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Statistical Correlation to Predict the Compressive Strength of Binary and Ternary Blended Concretes

Hariharan A.R.*, Santhi A.S. and Mohan Ganesh G.
Structural and Geotechnical Engineering Division, SMBS, VIT University, Vellore-632014, INDIA

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Abstract

This research paper presents the effects of using supplementary cementitious materials in binary and ternary blends of concrete incorporating fly ash and silica fume. A total of 12 concrete mixtures were designed having a total binder content of 400 kg/m^3 and water binder ratio of 0.4. Portland cement was replaced by fly ash at levels of 30%, 40% and 50%, silica fume at levels of 6% and 10% by weight. The compressive strength test were conducted on test specimens cured under different types of curing systems like accelerated curing, warm water curing along with normal curing were done and the results were compared. Based on the experimental results, polynomial regression models and coefficients were developed between standard compressive strength and early strength attained by accelerated curing and warm water curing at 28-90 days.

Keywords: Compressive strength, curing type, fly ash, silica fume, industrial waste.

Introduction

In recent years cement and concrete has been in high demand due to infrastructure development. Cement industry is one of the major sources of environment pollution[1]. For economic and environmental reasons cement has been replaced by some materials having pozzolanic and cementitious properties. These materials are industrial waste which comes as a by-product. Some of the most common industrial wastes are fly ash (FA), silica fume (SF), ground granulated blast furnace slag, metakaolin and rice husk ash[2]. These industrial materials are also referred to as supplementary cementitious materials (SCMs).

Fly ash is widely used in blended cements, and is a by-product of coal-fired electric power plants. Two general classes of FA can be defined: low-calcium fly ash (LCFA: ASTM Class F) produced by burning anthracite or bituminous coal; and high-calcium fly ash (HCFA: ASTM Class C) produced by burning lignite or sub-bituminous coal[3]. The use of FA in concrete is not only economical but also modifies the properties of concrete in both fresh and hardened state with improved workability. In addition, the storage and disposal problem of fly ash is also solved by the use of fly ash in concrete [4]. Despite the benefits of fly ash, practical problems remain in field application. At early stages of aging, the strength of concrete containing a high volume of fly ash as a partial cement replacement is much lower than that of control concrete, due to the slow pozzolanic reactivity of fly ash.

Silica fume appears to be a potential solution to this problem due to its highly reactive nature[5]. Silica fume is a pozzolanic material which is a by-product of the silicon melting process. It is used to improve concrete in two ways the basic pozzolonic reaction and also acts as micro filler. The addition of SF also affects the workability of concrete which can be compensated by addition of chemical admixtures. Therefore, utilization of SF together with FA provides an interesting alternative for cement[3,6].

The criterion for the quality of concrete is based on the 28-days compressive strength of cube specimen cast, cured and tested under controlled condition. Currently, however the increasing speed of construction calls for potential strength of concrete to be determined at the earliest possible time after the concrete has been placed [7]. Therefore methods for early determination of concrete strength are accelerated curing and warm water curing. Hence, this paper presents the experimental results of compressive strength of binary-ternary combinations of FA and SF under different curing condition. Polynomial regression analyses were performed to establish a relationship between standard compressive strength and accelerated/warm water compressive strength of concretes made with PC and different amounts of FA and SF.

Material and Methods

Experimental Study: The materials used in this study were tested for their chemical and physical properties as shown below.

Cement: Portland cement (PC) conforming to the requirements of BIS: 12269-1987[8] (53 grade) was used, for which the physical property tests of the cement were carried out in the laboratory and were found to have a specific gravity of 3.15 and the initial and final setting time were found to be 150 minutes and 265 minutes respectively.

Aggregates: The fine and coarse aggregates were local natural river sand and crushed gravel respectively. The coarse aggregate passing through 20 mm and retained on 4.75 mm was used for all mixtures. The specific gravity of coarse aggregate was 2.65. The specific gravity and fineness modulus of fine aggregates were 2.56 and 2.65.

Chemical Admixture: A new generation Polycarboxylic ether (PCE) based superplasticizer (SP) was used. The super - plasticizer is available as a medium brown colored aqueous solution. This chemical admixture was meeting the standards of ASTM specification C494/C494M-11[9]. The specific gravity and pH value of the superplasticizer is 1.056 and 6.5 respectively.

