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Estimation of Compressive Strength of Concrete by testing the Pozzolanic Reactions of Blended Cement Mortars using Bolomey's Equation

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Abstract: ***To experimentally investigate the effect of the presence of Supplementary Cementitious Materials (SCMs) in concrete strength gain by using the efficiency factors in Bolomey's equation to the cement mortar. The quaternary blended cement mortar consists of Fly ash (FA) at 0, 20 and 30%, micro silica (SF) at 0, 5 and 10% and Nano silica (NSF) at 0, 2, 3 and 6% replacement to cement. To study the compressive and flexural strength of mortars a total of 63 mortar mixes, with a cement-sand ratio of 1:2.75 were cast and tested; out of these mixes, 27 were variable w/b ratios based on consistency and remaining 36 were with fixed w/b ratio of 0.485. The mixes using SF and NSF had shown an improved performance while FA at 20% optimum indicated strength on par with the control mix. In triple blended mixes, all the combinations of NSF-SF, NSF-FA and SF-FA improved the performance of mortar. Bolomey's equation was used to find the Efficiency of SCMs in mortar and concrete mixtures. Concrete mixes with two different cement contents along with a confirmation test using another cement quantity were carried out to identify optimum proportions of quaternary blended mixtures.***

Keywords: ***Bolomey's Equation, Consistency, Initial setting time, Quaternary blended mixes, Supplementary Cementitious Materials.***

HIGHLIGHTS:

- Utilization of waste materials using Bolomey's equation while making Cement mortar and concrete making.
- Relating the efficiency of pozzolans in a mortar with concrete by using Bolomey's equation.
- Workability of Supplementary Cementitious Materials was identified by consistency, Initial setting time with reliability.

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I. INTRODUCTION

The utilization of chemical admixtures and a large quantity of OPC is one of the causes of increasing the cost of High Strength Concrete. Smith [1] defined the cementing efficiency factor 'k' of pozzolana by which the amount of cement it could replace changing the property to be investigated; typically the compressive strength (CS) is a factor related to many properties of concrete. It was initially applied to fly ash, and later many authors utilized this concept to all pozzolanic materials. Neville[2] has stated that by controlling the performance of cement mortar in concrete, a stronger concrete can be made. Therefore, several researchers carried out investigations to alter the properties of cement mortar and paste by using finely divided pozzolanic materials, which is an excellent alternative to reduce the cost, especially if they are industrial by-products or wastes. Nielsen[3] had proved that Bolomey's expression relating the strength of concrete could also be applied to hardened cement pastes when w/c > 0.15and also proposed two expressions with w/c less than and more than 0.4. Ganesh Babu and Nageswara Rao[4] proposed three efficiency factors for pozzolans in concrete after conducting tests on fly ash, micro silica and GGBS. Appa Rao[5] proved that the modified Abram's and Bolomey's equations give reasonably good predictions of the CS of mortar mixes. Tangpagasit *et al.*[6] had shown that pozzolanic reaction of fly ash mortar depends on the average size of particle and curing period. Considering Abram's law, Wong and Abdul Razak[7] recommended an approach for the evaluation of relative strength of pozzolanic material and also stated that before any mix design the 'k' value has to be re-ascertained. Erdem and KIrca[8] had stated that by mixing two pozzolanic materials can compensate for the shortcomings of the other material. Due to the rapid progress in Nanotechnology, new materials of Nano-scale with highly improved characteristics are available. Qing *et al.*[9] has stated that micro silica is a standard pozzolana for use in High strength concrete (HSC), but based on experimentation the pozzolanic activity of NSF is higher than SF hence a small amount of NSF can effectively digest Calcium Hydroxide (CH) at early ages when used along with SF and FA.

Shih *et al.*[10] utilized small dosages of NSF in mortar making and found that the strength of mortar increased up to 14 days of curing later, the increment is decreasing. Ltifi *et al.*[11] concluded that due to the presence of NSF, the microstructure had become dense, and hence, mechanical properties had improved. Hou *et al*.[12] and Pacheco-Torgal *et al.*[13] have stated that there is a significant change in the mechanical and microstructural performance in all of the cementitious composites by adding nanoparticles. Heikal *et al.*[14] studied the ternary mixtures of NSF and GGBFS combination on standard consistency, setting times and CS at different ages of 3 to 90 days and concluded that water demand increased and setting times decreased due to the presence of NSF. The CS and flexural strengths observed were more than control concrete. The investigations of Mukharjee and Barai[15] have indicated that the levels of interaction of NSF on w/c ratio were not significant on CS, but individually they are causing the dominant effect on CS. Li *et al.*[16] has stated NSF is more efficient in improving the mechanical properties of mortars as compared to other pozzolans. The combination of SF and NSF gives an effective combination of strength improvement, and its combination is more synergetic on densifying the microstructure of the hardened paste. They concluded that SP demand for 2% NSF is comparable to that of 10% of SF and also NSF alone should not be used for maximum performance. Determination of the ideal mixtures of materials depends upon several factors and performance constraints. The properties of the final product can be simplified with the utilization of efficiency factor design, and the objective of this investigation is to obtain optimum proportions suitable for the quaternary mixture of paste and mortar. The study also focuses on the generalization of Bolomey's equation and identifying the efficiency constants for pozzolans in quaternary blended mortars which can be utilized for the making of concrete with a minimum number of trials for desired strength.

