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Effect of Relative Levels of Mineral Admixtures on Strength of Concrete with Ternary Cement Blend

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Abstract: In the present scenario to fulfill the demands of sustainable construction, concrete made with multi-blended cement system of OPC and different mineral admixtures, is the judicious choice for the construction industry. Silica fume (SF) and fly ash (FA) are the most commonly used mineral admixtures in ternary blend cement systems. Synergy between the contributions of both on the mechanical properties of the concrete is an important factor. This study reports the effect of replacement of OPC by fly ash (20, 30, 40 and 50 % replacement of OPC) and/or silica fume (7 and 10 %) on the mechanical properties of concrete like compressive strength and split tensile strength, with three different w/b ratio of 0.3, 0.4 and 0.45. The results indicate that, as the total replacement level of OPC in concrete using ternary blend of OPC + FA + SF increases, the strength with respect to control mix increases up to certain replacement level and thereafter decreases. If the cement content of control mixes at each w/b ratio is kept constant, then as w/b ratio decreases, higher percentage of OPC can be replaced with FA + SF to get 28 days strength comparable to the control mix. A new method was proposed to find the efficiency factor of SF and FA individually in ternary blend cement system, based on principle of modified Bolomey's equation for predicting compressive strength of concrete using binary blend cement system. Efficiency factor for SF and FA were always higher in ternary blend cement system than their respective binary blend cement system. Split tensile strength of concrete using binary and ternary cement system were higher than OPC for a given compressive strength level.

Keywords: silica fume, fly ash, binary blend, ternary blend, synergic effect, efficiency factor.

1. Introduction

The scarcity of natural raw materials, depleting energy resources, problems of disposal of waste materials and global warming due to emissions of green house gases are the long-term results of rapid industrialization. Every industry tries its best to combat and minimizes these global problems. In concrete constructions, the primary route is to reduce the content of ordinary Portland cement (OPC) in concrete. The inclusion of mineral admixtures like fly ash, silica fume, granulated blast furnace slag, rice-husk ash, metakaolin, etc. as partial replacement of OPC helps in this effort.

For replacing high volume of OPC from concrete ternary blend cement system is used where OPC is replaced by two different mineral admixtures—one slow reactive mineral admixture like fly ash, blast furnace slag, etc. and other highly reactive mineral admixture like silica fume, metakaolin, etc. Fly ash and silica fume are the most commonly used two mineral admixtures. When OPC is replaced with fly ash the rate of strength gain of concrete is slower at early age. This limits its use in concrete where early strength is desirable. To overcome this problem, ternary blend of OPC, fly ash and silica fume is used. Addition of silica fume increases early strength of concrete by formation of secondary C–S–H gel at early stages due to fast pozzolanic reaction. The synergic effect of these materials in ternary blend cement system enhances mechanical properties as well as makes the resultant concrete durable (Mullick 2007; Kumar and Kaushik 2003; Radlinski and Olek 2012; Isaia et al. 2003). Ternary blend of SF and FA reduces the requirement of dose of superplasticizer for the same workability with respect to OPC concrete and concrete using binary blend of silica fume (Mullick 2007; Goyal et al. 2008) and hence reduces cost.

In India, problem of fly ash disposal is going to be critical, due to expansion of number and capacity of thermal power plants to meet the increasing demand of electricity. Considerable researches (Radlinski and Olek 2012; Isaia et al. 2003; Goyal et al. 2008; Hariharan et al. 2011; Thomas et al. 1999; Bouzoubaâ et al. 2002) have been carried out to investigate the effect of replacement of 20 to 30 % of OPC with FA and SF but higher replacement level of OPC in ternary blend cement system is still needed to investigate intensively. The addition of silica fume with fly ash was

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found to increase the compressive strength of concrete at early age and improve chloride ion permeability, when compared to concrete made with fly ash alone (Mullick 2007; Hariharan et al. 2011; Thomas et al. 1999). It has been found that there was no significant improvement in concrete containing 8 % SF and 40 % FA in the range of w/b ratio of 0.34–0.4 but it was advantageous for superplasticizer dosage, plastic shrinkage, drying shrinkage and chloride ion permeability (Bouzoubaâ et al. 2002; A.and Malhotra 1998). For concrete using binary blend of OPC + SF and for a ternary combination of OPC + FA + SF that has lesser amount of fly ash in it, 7 days of initial water curing was found to be necessary and sufficient to explore the pozzolanic activity but for mixes having larger percentage of fly ash, a long initial moist curing period was recommended (Goyal et al. 2008).

The tensile strength of concrete is more significant in the design of highway and airfield pavements, concrete dams, etc. where failure occurs due to cracking of concrete as stresses exceed the tensile strength of concrete. The tensile strength of traditional concrete were investigated vastly but more investigations are required to study the effect of using different mineral admixtures in blended concrete on tensile strength, especially of concrete using ternary blend cement system (Neville 2000; Selim 2008).

In this study effect of replacement level of OPC by FA in concrete using binary blend cement system and by FA + SF in concrete using ternary blend cement system on compressive strength and split tensile strength at different w/b ratio was investigated. Based on Bolomey's equation, a mathematical model is presented to evaluate the efficiency factor for SF and FA in concrete using ternary blend of FA + SF. The results are postulated to reflect the synergy between the two mineral admixtures. The relationship between split tensile strength and compressive strength was established by regression analysis and compared to the other empirical relationships.