Fly ash: High-calcium fly ash with a specific gravity of 2.46 from a source in Neyveli, India (lignite base fly ash) was used in this investigation. The chemical compositions of the fly ash are shown in table 1.

Silica fume: Uncompacted silica fume from Elkem, India with specific gravity of 2.02, bulk density of 602 (kg/m^3) and specific surface of 19 (m^2/g) was used in this study. The chemical analyses of the silica fume are presented in table 1.

Table-1
Chemical properties of Class C fly ash and silica fume

Characteristics	**From Test**	
	Fly ash-Class C	**Silica Fume**
Silica (as SiO_2), *Min*	57.65	85.72
Calcium Oxide (Lime Content) as CaO	11.64	-
Alumina (as Al_2O_3)	15.29	0.06
Iron oxide (as Fe_2O_3)	6.10	0.45
Magnesia (as MgO), *Max*	0.37	-
Sulphuric Anhydride (as SO_3), *Max*	1.82	-
Total Loss on ignition, *Max*	2.86	1.96
Total Chlorides (as Cl)	0.02	-
Sodium Oxide (as Na_2O)	0.44	-
Potassium Oxide (as K_2O)	0.04	-
Total alkalis (as Na_2O)	0.47	-
Silicon dioxide (SiO_2) + Aluminum oxide (Al_2O_3) + Iron Oxide (Fe_2O_3) in % by mass, *Min*	79.04	-

Mixture Proportions: A total of 12 concrete mixtures were designed having a total binder content of 400 kg/m^3 with a constant water/binder ratio of 0.4. Also, SP was added to all mixtures to increase workability of concrete. The concrete mixtures were divided as below: i. Control mixture with only PC as a binder. ii. Five binary mixtures with 30%, 40% and 50% FA replacement, 6% and 10% SF replacement respectively by weight of the PC for 400 kg/m^3, iii. Six ternary concrete mixtures (PC+FA+SF) with replacement levels of FA and SF as in binary mixtures of PC+FA and PC+SF.

The mixture ID are furnished in table 2 and the mix proportions, SP content, aggregate content and SCMs content by weight used in this experimental study are summarized in table 3 for 400 kg/m^3.

Casting: The mixing sequence and duration are very important to produce good quality concrete. For all the twelve mixture selected in this study, twenty one cubes of size 100 mm x 100 mm x 100 mm were cast per mix. Batching, mixing and placing of concrete in its moulds were done as per the ASTM C192/C192M-07 [10].

Table-2
Mixture ID of samples of Concrete Specimens

Mix ID of 400 kg/m^3	**Cement (%)**	**Fly ash (%)**	**Silica fume (%)**
T100	100	-	-
T906	94	-	6
T901	90	-	10
T730	70	30	-
T640	60	40	-
T550	50	50	-
T636	64	30	6
T546	54	40	6
T456	44	50	6
T631	60	30	10
T541	50	40	10
T451	40	50	10

Curing: The chemical process that ensures the hydration of cement in a newly placed concrete is curing. In this work it was decided to study the effect of curing, by adopting three types of curing methods as per ASTM C684-99 [11] standards. These curing conditions are: i. standard moist curing: after casting, the molded specimens were left in the casting room for 24 h. It was then demoulded and immersed in a curing tank full of water. The specimens were removed from the tank at the time of testing; ii. Warm water method: immediately after casting, the concrete moulds were sealed with cover plates and immersed in water maintaining 55°C. The specimen remained in warm water for 24 h. After which the concrete cubes were demoulded, and allowed to cool down at room temperature, and then tested; iii. Accelerated curing method: after 24 h from casting the molds were immersed in accelerated curing tank maintaining of 98°C for 3.5 h. After which the specimens were removed from the tank, demoulded and allowed to cool down and tested.

Testing of Specimens: The concrete cubes were tested in compression at 1, 3, 7, 28 and 90 days. All specimens for compression testing were done in accordance with Indian Standards BIS: 516-1959 [12] using digital compression testing machine with a capacity of 3000 kN at a loading rate of 2.5 kN/sec.