II. RESEARCH SIGNIFICANCE

There is a need for minimizing the wastage while designing the concrete mixes and also reduce its volume as a large quantity of natural aggregates is being used for the identification of appropriate optimum combinations. If research can show that mortar can be used for evaluating some basic parameters along with pozzolans, the economic benefits could be realized. This research programme evaluated the consistency of cement paste along with pozzolans for water demand, setting times, the CS and flexural strength of mortar mixes. Results of this work indicate that the specimens of both blended cement mortars and concrete can effectively show the pozzolanic reactions while achieving the strength. A satisfactory correlation between the pozzolanic action of the ingredients in mortars and concrete was observed, which reduces the volume of material in concrete to be cast for proper mix design. Based on the results of the investigation, modified Bolomey's equation can be used after identifying the efficiency factors of pozzolans in mortars and concrete with minimal experiments.

III. MATERIALS AND METHODOLOGY

A. *Materials Used*

- *Cement:* Commercially available OPC 53-grade cement conforming to IS 12269-2013[17]] was used for preparing paste and mortar whose properties were tabulated in Table 1. The available Potable water was used for casting.
- *Nano-Silica* is in a colloidal form and stabilized, and it is convenient to use due to easy dispersion, according to Quercia *et al.*[18]. For the experimentation, the commercially available product was used.
- *Fly Ash* particles are typically spherical and finer than OPC. Raw Fly-Ash (as brought from the source) cannot be used as it requires processing to work efficiently in concrete. Therefore a processed Fly-Ash named 'Pozzocrete 60'is used. It is manufactured by DIRK India Pvt. Ltd., Nashik and satisfies the specifications as per IS: 3812(Part-1):2013[19].
- *Micro Silica* The material is procured from M/s ELKEM Mumbai.
- *Fine Aggregate* The study is of comparative hence Local River sand of 4.75 down as per I.S.Seive and held on 150micron was used for preparing the mortars and concrete. The Grain size distribution of sand shows that it is close to the zone-III of IS:383-2011[20].
- *The coarse aggregate* is passing through 20mm and is angular material in shape.
- *Superplasticizer* is obtained from M/s Fosroc of Sulphonated Naphthalene Polymers conforming to ASTM C494 as Type A and Type F.

IV. PREPARATION OF SPECIMENS AND TESTS CONDUCTED

The preparation of samples was done in three stages. In the first phase, the consistency and setting time tests on paste were performed. In the second stage with the w/b at a calculated value based on Normal consistency test was used. In phase III, a constant value of 0.485 was used, and a small percentage of Superplasticizer was added for maintaining the flow.

Vicat apparatus was used for determining the Consistency and setting times of quaternary blended cement pastes as per IS 5513:1996[21]. The mixing was done mechanically by employing mixing apparatus as specified in Planetary Mixer conforming to IS 10890:1994[22]. The mortar flow was checked for a 110± 5 at 25 drops IS 5512-1983[23]. Freshly prepared cement mortars were moulded in 50mm x 50mm x 50 mm cube moulds, and after one day, the hardened mortar samples were kept in curing tank. The specimens were tested under 3000 kN compression testing machine at 0.01 MPa/sec as per IS 516-1959[24].

Two numbers of 40mm x 40mm x 160mm Prisms were cast and tested under three-point loading using a flexural instrument at a rate of 1.25mm/min loading rate at 56 days of curing as per ASTM C348-14[25].

The parametric study

includes flow tests for the determination of workability, mortar cube CS tests after 7 and 28 days of curing, flexural strength tests and also CS tests on broken pieces of prisms obtained from flexure test.

V. RESULTS AND DISCUSSION

A. *Standard Consistency and Setting Times of Cement*

The nomenclatures of mixes are defined in Table 2 and Referring to Fig.1 and based on regression analysis; it is observed that the variables are independently affecting the Consistency of cement paste. The presence of SF and NSF in the paste is increasing the water demand up to 50% and decreasing the setting times due to their fineness of particle size. The effect of FA is negligible on Consistency and IST as the p-value is above 0.05. The adj.R^2 value of consistency and setting time is at 79%.

The regression equation for Consistency (CON) is

CON=29.2+1.9 x NSF% +0.73 x SF% (1)

The regression equation for Initial Setting Time (IST) is

IST = 69.68-6.7 X NSF%-1.36 X SF% (2)

After collecting the data of water requirement from the Consistency test on cement paste, cement mortar cubes were cast with 1:2.75 binders to sand ratio with variable water quantity. A total of 27 mixes were cast, and the test is conducted according to ASTM C 109/C109M (2012)[26].