2. Materials Used

2.1 Binders

OPC 53 grade conforming to IS:12269 (IS 1987) was used. Low calcium fly ash was collected locally from Chabbra Thermal Power Plant, Motipura Chowki. Densified Silica fume, Grade 920D, conforming to ASTM C 1240 and IS: 15388 (IS 2003) was obtained from Elkem (India), Mumbai. The chemical properties of cement, fly ash and silica fume are given in Table 1.

2.2 Aggregates

Locally available crushed aggregate of maximum size 20 mm were used. River sand conforming to zone III of IS: 383 (IS 1970) was used.

2.3 Superplasticizer

PCE based superplasiticizer Glenium 141 Suretec from BASF chemicals was used for current study. It is a light brown colored liquid complying with requirements of IS 9103–1999 (IS 1999) and ASTM–C494 Type G. The specific gravity of superplasticiser was 1.07 and solid content was not less than 25 percent by mass.

3. Mix Proportions

To study the effect of relative increase of fly ash and silica fume, three w/b ratios were selected 0.3, 0.4 and 0.45. This

Table 1 Physical and chemical properties of OPC, fly ash and silica fume.

Description	OPC	Fly ash	Silica Fume
Physical properties			
Specific gravity	3.14	2.2	2.2
Blaine's fineness, m^2/kg	288	–	–
Percentage retained on 45µ sieve	–	17.5	8
Chemical properties			
Calcium oxide, CaO, %	61.87	3.36	3.94
Silicon dioxide, SiO_2, %	23.14	61.72	86.67
Aluminum oxide, Al_2O_3, %	5.84	24.12	2.14
Ferric oxide, Fe_2O_3, %	4.16	5.11	3.31
Sulfur trioxide, SO_3, %	1.76	0.30	0.58
Magnesium oxide, MgO, %	1.33	0.40	0.61
Potassium oxide, K_2O, %	0.58	–	–
Sodium oxide, Na_2O, %	0.19	–	–
Loss on ignition, %	1.32	1.49	1.94

will cover the range of strength from high to medium. The total quantity of binder was kept constant i.e. 450 kg/m^3 for all w/b ratios. Control mix, two mixes using binary blend of OPC + SF (7 and 10 % replacement by weight), four mixes using binary blend of OPC + FA (20, 30, 40 and 50 % by weight) and eight mixes using ternary blend of OPC + FA + SF (total OPC replacement of 20, 30, 40 and 50 % by weight) were adopted for each w/b ratio and in total 45 mixes were cast, whose description are given in Table 2.

Keeping the mass of coarse aggregate constant for each w/b ratio, mass of fine aggregate was adjusted for increase in volume of concrete due to inclusion of SF and FA. Details of the control mixes with w/b ratio of 0.3, 0.4 and 0.45 were given in Table 3. OPC content was kept constant for each control mix, so that same quantity of $Ca(OH)_2$ is available for reaction with mineral admixtures for all w/b ratios tested. Superplasticizer doses were adjusted for each mix to result in slump of 100 ± 20 mm. Compressive strength was tested on cube specimens of 100 mm size and split tensile test was conducted on cylindrical specimens of 100 mm diameter and 200 mm height according to IS:5816 (IS 1999).

OPC, FA, SF, coarse aggregate and fine aggregate were mixed dry for 60s. in a pan mixer. Then 75 % of water was added and again mixed for 60s. Required dose of superplasticizer was added to the balance 25 % water. This water was added at the end and the concrete mixed for another 30s. Concrete was poured into the moulds and compacted on vibration table. Specimens were cast in triplicate for each test and demoulded after 24 h of casting. They were cured under water till the day of testing. Compressive strength was measured at the ages of 7, 28 and 56 days. Split tensile strength was measured at the ages of 7 and 28 days.

4. Results and Discussions

4.1 Superplasticizer Dosage

The superplasticizer dosage required for obtaining 100 ± 20 mm slump for all control mixes, binary blend cement mixes and ternary blend cement mixes for different w/b ratio of 0.3, 0.4 and 0.45 are given in Table 4.

From the results, it is clear that SP dosages were higher in concrete using binary blend of OPC + SF with respect to

Table 2 Description of different mixes used.

	Total binder replacement %	Mix ID at w/b = 0.3	Mix ID at w/b = 0.4	Mix ID at w/b = 0.45	OPC (%)	FA (%)	SF (%)
Control	0	M1	M2	M3	100	0	0
Binary blend Cement mixes	20	M1F20	M2F20	M3F20	80	20	0
	30	M1F30	M2F30	M3F30	70	30	0
	40	M1F40	M2F40	M3F40	60	40	0
	50	M1F50	M2F50	M3F50	50	50	0
	07	M1S7	M2S7	M3S7	93	0	7
	10	M1S10	M2S10	M3S10	90	0	10
Ternary blend Cement mixes	20	M1F13S7	M2F13S7	M3F13S7	80	13	7
	30	M1F23S7	M2F23S7	M3F23S7	70	23	7
	40	M1F33S7	M2F33S7	M3F33S7	60	33	7
	50	M1F43S7	M2F43S7	M3F43S7	50	43	7
	20	M1F10S10	M2F10S10	M3F10S10	80	10	10
	30	M1F20S10	M2F20S10	M3F20S10	70	20	10
	40	M1F30S10	M2F30S10	M3F30S10	60	30	10
	50	M1F40S10	M2F40S10	M3F40S10	50	40	10

Table 3 Description of control mixes for different w/b ratio.

w/b ratio	OPC (kg/m^3)	Water (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Coarse agg. MSA 20 mm (kg/m^3)	Coarse agg. MSA 10 mm (kg/m^3)	Fine agg. (kg/m^3)
0.3	450	135	0	0	849	566	548
0.4	450	180	0	0	795	530	513
0.45	450	202.5	0	0	768	512	495

Table 4 Dosage of Superplasticizer in % weight of total binder.