Experimental Test Result: The compressive strength test results obtained from the experimental investigation involving various parameters are shown in table 4 and 5 for all the mixtures. Further in figure 1 and 2 graphs are plotted between compressive strength of binary- ternary mixtures with respect to the three curing methods and in figure 3 and figure 4 the compressive strength with respect to age (up to 90 days) were plotted.

Table-3
Mixture Proportion of Concrete Specimens

Mixture ID	W/B	Cement (kg/m^3)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Super plasticizer (kg/m^3)
T100	0.4	400	-	-	1104	736	0.117
T906	0.4	376	-	24	1104	736	0.147
T901	0.4	360	-	40	1104	736	0.206
T730	0.4	280	120	-	1104	736	0.235
T640	0.4	240	160	-	1104	736	0.264
T550	0.4	200	200	-	1104	736	0.323
T636	0.4	256	120	24	1104	736	0.411
T546	0.4	216	160	24	1104	736	0.382
T456	0.4	176	200	24	1104	736	0.352
T631	0.4	240	120	40	1104	736	0.323
T541	0.4	200	160	40	1104	736	0.440
T451	0.4	160	200	40	1104	736	0.499

Table-4
Compressive strength of binary and ternary concrete mixtures subjected to Accelerated, Warm water and One day normal curing methods

Curing Type	Compressive Strength N/mm^2											
	Control	OPC + SF		OPC + FA			OPC + FA +SF					
	T100	T906	T901	T730	T640	T550	T636	T546	T456	T631	T541	T451
Accelerating	35	34.25	45.53	27.57	25.13	16.87	25.35	35.85	30.25	31.3	26.15	27.35
Warm Water	29.75	31.9	44.65	24.55	19.83	15.15	19.75	29.85	23.45	31.35	16.75	21.1
1 day strength	21.03	21.5	22.67	14	12.97	12.35	18.4	17.4	12.48	19.3	16.53	10.55

Table-5
Compressive strength of binary and ternary concrete mixtures subjected to normal curing up to 90 days

Curing Age in Days	Compressive Strength N/mm^2											
	Control	OPC + SF		OPC + FA			OPC + FA +SF					
	T100	T906	T901	T730	T640	T550	T636	T546	T456	T631	T541	T451
1	21.03	21.5	22.67	14	12.97	12.35	18.4	17.4	12.48	19.3	16.53	10.55
3	33	35.45	37.65	26.23	22.35	20.25	33.4	26.4	20.45	33.55	25.7	18.47
7	42.43	43.43	43.7	32.55	31.5	25.7	44.95	41.07	24.85	42.6	36.4	26.3
28	50.5	56.83	53.27	44.9	41.73	38.8	51.5	45	39.15	50.95	50.6	38.27
90	60.6	64.03	61.2	60.9	56.9	50.5	61.1	59	51.1	60.97	57.9	49.05

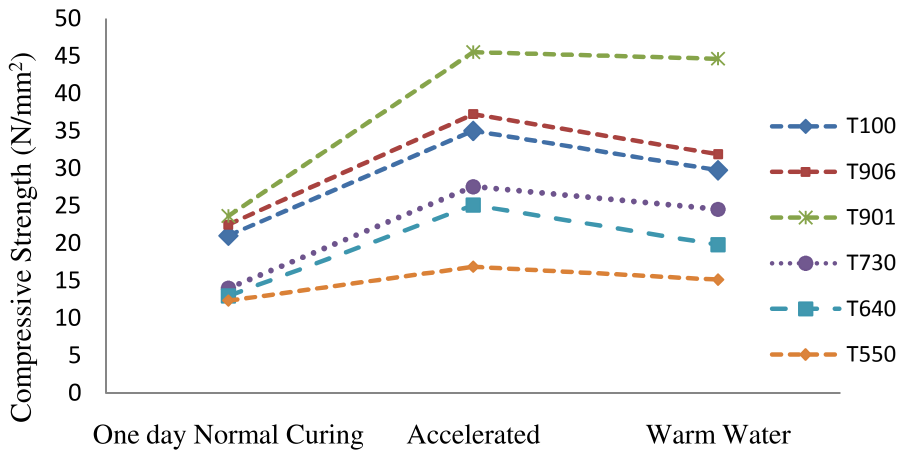

Figure-1
Compressive strength of binary concrete mixtures incorporating fly ash or silica fume under different methods of curing (PC+SF)/ (PC+FA)