B. *Influence of binary blending on mortar mix with a variable w/b ratio.*

Figure 2 shows a slight reduction or no change in water demand when FA is used in binary mixes, which are as observed by Mora *et al.*[27] while the water demand was increased for SF and NSF. The strength of 5% SF mortar is higher and also has more water demand than the control mix. The strength of the control mix is almost reached for the blend with 3% NSF though there was a higher water demand by 27%. It is understood that higher strengths than the control mix can be obtained with binary blends with NSF and SF by reducing the w/b ratio. However, Superplasticizer has to be used to meet the workability requirements. Based on the regression analysis the 7D and 28D cured mortar cubes have Adj R^2 is 95% and 85% the p-value is nearer to 0.05 for NSF and FA, and other variables are not much effective on the 7D and 28D CS.

C. *Influence of triple blending on mortar CS and water demand.*

Figure 3 shows the influence of triple blending on mortar CS. When the triple blending of mortar is done by the FA and SF for the higher w/b ratios, the CS is decreasing up to a maximum of 52%. The blending of NSF and FA is also showing the same result, but a little gain in strength is observed when compared to the fly ash mortar cube. This gain in strength may be attributed to the presence of NSF. Though there is a reduction in strength of ternary mixes with NSF and SF compared to control due to increased w/b ratio, there is an improvement in strength gain compared to ternary mixes using fly ash. The regression analysis with Adj. R^2 equal to 82% also shows that FA and NSF are significant in contributing strength to the mortar cubes.

D. *Influence of quaternary blending on mortar cubes*

Figure 4 shows the variation in the strength of mortar cubes with NSF, SF and FA, which has a positive effect, but there is a higher demand for water for workability. This had resulted in a reduction in the strength, which satisfies the Abram's Law. Table 3 displays the ANOVA results for the variables used in the model, which had a high R^2 and adj. R^2 values. This indicates a high impact on the experimental results. In addition, the results of the F-test had higher values than the F critical, which point towards their importance in making the mortar strong. Therefore, these variables are significant and had a predictive capacity.

VI. INFLUENCE OF POZZOLANS ON MORTAR CUBE CS WITH FIXED W/B OF 0.485.

It is observed that water addition is affecting the strengths considerably in the earlier phase of work and hence to know the reactivity of pozzolans, the w/b was constant at 0.485. Figure 5 show that the blending of cement with pozzolans has a positive effect with increased CS at different ages.

The CS was assessed by using the Modified Bolomey's Equation. In this equation, the additive constant is taken as 0.5 based on recommendations of Rajamane[28], which is in good correlation with the Indian Cement brands while designing the mixtures. The Cementing Efficiency Factor is defined as the ratio of the cementing efficiency of FA, SF and NSF to the cementing efficiency of the cement to which these admixtures were added.

Bolomey's modified Equation

$$\sigma c = A \times \left[\frac{(C + K1 * nS + K2 * SF + K3 * FA)}{W} - 0.5 \right] \quad (3)$$

Using MATLAB, the constants of the equation were calculated and given in Table 4. The equation under consideration is following the trends as specified by the earlier researchers. The efficiency of Nano silica is higher at 7days, but its value is decreasing with age, and the efficiencies of FA and SF are improving with age which is also confirming the test results as reported by Zhang and Islam[29].

A. *Analysis of Mortar Cube Strengths Using Minitab-16.*

Minitab is one of the powerful statistical tools for regression analysis to find the effects of the variables on the main parameters of strength. The regression equations for 7 and 28 days were obtained and found that when NSF and SF were combined with FA, they are losing their significance in enhancing the CS of mortar cubes (p-value less than 0.05). The only parameter affecting the strength is FA. The regression equations for 7, 28 and 56 days CS is given below.

7D CS= 26.8+0.2 x NSF% - 0.3 x SF% - 0.29 x FA% (4)

28D CS= 40.87 – 0.075 x NSF% - 0.31 x SF% - 0.43 x FA% (5)

56D CS= 44.75 – 0.49 x NSF% - 0.296 x SF% - 0.31 x FA% (6)

The Pareto diagram indicates FA has a significant effect on the 7, 28 CS of mortar cube strength. From the Figs. 6, 7 and 8, it is observed that 3% NSF is more effective in improving the strength of mortar and 5% SF and 20% FA combination along with NSF can give an average strength of mortar (mean value as per the graphs). In addition to this 10%SF and 20%, FA combination along with NSF is also offering an approximately same result at 56 days of curing. Hence a combination of 20% FA, 10% SF and 2% NSF provides an economical mix with more saving on cement.