Mix type	Percentage replacement of OPC	Mix with w/b = 0.3	SP dose (%)	Mix with w/b = 0.4	SP dose (%)	Mix with w/b = 0.45	SP dose (%)
Control mix	0	M1	2.00	M2	0.25	M3	0.15
Binary blend of OPC + FA	20	MIF20	1.00	M2F20	0.10	M3F20	0.05
	30	M1F30	0.65	M2F30	0.10	M3F30	0.05
	40	M1F40	0.60	M2F40	0.05	M3F40	0.00
	50	M1F50	0.50	M2F50	0.00	M3F50	0.00
Binary blend of OPC + SF	7	M1S7	2.20	M2S7	0.30	M3S7	0.20
	10	M1S10	2.30	M2S10	0.40	M3S10	0.25
Ternary blend of OPC + 7 %SF + FA	20	M1S7F13	1.50	M2F13S7	0.30	M3F13S7	0.15
	30	M1S7F23	0.70	M2F23S7	0.15	M3F23S7	0.10
	40	M1S7F33	0.60	M2F33S7	0.10	M3F33S7	0.05
	50	M1S7F43	0.60	M2F43S7	0.05	M3F43S7	0.00
Ternary blend of OPC + 10 %SF + FA	20	M1S10F10	1.50	M2F10S10	0.40	M3F10S10	0.25
	30	M1S10F20	0.80	M2F20S10	0.20	M3F20S10	0.20
	40	M1S10F30	0.75	M2F30S10	0.15	M3F30S10	0.10
	50	M1S10F40	1.70	M2F40S10	0.10	M3F40S10	0.05

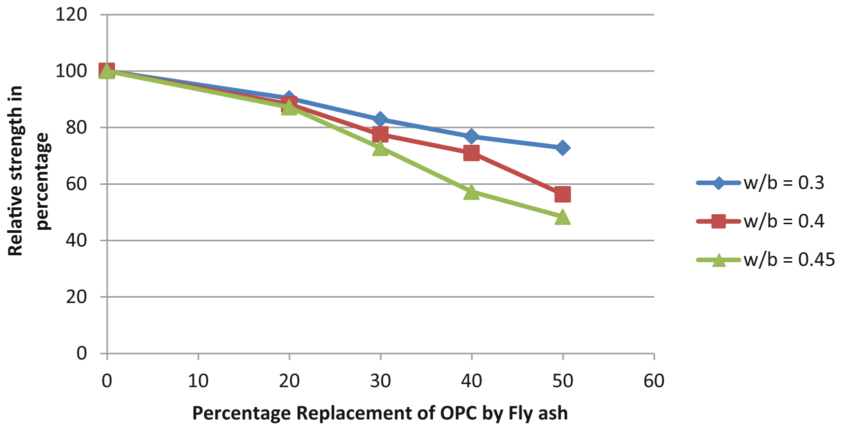

Fig. 1 Effect of replacement of OPC by fly ash on 28 days compressive strength at different w/b ratio.

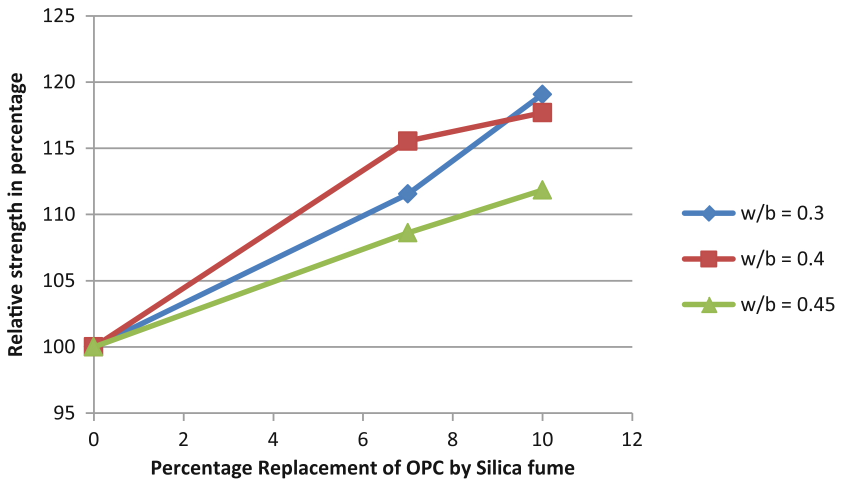

Fig. 2 Effect of replacement of OPC by silica fume on 28 days compressive strength at different w/b ratio.