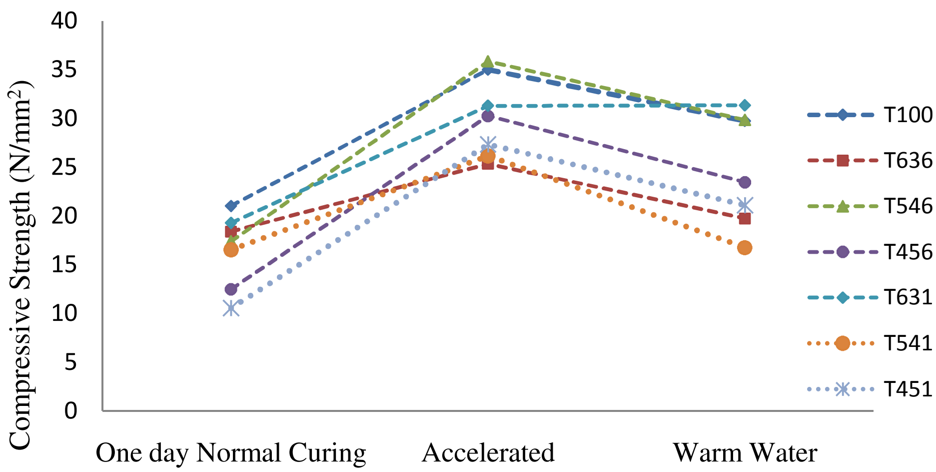

Figure-2
Compressive strength of ternary concrete mixtures incorporating fly ash and silica fume under different methods of curing (PC+FA+SF)

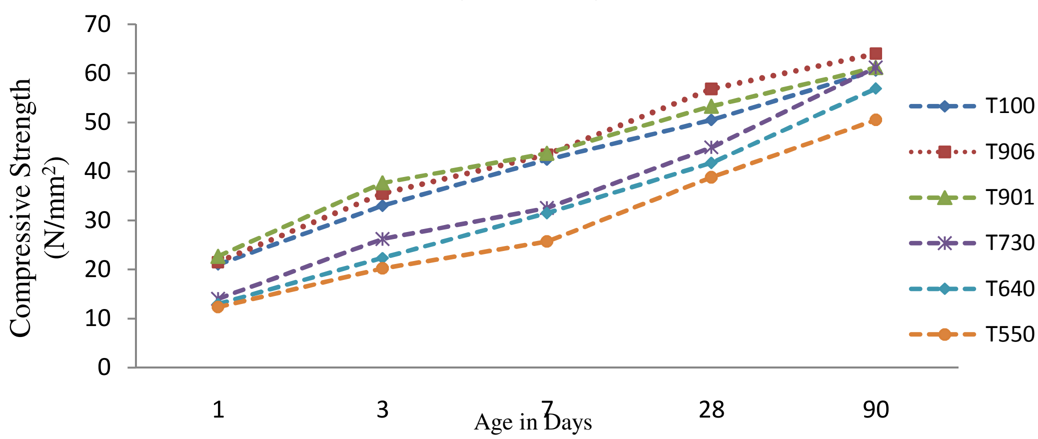

Figure-3
Binary effects of fly ash and silica fume on the compressive strength of concrete with reference to control concrete under normal curing

Regression Analysis: From the test results, graphs were plotted between standard compressive strength versus early age strength of binary and ternary concrete mixtures. In figures 5 the regression analyses were carried out for accelerating curing versus standard curing and warm water curing versus standard curing respectively at 28 days. The relation between the accelerated strength and standard strength upon normal curing was obtained as a second order polynomial equation as seen in equation (1). Similarly the relation between the warm water strength and standard strength was given equation (2). Based on equations proposed compressive strength of binary and ternary concrete cubes at 28 and 90 days can be predicted.

$$f_{cu} = \alpha f_{c.acc}^{2} + \beta f_{c.acc} + \gamma \quad (1)$$
$$f_{cu} = \alpha f_{c.ww}^{2} + \beta f_{c.ww} + \gamma \quad (2)$$

Where, f_{cu} – compressive strength of concrete at 28 or 90 days, $f_{c.acc}$ – Accelerated curing compressive strength at early age, $f_{c.ww}$ – Warm water curing compressive strength at early age and α ,β and γ are the regression constants.