VII. CALCULATION OF BOLOMEY'S CONSTANTS IN CONCRETE

Neville and Aitcin[30] observed that for making a high-performance concrete, the binder content could be up to 600kg/m^3 with a combination of Portland cement, FA, SF and NSF. To study the pozzolana effect on concrete with efficiency factors, two grades of concrete with cement at 500 and 650kg/m^3 with fixed water binder ratio were cast and tested. Substituting the values of these quantities in Bolomey's equation, the constants were calculated and given in Table 5.

To validate the efficiency factors, a concrete containing 450 kg/m^3 of cement with fixed 10%SF and 20%FA and 2-3% of Nano silica was tested for CS. The results are compared by a statistical term of Mean Absolute Percentage Error (MAPE).

$$MAPE = \sum_{i=1}^{n} \left| \frac{observed\ strength - predicted\ strength}{observed\ strength} \times 100 \right| \% \quad (7)$$

The observed values and predicted CS was within 10% error. The trend in the strength gain of concrete with pozzolans is similar to blended mortars, and the variation in the efficiency factors of concrete is the same as those of mortar. Hence by testing of cement mortars, an efficient concrete with pozzolanic materials can be obtained.

VIII. RESULTS OF FLEXURAL STRENGTH

Figure 10 illustrates the flexural strength variation, and when the results of compression and flexure were analysed, the following relation is obtained:

$f_k = 0.91 \times \sqrt{f_{ck}}$ or equivalent to $f_k = 0.15 \times f_{ck}$ (where f_{ck}=56 day CS of mortar) The values obtained by this relation are lower than the results obtained by Haach *et al.*[31]

A. *Influence of pozzolans on flexural strength of prisms.*

The flexural strength is increasing up to 20% FA, and with 30% FA, the strength is reduced to 8% (Fig. 10). The trend is the same as that reported by Siddique[32]. Addition of 5% SF improved the strength by over 36% than the control mix and the raise in strength is only 10% when 10% SF was used which is similar as reported by Appa Rao[33]. The presence of NSF at all levels is showing an improved performance up to a maximum of 76% with 2%NSF. The blending of SF and FA at 10% and 20% respectively is showing a maximum increase in the strength by 34% compared to the control mix. The strength of mortar with FA and NSF is more than that of control mix, reaching a maximum of 68% with 3% NSF and 20% FA. The ternary blend of SF and NSF is also reaching a maximum value of 60% with 3%NSF and 5% SF. The quaternary blending is giving a positive trend and improving up to a maximum of 48% with 2%NSF, 5%SF and 20% of FA and the results are stabilized at 10%SF with a reduction in strength on further increase in dosages of NSF. In all the above tests, the prisms failed suddenly indicating brittle failure.

$$\text{Flexural strength (MPa)} = 5.90 - 0.156 \times NSF\% - 0.047 \times SF\% - 0.03 \times FA\% \quad (8)$$

IX. OPTIMUM MIXES

On the whole, referring to the figures 6, 7 and 8 of main effect plots, the mixes having 20% fly ash, 5% SF and 3% NSF as a partial replacement of cement are giving optimum strengths. But to get optimum utilization of Cement in concrete at higher ages, i.e. at 56 days of curing and referring to Fig. 9, a combination of 20% fly ash, 10% SF and 2% NSF as a replacement to cement may be considered.

X. CONCLUSIONS

Conclusions drawn from the experimental investigation are

- The addition of Silica Fume and Nano silica decreased the consistency of cement paste, increasing water demand while a marginal increase in the consistency was observed with the addition of Fly ash.
- The setting times were decreased by the addition of Silica Fume and Nano silica, which indicates the necessity of retarder to maintain the plasticity of concrete.
- Equations were proposed for estimating consistency and initial setting time with an R^2 value of 78%.
- The 28-day CS of triple blended mortars with fixed w/c ratio was reduced marginally.
- The optimum percentages of pozzolans in quaternary blended mortars / concretes are obtained as 20% fly ash, 5% SF and 3% NSF considering the CS at 28 days and optimum percentages are 20% fly ash, 10% SF and 2% NSF corresponding to the CS at 56 days.
- The flexural strength is increased to the tune of 76% when 2 to 3% cement is replaced by NSF
- The flexural strength of mortar prisms is found to be optimum in quarternary mixes when cement is replaced by FA, SF and NSF by 20%, 5% and 2 or 3% respectively. The maximum increase in strength is to the tune of 50%.
- The proposed equation expressing the flexural strength in terms of CS is predicting the flexural strength with more than 90% accuracy.
- The presence of fly ash in the mix improved the workability, while the presence of SF or NSF enhanced the strength of both concrete and mortar.
- By using the efficiency factors, Modified Bolomey's equation predicts the CS of concrete reasonably.