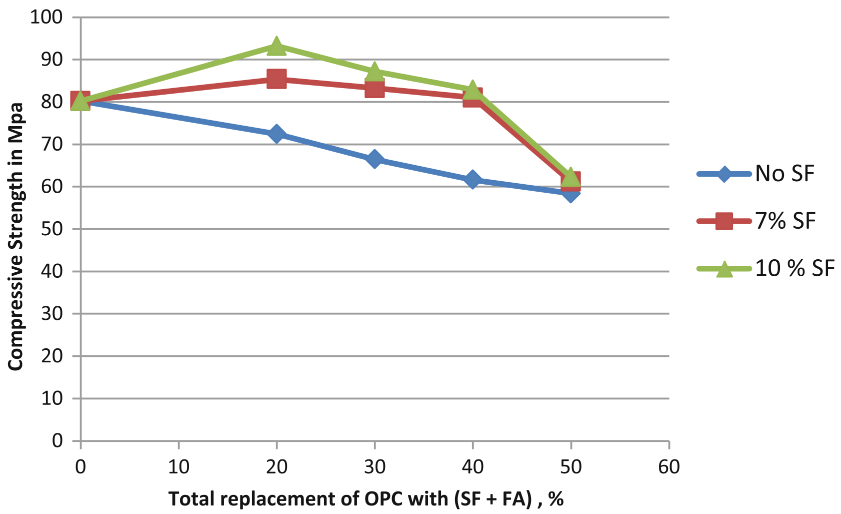

Fig. 3 28 days compressive strength of binary and ternary mixes at w/b = 0.3.

control mix, but it was significantly reduced in concrete using binary blend of OPC + FA at all w/b ratios. SP dosages for concrete using ternary blend of OPC + FA + SF were also lesser with respect to control mix and binary blend of OPC + SF, but higher than binary blend of OPC + FA. This is due to spherical particles of FA which act as small ball bearings and compensate the higher SP demand which arises due to inclusion of SF with very high specific surface area in ternary blend cement system (Goyal et al. 2008).

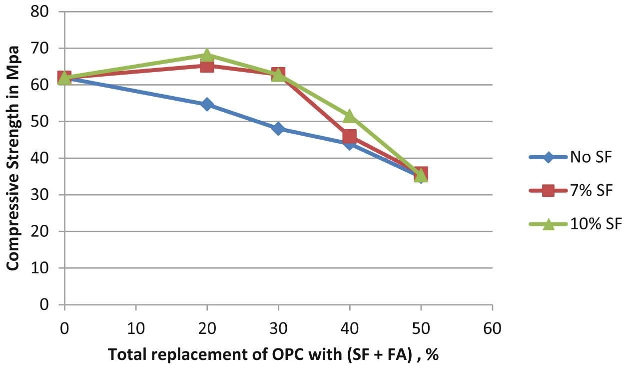

Fig. 4 28 days compressive strength of binary and ternary mixes at w/b = 0.4.

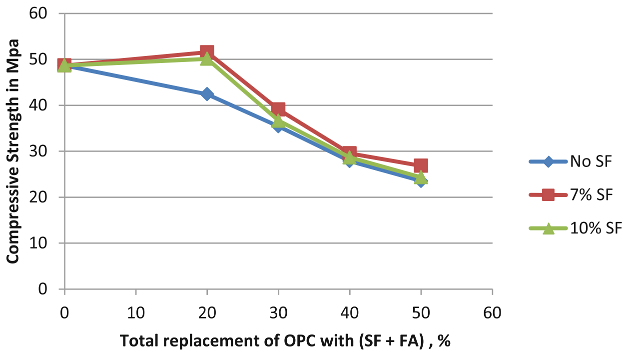

Fig. 5 28 days compressive strength of binary and ternary mixes at w/b = 0.45.

4.2 Compressive Strength

4.2.1 Compressive Strength of Concrete Using Binary Blend Cement

The graph between FA replacement level and compressive strength is plotted for all w/b ratios at the age of 28 days for concrete using binary blend of OPC + FA in Fig. 1.

It indicates that when OPC is replaced with fly ash, the strength decreases with respect to control mix for all w/b ratios (Siddique 2004). As the w/b ratio increases the percentage reduction in strength is more for same replacement level. For w/b ratio of 0.3, 0.4 and 0.45, at 20 % replacement level reduction in strength with respect to control mix is 9.71, 11.76 and 12.88 % respectively but at 50 % replacement level the reduction is 27.22, 43.66 and 51.64 % respectively. The reduction in strength is comparatively low at w/b ratio of 0.3 and higher at w/b ratio of 0.4 and 0.45. At lower w/b ratios, the contribution to strength by the fly ash was higher than in the mixes prepared with higher w/b ratios (Poon et al. 2000). This may be due to filler effect of fine particles of fly ash which densify the matrix and improved the interfacial bond between paste and aggregate.

The graph between SF replacement level and compressive strength is also plotted for all w/b ratios at the age of 28 days as shown in Fig. 2. It shows that as the percentage replacement level of OPC with SF increases, the strength increase for all w/b ratios. It attributes to fast pozzolanic reaction at early age and filler effect of SF (Erdem and Kırca 2008).

Table 5 Relative strength gain in strength of ternary blend of OPC + 7 % SF + FA cement system with respect to control mix and binary mix of OPC + FA cement system at the age of 28 days.

% Rep. OPC	w/b = 0.3		w/b = 0.4		w/b = 0.45	
	% Gain in strength of (OPC + FA + 7 % SF) w.r.t.		% Gain in strength of (OPC + FA + 7 % SF) w.r.t.		% Gain in strength of (OPC + FA + 7 % SF) w.r.t.	
	Control mix (%)	OPC + FA (%)	Control mix (%)	OPC + FA (%)	Control mix (%)	OPC + FA (%)
20	6.42	16.13	5.38	17.14	5.90	18.78
30	3.80	20.96	1.52	23.99	−19.68	7.53
40	0.99	24.20	−25.82	3.23	−39.32	3.44
50	−23.76	3.46	−42.23	1.44	−44.83	6.81

Table 6 Relative strength gain in strength of ternary blend of OPC + 10 %SF + FA cement system with respect to control mix and binary mix of OPC + FA cement system at the age of 28 days.