This relationship is in line with the findings of the other researchers who have adopted regression analysis to predict the strength of normal concrete and concrete incorporating FA[7,13]. The constants α, β and γ of the above equation depends on the age and type of the SCM's used in the concrete. The regression coefficients for binary-ternary combinations of FA and SF are given in table 6 and 7 for 28 and 90 days respectively.

The early strength of concrete under different curing condition obtained from experiments was substituted in equations 1 and 2, and the compressive strength of concrete at 28 and 90 days were predicted. The compressive strength obtained by the predicted values and experimental results under accelerated curing and warm water curing along with the percentage of errors are tabulated in table 8 and 9. From these tables, it is observed that, the binary PC+SF mixtures have a maximum error for mixtures incorporating higher percentage of SF (10%) on both 28 and 90 days. On the other hand, the binary PC+FA mixtures showed a maximum error for mixture incorporating lesser percentage of FA (30%) on all days under both curing conditions. The percentage of error decreases with increase in FA content. For analysis, the ternary mixtures are split into two categories; (1) (PC+SF+FA) incorporating 6% SF and (2) (PC+SF+FA) incorporating 10% SF. The ternary mixtures with 6% SF showed a maximum error of 0.056% for T546 at 28 under accelerated curing. Also the mixture with lesser percentage of FA, T636 showed a least error on all days. The ternary mixtures with 10% SF showed maximum error for T451 (0.21%) at 28 days under accelerated curing. In general all the mixtures showed lesser percentage or zero error at 90 days compared to 28 days, which means the prediction equations, predicts the actual result at later ages. The proposed relationship is independent of the amount of FA and SF present in them. The average percentage of error values are 0.073 and 0.047 for accelerated curing and warm water curing respectively at 28 days as shown in table 8. Similarly, the average error for accelerated curing and warm water curing at 90 days are 0.028 and 0.037 respectively as shown in table 9. Therefore the average error is less than 1% which is negligible.

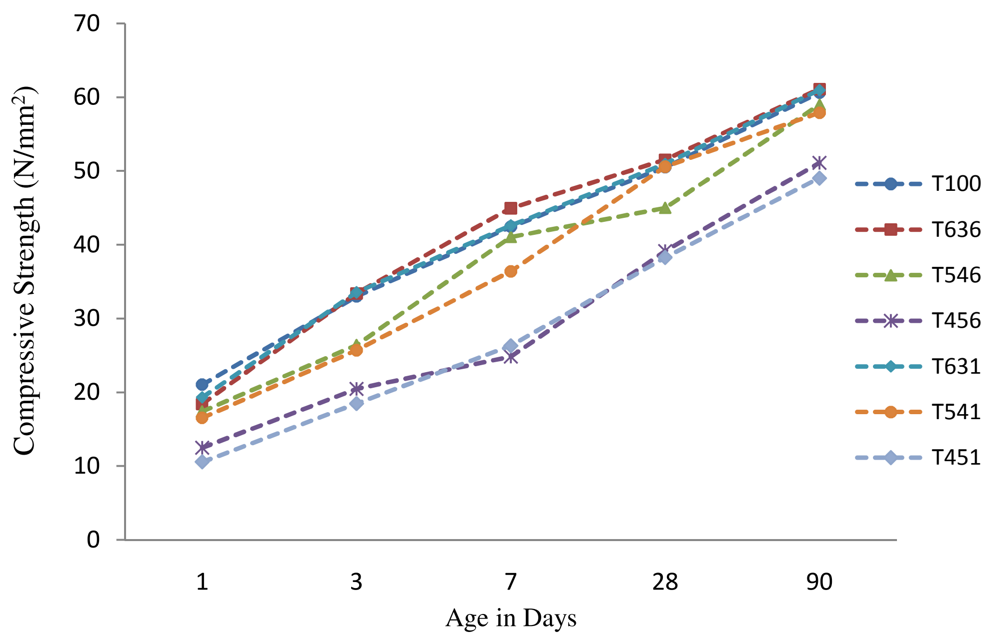

Figure-4

Ternary effects of fly ash and silica fume on the compressive strength of concrete with reference to control concrete under normal curing