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Table 1: Physical properties and chemical composition of materials

		OPC	Fly ash (FA)*	Micro silica (SF)*	Nano silica (NSF)*
Chemical composition (%)	CaO	63.4	3.9	0.2	-
	SiO_2	20.1	46.3	95.9	>99.8*
	Al_2O_3	4.1	28.5	0.3	-
	Fe_2O_3	3.3	18.5	0.3	-
	MgO	3.6	1.8	0.4	-
	Na_2O	0.2	0.2	0.05	-
	K_2O	0.4	0.6	0.6	-
	SO_3	2.1	0.2	0.2	-
	LOI	2.4	2.3	1.5	-
Mineral phases (%)	C_3S	66.8	-	-	-
	C_2S	7.3			
	C_3A	5.3			
	C_4AF	10.1			
Physical properties (%)	Blain fineness (m^2/kg)	308			
	BET surface area (m^2/g)	-	-	21.3	200.1
	Average primary particle size	28.2 µm	27.3 µm	150nm	12nm
	Specific gravity	3.15	2.5	2.2	2.2

*Information provided by the supplier.

Table 2:Nomenclature of the mortar mixes used for setting time and consistency and other mechanical tests.

Mixes with Variable w/b	Mixes with fixed w/b	mix	cement	NSF	SF	FA
A1	**B1**	(0,0,0)	100	0	0	0
A2	**B2**	(0,0,20)	80	0	0	20
A3	**B3**	(0,0,30)	70	0	0	30

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Mixes with Variable w/b	Mixes with fixed w/b	mix	cement	NSF	SF	FA
A4	B4	(0,5,0)	95	0	5	0
A5	B5	(0,5,20)	75	0	5	20
A6	B6	(0,5,30)	65	0	5	30
A7	B7	(0,10,0)	90	0	10	0
A8	B8	(0,10,20)	70	0	10	20
A9	B9	(0,10,30)	60	0	10	30
NC	B10	(2,0,0)	98	2	0	0
NC	B11	(2,0,20)	78	2	0	20
NC	B12	(2,0,30)	68	2	0	30
NC	B13	(2,5,0)	93	2	5	0
NC	B14	(2,5,20)	73	2	5	20
NC	B15	(2,5,30)	63	2	5	30
NC	B16	(2,10,0)	88	2	10	0
NC	B17	(2,10,20)	68	2	10	20
NC	B18	(2,10,30)	58	2	10	30
A10	B19	(3,0,0)	97	3	0	0
A11	B20	(3,0,20)	77	3	0	20
A12	B21	(3,0,30)	67	3	0	30
A13	B22	(3,5,0)	92	3	5	0
A14	B23	(3,5,20)	72	3	5	20
A15	B24	(3,5,30)	62	3	5	30
A16	B25	(3,10,0)	87	3	10	0
A17	B26	(3,10,20)	67	3	10	20
A18	B27	(3,10,30)	57	3	10	30
A19	B28	(6,0,0)	94	6	0	0
A20	B29	(6,0,20)	74	6	0	20
A21	B30	(6,0,30)	64	6	0	30
A22	B31	(6,5,0)	89	6	5	0
A23	B32	(6,5,20)	69	6	5	20
A24	B33	(6,5,30)	59	6	5	30
A25	B34	(6,10,0)	84	6	10	0
A26	B35	(6,10,20)	64	6	10	20
A27	B36	(6,10,30)	54	6	10	30

*NC: Not Prepared

Table 3: ANOVA results for 7D CS of mortars with variable w/b ratio.

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	226.8705	56.71762	16.3009	0.000651
Residual	8	27.83533	3.479417		
Total	12	254.7058			
ANOVA results for 28D CS strength of mortars with variable w/b ratio					

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	238.1078	59.52696	2.949534	0.09021
Residual	8	161.4546	20.18182		
Total	12	399.5624			

Table 4. Modified Bolomey's equation constants

Constants		**Coefficients obtained at different ages**		
		7D	**28D**	**56D**
A	A	15.69	25.80	28.65
nS	K1	1.92	0.62	0.17
SF	K2	0.25	0.64	0.50
FA	K3	0.14	0.16	0.47

Table 5: Efficiency factors of pozzolans in concrete based on Bolomey's Equation.

