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Influence of Water Binder Ratio and Chemical Admixture on the Properties of Self- Compacting Concrete with composite Cement- Fly Ash binder

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ABSTRACT. *This paper describes an experimental investigation to study the combined effect of water binder ratio and chemical admixture on mechanical properties of self- compacting concrete (SCC) prepared using composite fly ash–cement binder. For this purpose, the mixture proportioning for SCC was based upon creating a high-degree of flowability by using High-Range Water-Reducing Admixtures (HRWRA) combined with Viscosity Modifying Admixture (VMA) to ensure homogeneity of the mixture. The flowability test results showed that the spread for all mixes was within the specified range recommended by EFNARC 2005 and EN 206. The J Ring height for all SCC mixes was observed to be between 17-20 mm, which was within the specified limits of EFNARC 2005. A visual stability index has been provided to all SCC mixes for qualitative assessment of the flowability indexes. The cementing efficiency factor of fly ash, adopted in the presented work, restores the cementitious content in the mix. At 0.36 w/b ratio, the cube compressive strength at 28 days was almost 51MPa when 2.2% HRWRA with VMA was added to the mix. Through the different flowability test results, an effort has been made to develop a correlation between different flowability parameters using regression analysis in MINITAB software. An empirical formula in the form of basic equations suggested by CEB-FIP and ACI 363R -92 to express the relationship between split tensile strength and compressive strength of SCC has also been proposed.*

Keywords: Fly Ash, Flowability Index, Compressive Strength, Split Tensile Strength

1. INTRODUCTION

Self-Compacting Concrete (SCC), first used in Japan in the late nineteen eighties (1) is a new kind of concrete that combines a high flowability and a high resistance to segregation obtained by a large amount of fine particles and the use of superplasticizers (2). Unlike ordinary vibrated concrete, SCC does not need any external compaction energy, eliminating possible problems caused by poor external compaction (3). There are numerous more focal points as far as innovation, working conditions and health monitoring is concerned (4).

In general, the important performance indexes for SCC are good workability with high fluidity and high-quality control (5). Viscosity Modifying Admixtures (VMA) which contain a water-soluble polymer, acrylic water-soluble polymers or biological glue, helps resolve this problem (6–9). The viscosity of SCC mixes decreases with increase in water to binder ratio (w/b) ratio, while flowability increases and mechanical and durability properties decrease. According to Rao et al. 2010 (10), segregation and cohesiveness in fresh concrete are interrelated and can be enhanced by adding VMA along with High-Range Water-Reducing Admixtures (HRWRA). According to Jayasree et al. 2011 (11), the reduction in water content is as much as 40% when polycarboxylate ether based superplasticizers (PCE SP) is used.

Further, with the help of this chemical admixture, any delay in the gain of strength of concrete is minimized. PCE SP, with its diverse molecular structure and mode of chemical activity, represents an improvement over sulfonate-based HRWRAs by preventing flocculation of cement particles. Ozawa 1995 (12) and Khayat 1998 (7) concluded that VMA could enhance the viscosity and cohesiveness of SCC mixes through the addition of filler material like limestone powder. They further concluded that the viscosity of concrete mixes can also be increased by decreasing the w/b ratio.

High flowability requirement of SCC stimulates the utilization of mineral admixtures. Use of mineral admixtures such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Rice Husk Ash (RHA), allcofine, and other similar fine powder additives, increases the fine materials in the concrete mixture and increases the flow of the mix (13,14). Utilization of mineral admixtures additionally reduces the cost of concrete by subsequently reducing the dosage of superplasticizers (15–20). The incorporation of mineral additives can improve particle-packing density and reduce inter-particle friction and viscosity because of its different morphology and grain-size distribution compared to cement (21). Yazici 2008 (22) in his study concluded that the use of FA could increase the slump flow of the SCCs mixes. Moreover, the need for viscosity-enhancing chemical admixtures is minimized. The Indian standard IS 456: 2000 (23) permits the use of FA and silica fume for modifying the properties of concrete. The w/b ratio must be lower than the water to cement ratio, for FA mixture to be equivalent in strength to a plain cement mixture. This is acceptable due to the fact that FA acts like a water reducer.

Smith 1967 (24) introduced the cementing efficiency factor for FA for effective utilization of this cementing material. For FA replacement up to 25 % in cement, a cementing efficiency factor k = 0.25 was further suggested. The German code (25) and the British code (26) adopted a value 0.3 for FA replacement up to 50% with cement. Cementing efficiency factor of 0.5 for water to cement ratio in the range of 0.5 to 0.65 was reported by Schiess 1991 (24). He further reported that for a w/c ratio between 0.5 and 0.65, a value of 0.5 is more appropriate for the cementing efficiency factor. The Danish standards further stipulated an efficiency value of 0.5 for FA.