Table-6
Regression coefficients for accelerated curing and warm water curing of binary-ternary concrete mixtures at 28 days

Description	Mixture ID	28 Days Strength							
		Accelerated Curing				Warm Water Curing			
		α	β	γ	R^2	α	β	γ	R^2
Control	T100	0.7715	-61.87	1270.8	1	-0.216	16.281	-242.4	1
Binary Mix PC+SF	T906 T901	0.7715	-61.87	1270.8	1	-0.216	16.281	-242.4	1
Binary Mix PC+FA	T730 T640 T550	0.0883	-3.352	70.236	1	0.0048	0.4566	30.771	1
Ternary Mix PC+SF+FA With 6% SF	T636 T546 T456	0.3395	-21.39	375.76	1	0.421	-21.524	312.39	1
Ternary Mix PC+SF+FA With 10% SF	T631 T541 T451	2.6185	-150.3	2192	1	0.2789	-13.39	196.64	1

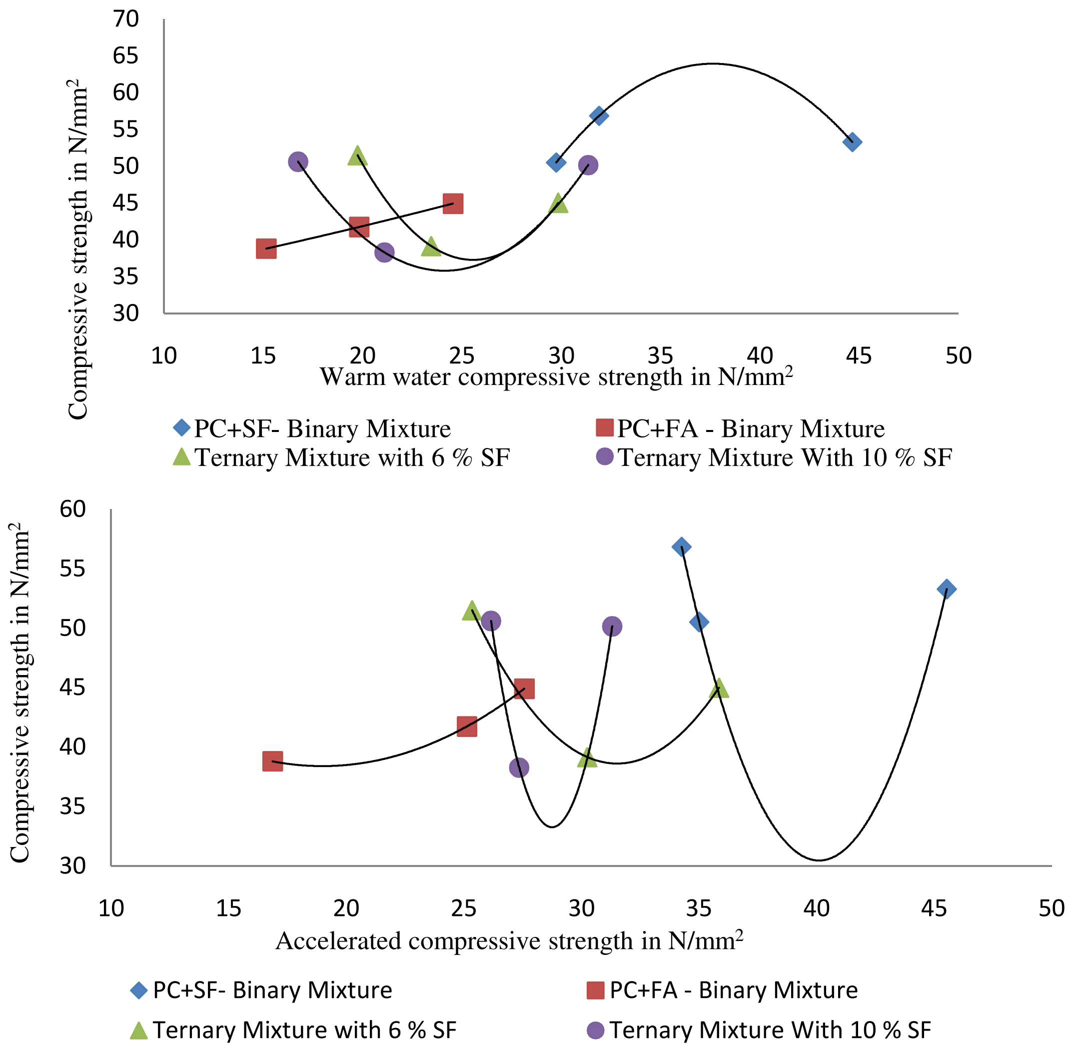

Figure-5
Regression plot for binary and ternary concrete samples subjected to accelerated and warm water curing methods versus 28 days strength of normal curing

Table-7
Regression coefficients for accelerated curing and warm water curing of binary-ternary concrete mixtures at 90 days

Description	Mixture ID	90 Days Strength							
		Accelerated Curing				Warm Water Curing			
		α	β	γ	R^2	α	β	γ	R^2
Control	T100	0.4105	-33	712.74	1	-0.122	9.1146	-102.6	1
Binary Mix PC+SF	T906	0.4105	-33	712.74	1	-0.122	9.1146	-102.6	1
	T901								
Binary Mix PC+FA	T730	0.0923	-3.10	76.553	1	-0.048	3.0663	15.19	1
	T640								
	T550								