CONSTANTS		**Coefficients 28D**
A	A	25.457
NSF	K1	1.328
SF	K2	0.748
FA	K3	0.340

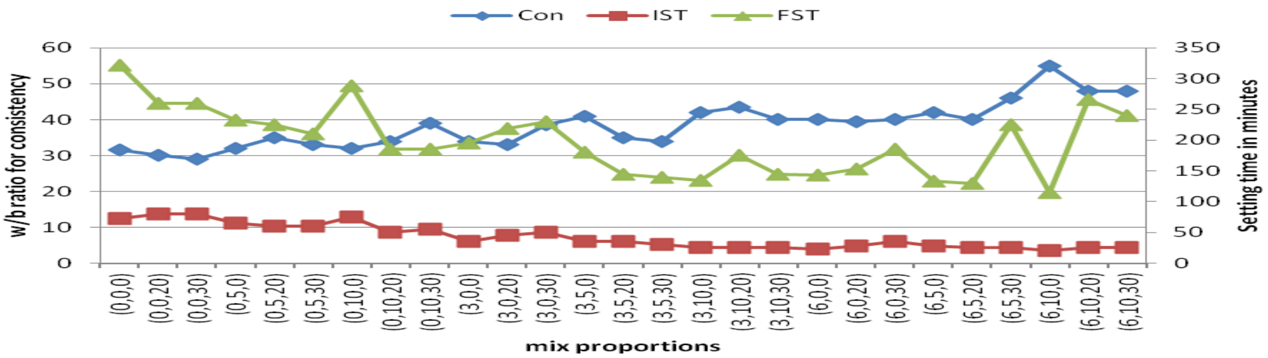

Fig. 1:Variation of consistency and setting times in different mixes

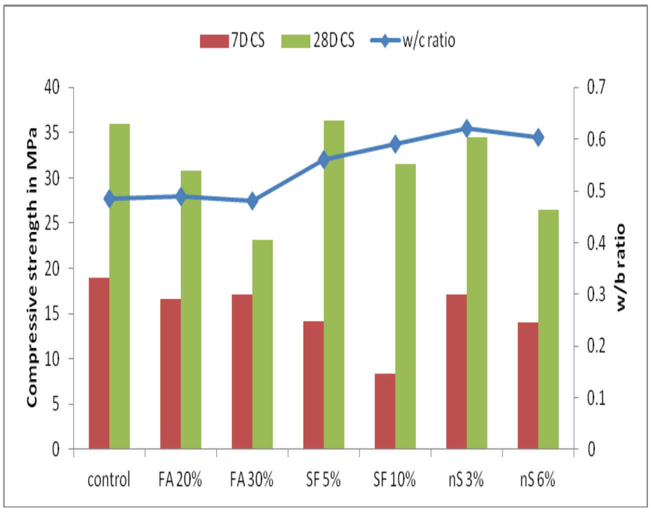

Fig. 1. The CS of binary mortar mixes with variable w/b ratio

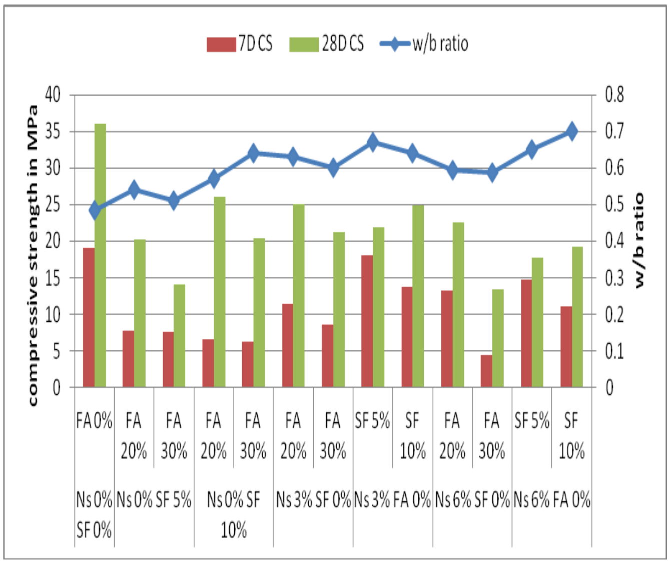

Fig. 2.The CS of ternary blended mortar with variable w/b ratio.

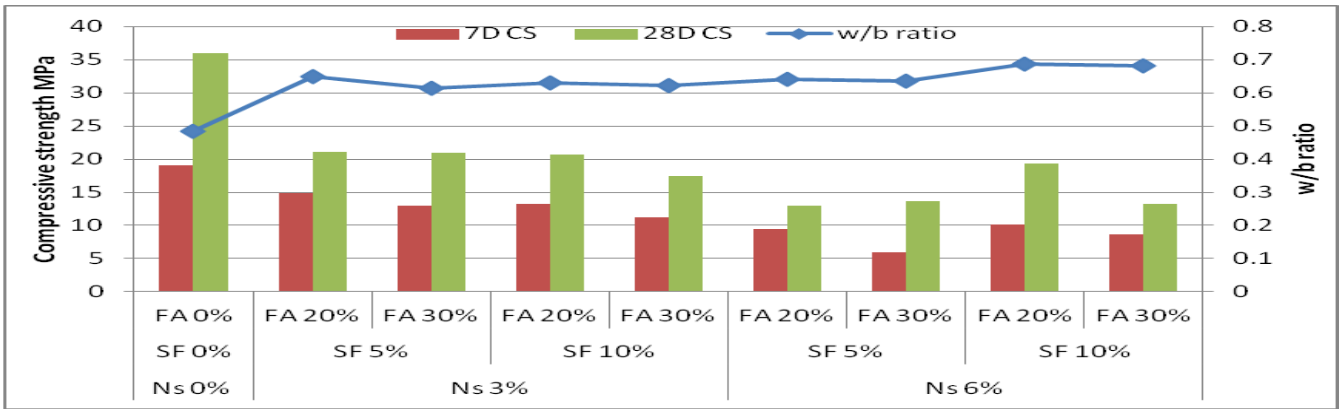

Fig. 3. Compressive strength of quaternary blended mortar cubes using Nano silica.