% Rep. OPC	w/b = 0.3		w/b = 0.4		w/b = 0.45	
	% Gain in strength of (OPC + FA + 10 % SF) w.r.t.		% Gain in strength of (OPC + FA + 10 % SF) w.r.t.		% Gain in strength of (OPC + FA + 10 % SF) w.r.t.	
	Control mix (%)	OPC + FA (%)	Control mix (%)	OPC + FA (%)	Control mix (%)	OPC + FA (%)
20	16.19	25.90	10.13	21.89	2.97	15.85
30	8.69	25.85	1.30	23.77	−24.72	2.49
40	3.32	26.52	−16.77	12.28	−41.15	1.62
50	−22.35	4.87	−42.98	0.68	−49.99	1.65

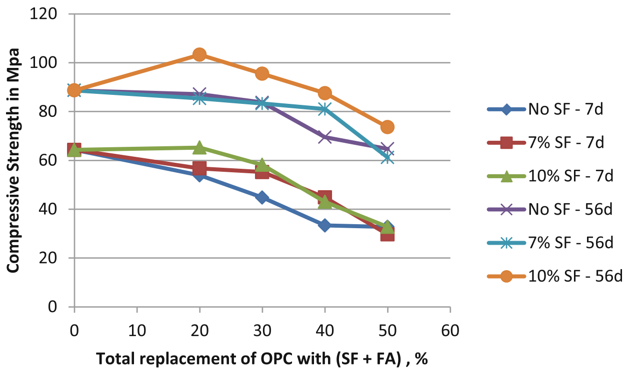

Fig. 6 Compressive strength of concrete at 7 days and 56 days at w/b = 0.3.

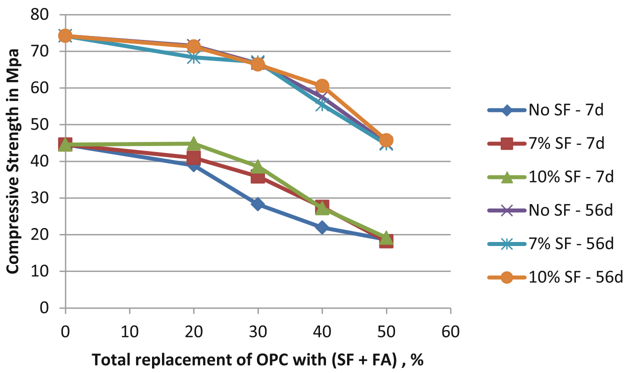

Fig. 7 Compressive strength of concrete at 7 days and 56 days at w/b = 0.4.

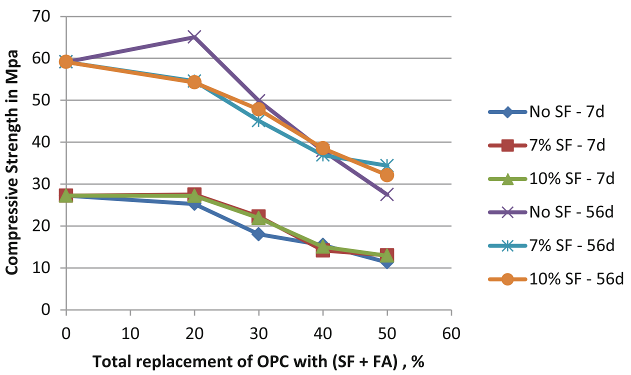

Fig. 8 Compressive strength of concrete at 7 days and 56 days at w/b = 0.45.

4.2.2 Compressive Strength of Concrete Using Ternary Blend Cement

In the present study, concrete mixes using binary blend of OPC + FA were converted into concrete mixes using ternary blend cement system by substituting FA with either 7 % or 10 % SF. The trend between compressive strength at 28 days for different levels of replacement of OPC, by combination of FA and 0, 7 or 10 % SF are shown in Figs. 3, 4 and 5 for w/b ratio of 0.3, 0.4 and 0.45 respectively.

The graphs indicate that the compressive strength with respect to control mix increases first and then decreases after certain percentage of replacement level of OPC for all w/b

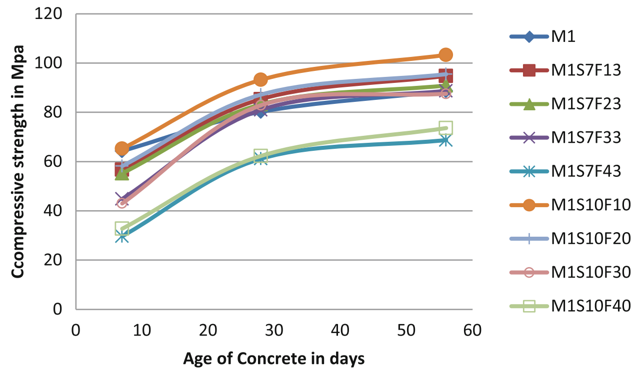

Fig. 9 Development of compressive strength of ternary blend mixes with age at w/b = 0.3.

