c = \beta_o + \Sigma\beta_i X_i + \Sigma\beta_{ii} X_i^2 + \Sigma\beta_{ij} X_i X_j \text{ ----------- (1)}$$

Where f_c = Predicted response, β_o = constant, X_i = Independent variables, β_i = linear coefficients, β_{ii} = Quadratic coefficients β_{ij}= Cross product coefficients.

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The multiple regression coefficients and the associated standard errors were determined by using statistical software MINITAB14. Water-to-cement ratio (w/cm) (X_1), amount of admixture (X_2), age of concrete (X_3) were chosen as predictor variables and the strength of the concrete fc as response variable. The student t- test was used to determine the significance of the regression coefficients of the parameters and the P values <0.05 indicated the significance of the model terms (table 8). In general larger the magnitude of t and smaller value of P, the more significant is the corresponding coefficient term.

A quadratic regression model was developed by using codal units from the experimental data and is shown in table 8.

Full quadratic model equation for SF concrete

$$fc = 51.274 - 3.787X_1 - 1.193X_2 + 14.344X_3 - 1.846X_1^2 - 1.946X_2^2 - 12.781X_3^2 + 1.034X_1X_2 + 0.049X_1X_3 - 0.489X_2X_3 \text{---------(2)}$$

It was observed that, the linear and quadratic effects of all the variables are found to be highly significant whereas the interaction effects between the variables w/cm and Time, w/cm and SF were considered to be insignificant in comparison to the linear and quadratic effects. Therefore these non-significant values (i.e., *X1X2*, and *X1X3*) are eliminated from model and regression was repeated for the reduced model. The contour and surface plots are shown in figures 3.0 & 4.0, curved lines in the plot visually illustrate the interactive and quadratic effects of the process variable on the response. In conventional analysis this observation is not possible. From fig 3.0 & 4.0 it is understood that, the interactive effects between w/c and SF is more significant than other interactive effects. Thus relatively lower w/c ratio and lower percentage of SF played an important role in increasing the strength. The optimum conditions of the process variables are shown in fig 5.0. It was observed that the maximum strength of 57.75 N/mm^2 was obtained when cement was replaced by 3.6% SF at 70 days of curing with 0.32 w/c. From the optimization graphs, it is understood that there is slight over prediction of strength by the SF model, When compared with experimentally observed results. However this variation is not significant to affect the experimental results.

High R^2 value indicated the validity of the model (0.9610), in which only 3.9% was left out for residuals. Therefore the model explains the variations in the predictor variables satisfactorily. Hence these model shown in Eq.(2) can be used to predict the strength of silica fume concrete within the experimental values under similar conditions.

TABLE 8 . Multiple Regression Coefficients, T and P Values for Strength of SF Concrete - Full Model

Term	Coef	SE Coef	T	P
Constant	51.247	0.886	57.860	0
w/cm	-3.787	0.400	-9.457	0
SF	-1.193	0.415	-2.887	0.005
Time	14.344	0.377	38.077	0
w/cm*w/cm	-1.846	0.639	-2.888	0.005
SF*SF	-1.946	0.591	-3.295	0.002
Time * Time	--12.781	0.863	-14.819	0
w/cm*SF	1.034	0.464	2.230	0.029
w/cm* Time	0.049	0.471	0.103	0.918
SF*Time	-0.489	0.479	-1.021	0.311