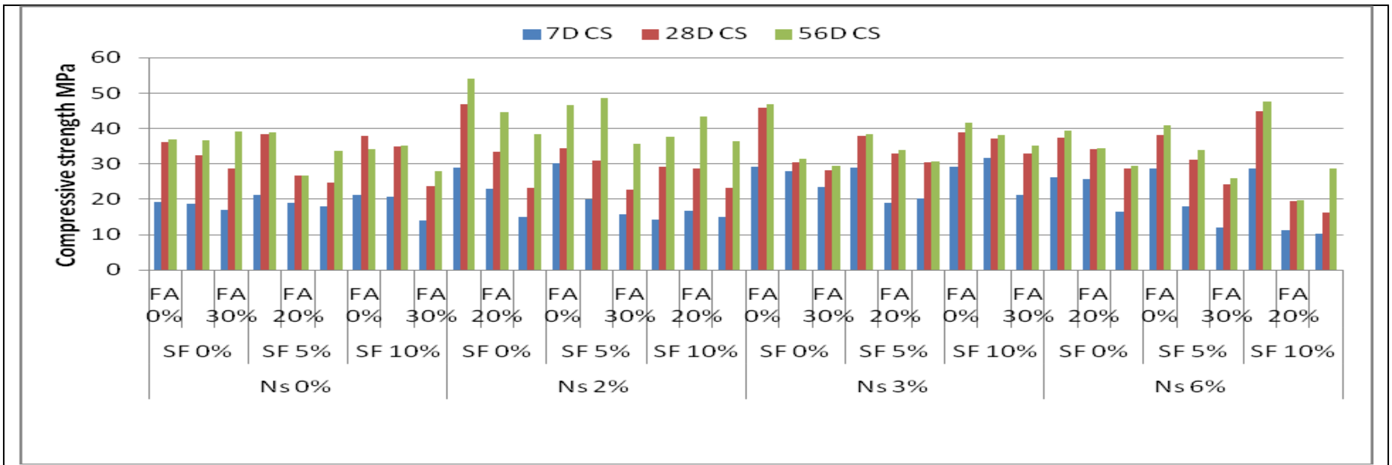

Fig. 4.The CS of cement mortar with fixed w/b ratio at 0.485

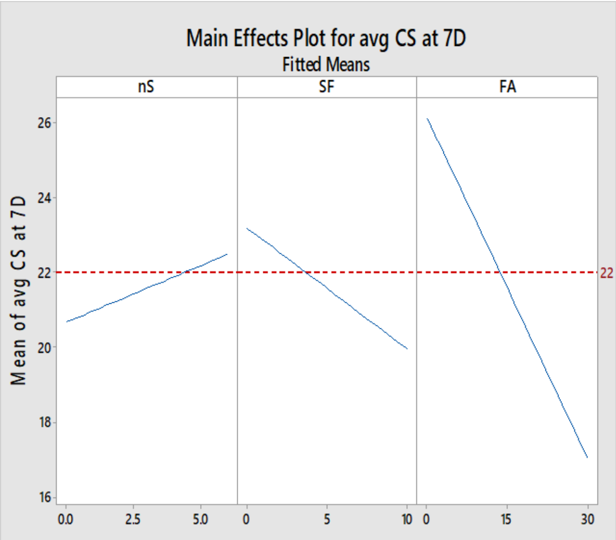

Fig. 6: Main effects plot for 7 Days compressive strength

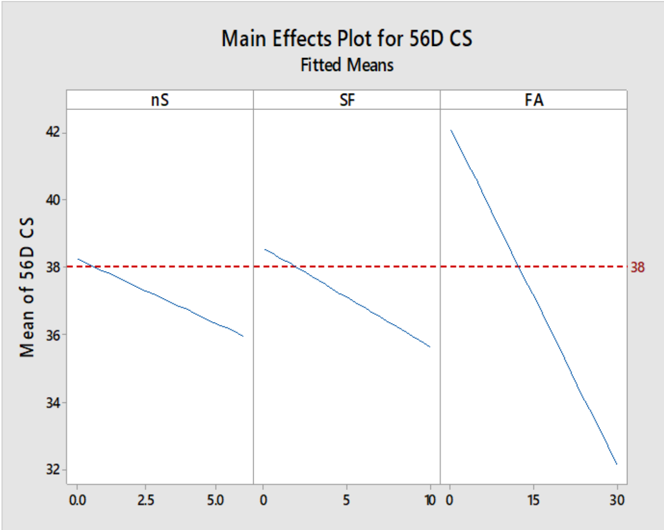

Fig. 6: Main effects plot for 56Days compressive strength