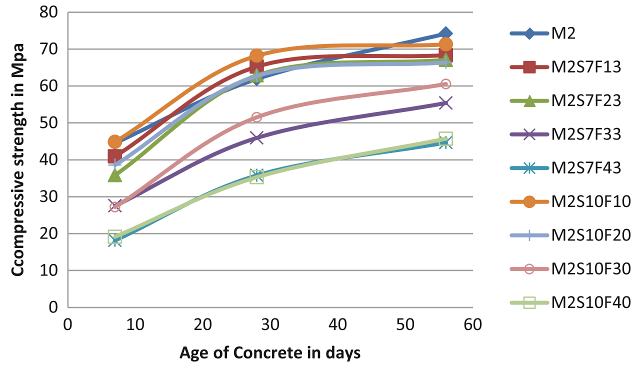

Fig. 10 Development of compressive strength of ternary blend mixes with age at w/b = 0.4.

ratios. When w/b ratio is 0.3 the strength of concrete using ternary blend cement system are higher than control mix up to total binder replacement of 40 %. Whereas for 0.4 and 0.45 strength concrete using ternary blend cement system are higher than control mix up to total binder replacement of 30 and 20 % respectively. This indicates that as w/b ratio decreases higher percentage of OPC can be replaced with mineral admixtures to get strength comparable to control mix. In the other word as w/b ratio increases, the amount of OPC reduction decreases to get strength comparable to control mix in concrete using ternary blend system. This may be due to larger size of pores at higher w/b ratio which are not reduced considerably due to formation of additional C–S–H gel and filler effect of finer materials.

Inclusion of SF in cement system increase the strength of concrete at early stage and increase the strength significantly of the concrete mixes, using binary blend of OPC + FA. The percentage gain in strength of concrete mixes of OPC + 7 %SF + FA and OPC + 10 %SF + FA with respect to control mix and with respect to concrete mixes of OPC + FA at the age of 28 days are tabulated in Tables 5 and 6 respectively for all w/b ratios tested. Results indicate that strength of concrete using ternary blend system is always higher than concrete using binary blend of OPC + FA, whether gain in strength is more significant (at lower replacement level) or marginal (at higher replacement level). In the other words, ternary blends of OPC + SF + FA compensate the loss of strength of binary blends of

Table 7 Efficiency factor of SF and FA in concrete using ternary blend cement system.

Days	A_1	A_2	k_{SF}	k_{FA}	k_{TB}	$k'_{SF} = k_{TB} * k_{SF}$	$k'_{FA} = k_{TB} * k_{FA}$
7	31.13	38.23	1.485	0.378	1.056	1.568	0.399
28	26.90	−8.64	2.524	0.469	1.090	2.750	0.511
56	24.45	8.35	2.692	0.563	1.065	2.866	0.599

OPC + FA (Kazim 2012). This is due to higher efficiency of SF as pozzolana, formation of additional C–S–H gel at early age, better particle packaging and strengthening of interfacial zone (Isaia et al. 2003; Thanongsak et al. 2010).

The graphs between compressive strength at 7 and 56 days versus percentage OPC replacement by SF and FA for concrete mixes using OPC + FA, OPC + 7 %SF + FA and OPC + 10 %SF + FA are plotted for w/b ratio of 0.3, 0.4 and 0.45 in Figs. 6, 7 and 8 respectively.

From the graphs, it is clear that only 20 % replacement level with 10 % SF gives higher compressive strength than control mix for all w/b ratios at 7 days. This indicates that higher replacement level more than 20 % is not desirable in ternary blend cement system, where early strength is required.

However, it is clear that if early strength is not the barrier, it is possible to produce a high strength concrete with a compressive strength value of 50 MPa with 20–50 % FA replacements with adopting lower w/b ratio (w/b < 0.4). The results also indicated that where early strength is not critical then it is possible to get the same strength concrete with adopting a mix with lower w/b ratio and higher replacement level of OPC with SF + FA, instead of adopting a mix with higher w/b ratio and lower replacement level. For example, for making concrete having 60 Mpa strength at 28 days, it can be achieved by using 50 % replacement level of OPC at w/b ratio of 0.3, instead of using 30 % replacement level of OPC at w/b ratio of 0.4 in ternary blend cement system.

At 56 days, the strength shows similar trend to 28 days strength for concrete using ternary blend cement system. But the strength increases significantly in concrete using OPC + FA and is almost equal to respective concrete using ternary blend cement system which show the pozzolanic activity of FA has been activated at later stage.

The development of compressive strength with age for concrete mixes using ternary blend cement system at w/b ratio of 0.3 and 0.4 are shown in Figs. 9 and 10 respectively.

4.2.3 Synergic Effect and Efficiency Factor of FA and SF in Concrete Using Ternary Blend Cement System

The cementing efficiency factor, k of a pozzolan is defined as the number of parts of cement in a concrete mixture that could be replaced by one part of pozzolan without changing the property being investigated, which is usually the compressive strength (Wong and Razak 2005) and synergy can be defined as the interaction of two or more additives so that their combined effect is greater than the sum of their individual effects (Radlinski and Olek 2012). In the other words, for reflecting synergic effect, the efficiency factor of SF and FA should be higher in ternary blend cement system than the efficiency factor calculated in their respective binary blend cement system.

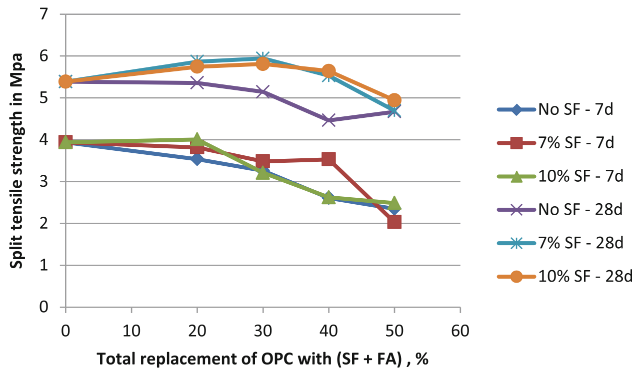

Fig. 11 Split tensile strength of binary and ternary mixes at w/b = 0.3.