R^2 = 96.10 %, SE Coef – Standard Error Coefficient

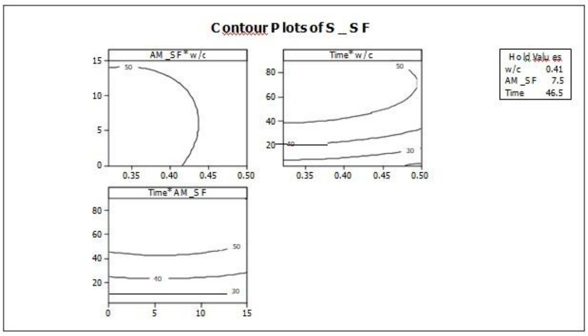

Fig 3.0: Contour plots for strength of SF concrete

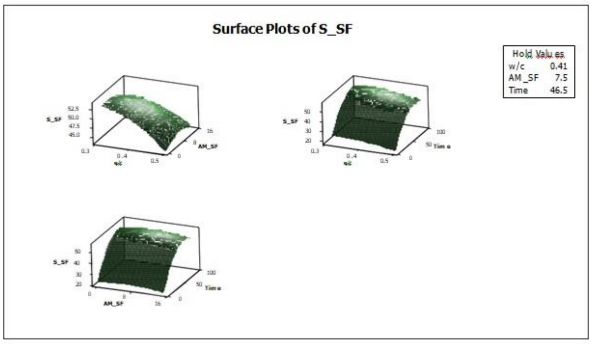

Fig 4.0 Surface plots for strength of SF Concrete

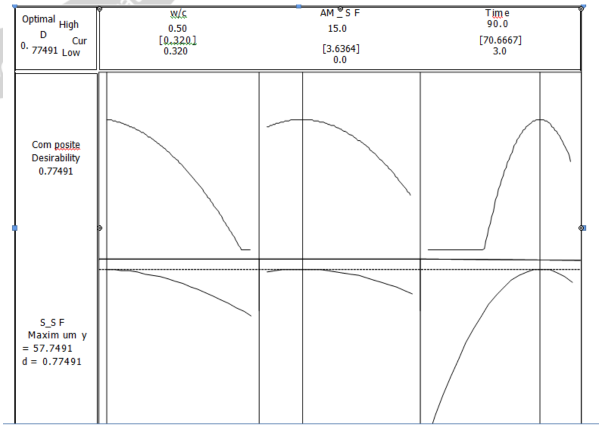

Fig 5.0 Response Optimization

D. *PH OF CONCRETE*

The pH value is very important for maintaining the passivity of steel. The results of pH of control and admixed concrete are shown in Fig.6. The pH value for control concrete varies from12.2 to 13, with slight increase as the age of the concrete increases. This is due to the fact that during hydration, more

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calcium hydroxide is liberated, which increases the pH. The pH values of SF were measured for various replacement levels and these ranges between 11.7 to 12.7 from 3 to 28 days and these values are marginally lower than that of control mix, but the reduction is insignificant. Since the reduction in pH is not significant, it is inferred that addition of SF up to 15% does not adversely affect the alkalinity of concrete.SF concrete showed slightly lesser values at 3 days than 7 days and this reduction can be attributed to the fact that since the rate of pozzolanic reaction will be higher at early ages, the absorption of calcium hydroxide by SF was more, which reduces the pH at early ages.

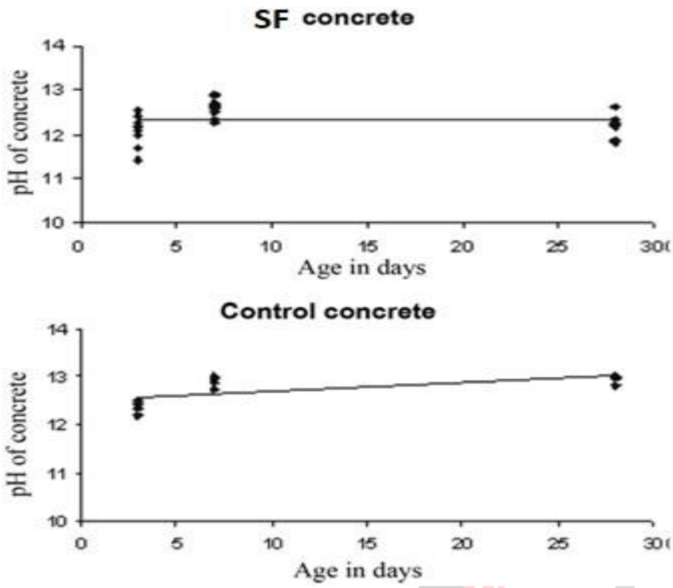

Fig. 6. pH Values of Control and SF Concrete

IV. CONCLUSIONS

The effects of SF as a mineral admixtures on the various properties of concrete such as workability, compressive strength and pH were investigated. The compressive strength was determined at various ages (3,7,14,28 & 90 days) for various w/cm ratios of 0.32, 0.35, 0.4 and 0.5. The results were compared to the same properties of a control concrete mixture. pH of each concrete mixture was measured to know the alkalinity of concrete. A Multi variate non-linear regression model was established to predict the strength of various concretes.Based on the analysis of the experimental results the following conclusions are derived from this study.

The conclusions are:

1.From the results of slump test shown in table 6, it was observed that SF concrete gives improved workability than the control mix. This is due to reason that, better lubricating effect is attributed by fineness and glassy surface of the pozzolanic material and hence better workability.It can also be observed that SF requires higher dosage of superplasticiser especially at lower w/c ratios, because its water demand is so high. The higher demand of superplasticiser can be attributed to its high chemical activity and high specific surface resulting in increased water requirement.

2.The enhancement of compressive strength by SF concrete is effective only at the later stage of concrete and in the early stages the strength increase is only marginal. The increase in compressive strength for SF concrete was more or less consistent for all water cement ratios. From the studies an optimum percentage of SF was found to be 5% for all w/cm ratios and longer curing period is found to be more beneficial at higher w/c ratios. As far as increase in strength with respect to variation in w/c ratios is concerned, it was found that a maximum increase of 8% and 19% were observed with 5% SF at0.35 and 0.4 w/c ratios respectively. Also it was observed that maximum compressive strength was obtained at 0.32 w/c ratio.

3. The strength of concrete predicted from the multiple non-linear regression model was found to be in close agreement with R2 value of 0.961. It was observed that the maximum strength of 57.75 N/mm^2 was obtained when cement was replaced by 3.6% SF at 70 days of curing with 0.32 w/c.It is a good technique for studying the influence of various process variables on response by reducing the number of experiments and therefore saving time, energy and money.

4. Addition of SF reduced the pH values, but the reduction is insignificant, since the pH values are still above 11.5, which will be helpful for maintaining the steel in a passive state itself.

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