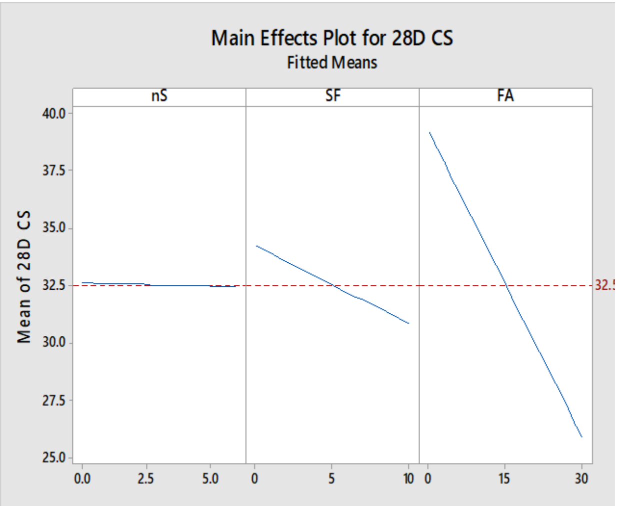

Fig. 5: Main effects plot for 28Days compressive strength

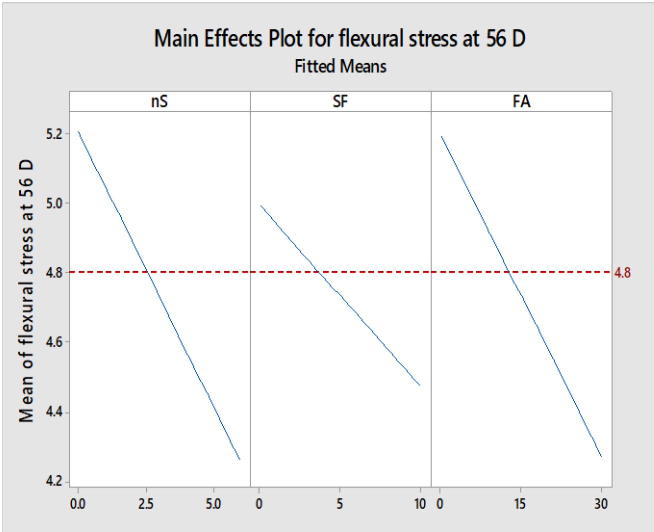

Fig. 9: Main effects plot for 56Days flexural strength

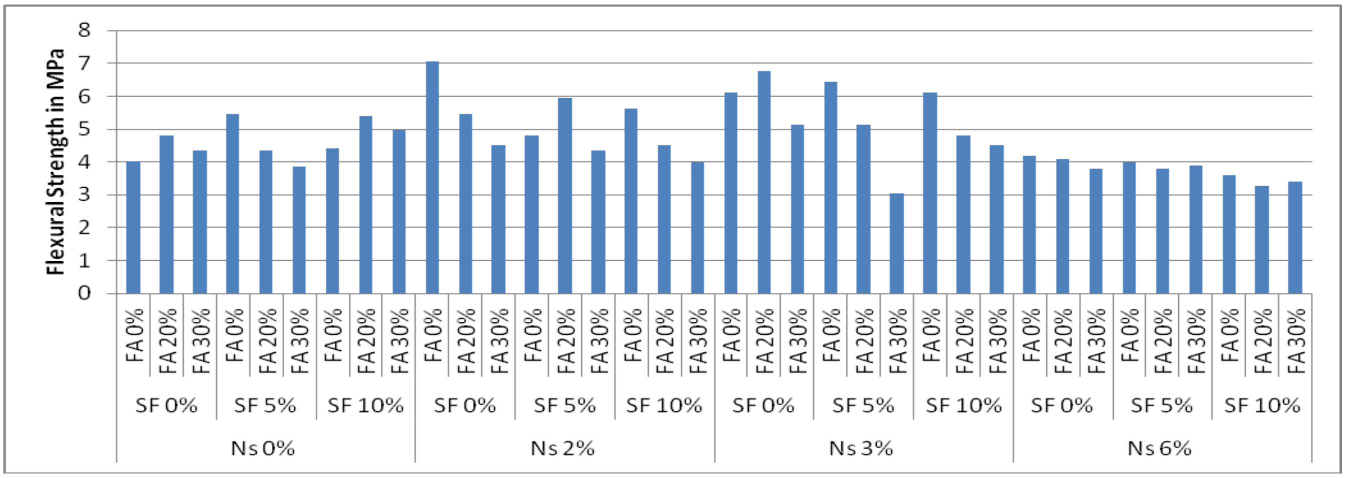

Fig. 7: Flexural strength of cement mortar beams