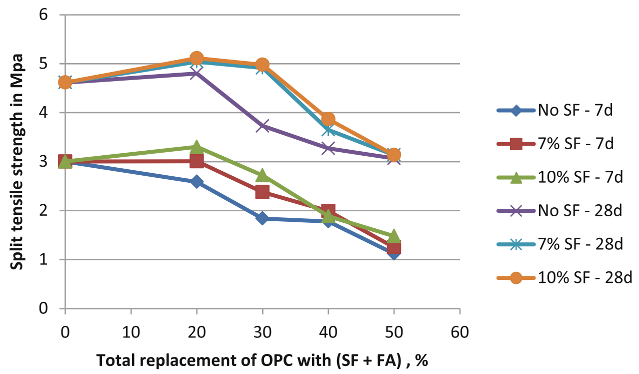

Fig. 12 Split tensile strength of binary and ternary mixes at w/b = 0.4.

Pozzolanic activity index method (Papadakis et al. 2002), modified Abram's law(Wong and Razak 2005), modified Bolomey's equation (Bharatkumar et al. 2001; Malathy and Subramanian 2007), etc. have been used by researchers to calculate the efficiency of different mineral admixtures individually in their binary blends or combined efficiency in their ternary blends.

For calculating the efficiency of SF and FA individually in ternary blend cement system, an equation was proposed by author based on the principle of modified Bolomey's equation for concrete using binary blend cement system. For control mix the Bolomey's equation for compressive strength prediction is given by following equation (Bharatkumar et al. 2001; Malathy and Subramanian 2007):

$$f_c = A_1(C/W) + A_2 \qquad (1)$$

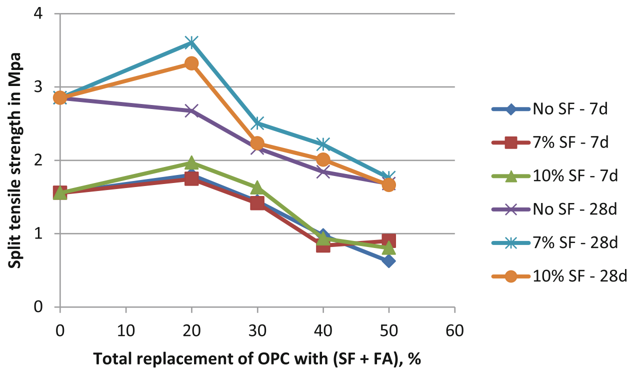

Fig. 13 Split tensile strength of binary and ternary mixes at w/b = 0.45.

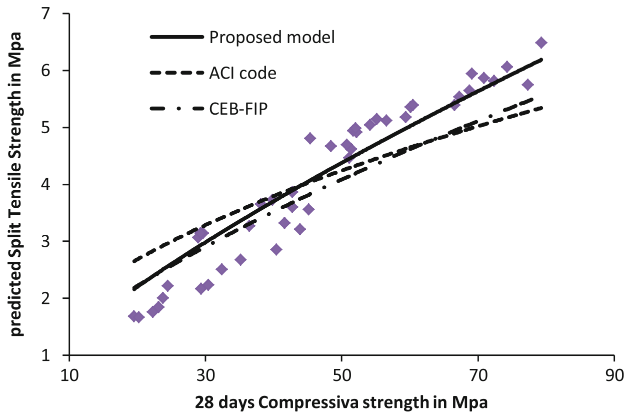

Fig. 15 Relationship between split tensile strength and compressive strength at 28 days.

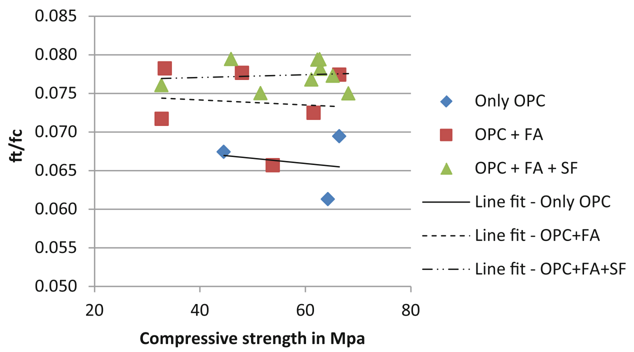

Fig. 14 Ratio of split tensile strength and compressive strength vs compressive strength.

where f_c is compressive strength of concrete in MPa, C is the cement content in kg/m^3, W is the water content in kg/m^3 and A_1, A_2 are constants influenced by ingredients and age of concrete.

It is modified by researchers for concrete using binary blend of FA and SF as follow (Bharatkumar et al. 2001; Malathy and Subramanian 2007):

$$f_c = A_1\{(C + k_{SF}P_{SF})/W\} + A_2 \quad (2)$$

$$f_c = A_1\{(C + k_{FA}P_{FA})/W\} + A_2 \quad (3)$$

where P_{SF} is SF content in kg/m^3, P_{FA} is FA content in kg/m^3 and k_{SF} k_{FA} are the efficiency factor of SF and FA respectively in their respective binary blend cement system.