Ternary Mix PC+SF+FA With 6% SF	T636	0.3287	-20.31	364.91	1	0.389	-19.54	295.01	1
	T546								
	T456								
Ternary Mix PC+SF+FA With 10% SF	T631	-0.091	5.8643	-32.74	1	-0.005	0.4641	51.607	1
	T541								
	T451								

Table-8
Predicted compressive strength of binary-ternary concrete mixtures at 28 days and their corresponding error values

Mixture Id	Curing age in days	Accelerated Curing Vs. Normal Curing				Warm water Curing Vs. Normal Curing			
		$f_{c.acc}$	f_{cu}	$f_{cu \cdot pre}$	% Error	$f_{c.ww}$	f_{cu}	$f_{cu \cdot pre}$	% Error
T100	28	35	50.5	50.43	0.123	29.75	50.5	50.52	0.041
T906	28	34.25	56.83	56.77	0.105	31.9	56.83	56.85	0.043
T901	28	45.53	53.27	53.16	0.2	44.65	53.27	53.32	0.105
T730	28	27.57	44.9	44.92	0.055	24.55	44.9	44.87	0.059
T640	28	25.13	41.73	41.75	0.049	19.83	41.73	41.71	0.041
T550	28	16.87	38.8	38.8	0.023	15.15	38.8	38.79	0.025
T636	28	25.35	51.5	51.49	0.017	19.75	51.5	51.5	0.014
T546	28	35.85	45	44.97	0.056	29.85	45	45.01	0.042
T456	28	30.25	39.15	39.13	0.04	23.45	39.15	39.17	0.028
T631	28	31.3	50.95	51.05	0.196	31.35	50.95	50.97	0.044
T541	28	26.15	50.6	50.67	0.148	16.75	50.6	50.6	0.012
T451	28	27.35	38.27	38.35	0.21	21.1	38.27	38.28	0.026
Average Error					0.101	Average Error			0.04

Table-9
Predicted compressive strength of binary-ternary concrete mixtures at 90 days and their corresponding error values