The explicit objective of the present research program was to obtain an optimum combination of w/b ratio and superplasticizer for achieving SCC. The scope of this experimental research program included an examination of the effect of chemical admixture and water binder ratio on SCC. For this purpose, PCE SP combined with stabilizing agents like VMA was utilized in the mixture composition of SCC to create a high-degree of flowability and to ensure homogeneity of the mixture.

2. MATERIALS AND MIX PROPORTIONING

2.1. Materials

Ordinary Portland Cement (OPC) of grade 43 conforming to IS8112:1989 (27) was used in this investigation. The physical properties of cement were tested in accordance with IS 4031 (28). ASTM Class C FA obtained from Kahalgaon thermal power generation plant located in India was used in the present study for the partial replacement of OPC. Physical properties of the FA were tested in accordance with IS 3812-2003 (29). The physical properties of FA and cement are given in Table 1.

Table 1: Physical Properties of Cement and Fly Ash

Sl. No.	Physical Properties	Observed values for Cement	Observed values for Fly Ash
1	Specific Gravity	3.15	2.2
2	Initial Setting	30 min	-
3	Final Setting	600 min	-
4	Soundness (autoclave expansion) %	0.8	0.06
5	Fineness (m^2/g)	0.225	0.368

River sand and crushed gravel obtained from local sources were used as fine aggregate and coarse aggregate, respectively. Physical properties of the aggregates were determined per IS 383:1970 (30) requirements. Selected properties of the aggregates are given in Table 2. Fig 1 presents the grain size distribution of aggregates used in the present work. Poly-carboxylic ether based Super plasticizers with and without inbuilt VMA was used in this study. The chemical admixtures used were supplied by BASF India limited with a brand name of Master Glenium SKY 8630/8632. The chemical and physical properties are presented in Table 3. The dosages of admixtures were varied to achieve the desired fresh concrete properties for the SCC mixtures.

Table 2: Physical Properties of River Sand and Coarse aggregate

Sl. No.	Parameters	River sand	Coarse aggregate
1	Specific gravity	2.66	2.74
2	Fineness modulus	2.60	-
3	Water absorption	1.35	0.78
4	Aggregate crushing value	-	24%
5	Aggregate impact value	-	29%

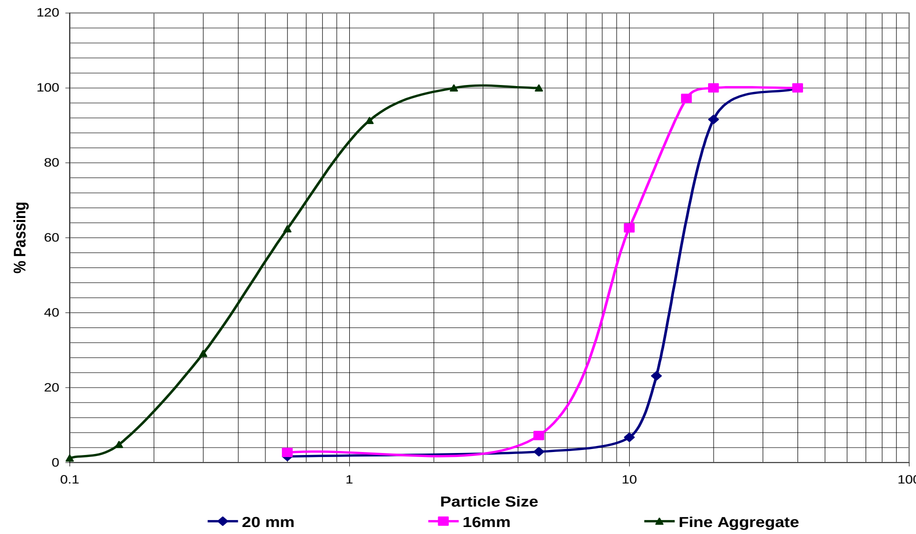


Fig 1: Particle Size distribution curve of aggregates

Table 3: Properties of Chemical Admixture (BASF India Ltd.)