It can be further modified for concrete using FA and SF in ternary blend cement system by author as given below:

$$f_c = A_1\{C/W + k_{TB}(k_{SF}P_{SF} + k_{FA}P_{FA})/W\} + A_2 \quad (4)$$

where k_{TB} is a factor representing synergic effect of FA + SF in ternary blend cement system.

$$k'_{SF} = k_{TB*}k_{SF} \quad (5)$$

$$k'_{FA} = k_{TB*}\, k_{FA} \quad (6)$$

where k_{SF}' and k_{FA}' are the efficiency factor of SF and FA respectively in concrete using ternary blend cement system.

A_1 and A_2 were obtained at the age of 7, 28 and 56 days from regression analysis with the compressive strength results of control mixes. Those mixes were not considered in analysis which resulted in very high or very low efficiency factor. Then using Eqs. (2) and (3) k_{SF} and k_{FA} were calculated using results of respective concrete mixes of binary blend cement system. Then k_{TB} was calculated using Eq. 4 with the results of mixes of ternary blend cement system. Finally efficiency factor of SF and FA in ternary blend cement system were calculated by Eqs. (5) and (6). The results are tabulated in Table 7.

The results clearly shows that efficiency factor for SF and FA are always higher in ternary blend cement system than their respective binary blend cement system, indicating synergic effect i.e. their combined effect in ternary blend system is more than the sum of their individual effects. The synergic effect is due to change in microstructure of hardened concrete (Isaia et al. 2003). The size of pores reduced due to pozzolanic activity of mineral admixtures and filler effect of fine particles of FA and still finer particles of SF.

4.3 Split Tensile Strength

The results of split tensile strength also reflects similar trend as compressive strength. As w/b ratio increases, the effectiveness of silica fume to increase the tensile strength of concrete, using binary blend of OPC + FA, is decreases in concrete using ternary blend cement system. Strength at 7 and 28 days at 0.3, 0.4 and 0.45 are compared in Figs. 11, 12 and 13 respectively.

The graphs are plotted between ratio of split tensile strength, f_t to compressive strength, f_c vs compressive strength for control mixes, mixes using binary blend of OPC + FA and mixes using ternary blend of OPC + FA + SF at 28 days. Only those mixes were considered whose compressive strength was between 20 and 70 MPa so that all type of mixes were having common range of strength level. From Fig. 14 it is clear that for same compressive strength level, the value of f_t/f_c is higher for binary blend cement system of OPC + FA as well as ternary blend cement system. This is due to filler effect of the finer particles of mineral admixtures and pozzolanic activity which make the concrete matrix denser and also strengthening the interfacial transition zone between aggregate and mortar (Mullick 2007). This leads to better bonding between aggregate and mortar and hence tensile strength is higher.

There are several empirical formulations for evaluating splitting tensile strength f_t and compressive strength f_c and most researchers achieved the expression of the type: (Neville 2000).

$$f_t = k\,(f_c)^n. \tag{7}$$

where f_t and f_c are splitting tensile strength and compressive strengths in MPa respectively, measured on 150 mm $\Phi \times 300$ mm cylinders at 28 days, k and n are constants of regression analysis. The value of n lies in the range of 0.5–0.75.

In the current study 100 mm cubes were use to measure compressive strength. So, 100 mm cube compressive strengths were converted to 150 mm $\Phi \times 300$ mm cylinder strengths by multiplying by a factor of 0.83 (Erhan et al. 2007), Analyzing the present strength results of all concrete mixes and performing regression analysis for n value between 0.5 and 0.75, the best fit curve was obtained at $n = 0.75$ with more than 90 % confidence level by the following equations:

$$f_{t,28} = 0.23\,(f_c)^{0.75} \tag{8}$$

$$f_{t,7} = 0.19(f_c)^{0.75}. \tag{9}$$

The predicted value of split tensile strength by proposed model, ACI code (ACI 363R-92, State of art report on high strength concrete (ACI Committee 363) (Reapproved 1997) and CEB-FIP model (CEB-FIP, Committee Euro-International du Beton (CEB-FIB), CEB-FIB Model Code 1990) are compared in Fig. 15. It is clear that ACI code over estimate the tensile strength at lower compressive strength and under estimate at higher strength. Similarly CEB-FIP model also under estimate the tensile strength at higher level. Proposed equation predicts tensile strength closer to experimental value at higher strength level. Also Selim (2008), Bhanja and Sengupta (2005) used higher n value of 0.717 and 0.948 respectively.

5. Conclusions

1. Ternary blend cement system of OPC + FA + SF compromise a better choice than binary blend cement system of OPC + SF to get strength comparable to control mix due to its economical and environmental benefits. The superplasticizer dose is lesser and percentage replacement of OPC is larger in concrete using ternary blend of OPC + FA + SF.
2. If the cement content of control mixes at each w/b ratio is kept constant then as w/b ratio decreases higher percentage of OPC can be replaced with FA + SF to get strength comparable to respective control mix.
3. If early strength is desirable the OPC replacement level in concrete using ternary blend system is limited to 20 % with combination of 10 % SF and 10 % FA.
4. If early strength is not the barrier, it is possible to achieve the same 28 days strength of concrete with adopting a mix with lower w/b ratio and higher replacement level of OPC with SF + FA, instead of adopting a mix with higher w/b ratio and lower replacement level.
5. In concrete using ternary blend of FA + SF, 20 % replacement level of OPC with combination of 10 % SF and 10 % FA showed higher strength than control mix for all w/b ratios and at all ages.
6. The efficiency factor for SF and FA were always higher in ternary blend cement system than their respective binary blend cement system, indicating synergic effect.
7. The split tensile strength of concrete using ternary blend cement system was higher than control mix due to strengthening of interfacial transition zone due to filler effect and pozzolanic reaction.

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