Mixture Id	Curing age in days	Accelerated Curing Vs. Normal Curing				Warm water Curing Vs. Normal Curing			
		$f_{c.acc}$	f_{cu}	$f_{cu\cdot pre}$	% Error	$f_{c.ww}$	f_{cu}	$f_{cu\cdot pre}$	% Error
T100	90	35	60.6	60.6	0.004	29.75	60.6	60.57	0.046
T906	90	34.25	64.03	64.03	0.003	31.9	64.03	63.99	0.051
T901	90	45.53	61.2	61.2	0.014	44.65	61.2	61.13	0.106
T730	90	27.57	61.2	61.2	0.012	24.55	61.2	61.17	0.035
T640	90	25.13	56.9	56.9	0.011	19.83	56.9	56.88	0.024
T550	90	16.87	50.5	50.5	0.004	15.15	50.5	50.49	0.016
T636	90	25.35	61.1	61.14	0.006	19.75	61.1	61.1	0.003
T546	90	35.85	59	58.99	0.003	29.85	59	59	0.003
T456	90	30.25	51.1	51.1	0.003	23.45	51.1	51.1	0.004
T631	90	31.3	60.97	60.97	0	31.35	60.97	60.94	0.036
T541	90	26.15	57.9	57.89	0	16.75	57.9	57.89	0.01
T451	90	27.35	59.05	59.04	0.001	21.1	59.05	59.03	0.017
Average Error					0.005	Average Error			0.029

Results and Discussion

The experimental results and the statistical results of compressive strength with different replacement levels of FA and SF under different curing conditions are discussed in the following paragraphs; i. The addition of 6% and 10% SF as a binary mixture showed a higher compressive strength of 7-10% in average than control concrete on all days under all three curing conditions, irrespective of the percentage of SF present in them. ii. The dosage of SF has a significant effect on the compressive strength of concrete under normal curing. The concrete mixture with 10% SF (T901) showed a 5% higher strength than 6% SF (T906) mixture at 1 day and 3 days. At 7 days the compressive strength of PC+SF mixtures was almost equal irrespective of percentage of SF. The increase in the curing period increases the strength of T906 concrete specimens by 6% compared to T901 at 28 and 90 days. These observations are consistent with the results of Ali Behnood, Hasan Ziari[14]. iii. The 1, 3, 7 and 28 days compressive strength of (PC+FA) binary mixture incorporating 30%, 40% and 50% FA was lower by 17-42% in average than control concrete under normal curing with the same binder content. However as the curing period is extended up to 90 days the concrete incorporating 30% FA (T730) mixture had 2% higher compressive strength than control concrete. This is because the pozzolanic reaction is slow and the formation of calcium hydroxide requires time. iv. It is evident from the experimental results that the compressive strength decreases when the percentage of fly ash increases. Too high FA content (40% and 50%) as a binary mixture reduces the strength at all days under normal curing. The accelerated and warm water curing methods accelerates the strength of high volume fly ash concrete compared to normal curing at the early age. v. The test results of the ternary mixtures T636 and T631 (30% FA and 6-10% SF) showed 2-5% higher compressive strength than the control concrete on all days under normal curing. The other ternary mixtures made with 40%-50% FA with 6%-10% SF showed a more or less equal compressive strength of the control concrete at later ages. But all the ternary mixture except T456 and T451 showed a higher strength than the binary PC+FA mixtures on all initial days. vi. Equation (1) and (2) are proposed for two relationships between the early age strength and long term strength, based on the curing condition at the early age. The percentage error for the proposed equations is negligible (less than 1%). Hence these equations are useful to predict the compressive strength of concretes incorporating binary blends of fly ash and silica fume and also for the ternary mixtures incorporating both of these mineral admixtures at 28 and 90 days.

Conclution

From the experimental study and statistical model, the following conclusions can be drawn; The utilization of fly ash along with silica fume was found to increase the compressive strength of concrete mixes. The replacement level of cement by these supplementary cementitious materials was 30% FA and 6 to 10% SF. Apart from the increase in strength, it also allows to use two industrial by-products which would offer ecological benefits by using the available mineral admixtures, helps in cutting down the use of cement, energy saver and reduce the cost of concrete construction in the countries with abundant supply of fly ash. The proposed model would possibly provide 332equality between the quality of concrete, time and cost. By predicting the 28 and 90 days strength of concrete by conducting the early age strength could avoid the situation where the concrete does not reach the required design strength. Since the error is less than 1% the prediction equation allows too fast and accurate prediction of compressive strength values which is eliminating the waiting period for 28 and 90 days results.

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