Parameter	Specifications (as per IS 9103) (31)	Results
Physical state	Reddish brown liquid	Reddish brown liquid
Chemical name of active ingredient	Polycarboxylate polymers	Polycarboxylate polymers
Relative density at 250C	1.06 ± 0.01	1.066
PH	≥ 6 at 250 C	7.22
Chloride ion content (%)	< 0.2	< 0.1%
Dry material content	18± 5%	18.42

2.2. Mixture proportions

Mix design calculations for SCC was done in accordance with IS 10262:2009 (32). Water adsorption for fine aggregate and coarse aggregate has been considered in mix design calculations. To convert the aggregates into saturated surface dry condition, extra water was added in the SCC mix. The amounts and percentage of the constituents utilized in the SCC mixes are given in Table 4. This extra water is presented separately in column 9 of table 4 as it is not going to participate in the reaction mechanism of concrete. Further, a cementing efficiency factor, K, for fly ash has been considered in the mix design calculations. "The K value of fly ash relative to cement is measured as the number of parts of cement that may be replaced by one part of the ash without changing the property being investigated, generally the compressive strength (24)". Thus for concrete containing fly-ash, the effective water/cement ratio is represented as

$$\frac{w}{c} = \frac{w}{C_1 + kFA} \qquad \text{.. (1)}$$

where, w is water content; C is cement content of control concrete, and C_1 is the cement content of fly ash concrete. Based upon the previous work (33), in the present investigation, a cementing efficiency factor (k) of 0.30 has been considered for fly ash percentage replacement, less than 30% and 0.55 for fly ash percentage replacement greater than or equal to 30%. Four sets of SCC mixes with five different fly ash replacement percentages (0%, 10%, 20%, 30% and 40%) were cast at different water to binder ratio with different chemical admixture dosage.

2.3 TEST PROGRAM AND PROCEDURES

2.3.1 Flowability Test

The fresh concrete properties were measured as per the acceptance criteria for self-compacting concrete given in EFNARC: 2005 (34) and EN 206 (35) to evaluate the flow and self-compacting behaviour of the concrete. The various flowability tests conducted in the lab were Slump Flow Test (T-500 time in sec), J- ring Test, L-box and V-funnel Test.

The slump flow test is a measure of the viscosity of SCC mixes. T-500 test measures the time taken for concrete to reach a spread diameter of 500mm from the moment the slump cone is lifted. A higher T-500 value indicates a more viscous mix. The L-box and J-ring test measures the passing ability of SCC mixes in congested reinforcement while the V-funnel test shows how quickly the SCC mixture passes through the constricted area.

2.3.2 Strength Test

A Digital Compression Testing Machine of 2000kN capacity was used for measuring the compressive strength of test specimens. Compressive strength was measured on 150 mm cubes in accordance with Indian Standard IS 516-1959 (36).

Cylindrical specimens of size 150mm x 300mm were cast to measure the splitting tensile strength in accordance with Indian Standard IS 5816,-1976 (37). The horizontal tensile stress is expressed as:

$$\text{Horizontal Tensile Stress} = \frac{2P}{\pi DL} \qquad (2)$$

where P = compressive load on cylinder L = Length of cylinder D = Diameter of cylinder
For both, the tests, three test samples were tested, and the average values were obtained.

2.3.3 Visual Stability Index (VSI) Rating

The Visual Stability Index (VSI) is the qualitative measure of the fresh concrete ability to resist segregation (38,39). It can be used as the measure of the relative quality control of the mixed concrete. This test is subjective and its best used to relatively compare several similar SCC mixes. The VSI rating varies from 0 to 3. If SSCs mixes show no evidence of segregation and bleeding, then a rating of 0 is provided further, if there is evidence of segregation and bleeding, then a rating of 3 is provided to the SCC mixture. Further, a rating of 1 is indicative of slight bleeding with no mortar halo in the slump flow of the mix while a rating of 1.5 indicates noticeable bleeding with a just noticeable aggregate piling during the slump flow test. A VSI rating has been provided to all the mixes and is depicted in table 5.

3. RESULTS AND DISCUSSIONS

Twenty mixes with partial replacement of FA with cement were prepared. Three sets of experiments were conducted wherein the first set of the experiment; the PCE SP dosage for the ten mixes was fixed at 2.8% by weight of cement. For the first five mixes, the w/b ratio was fixed at 0.38, and for the next five, the water to binder ratio was 0.36. In the second set of the experiment, the w/b ratio was fixed at 0.36. The dosage of PCE SP was fixed at 2.4% by weight of cement. In the third set of experiment, another chemical admixture was used which contained PCE SP with inbuilt VMA. The dosage for this chemical admixture was fixed at 2.2% by weight of cement and water to binder ratio was fixed at 0.36.

Table 4: Mix Proportioning of Trial Mixes

Mix No.	Cement (Kg)	Fly Ash (kg)	% of Fly Ash	Water/ powder ratio	Coarse aggregate (kg)	Fine aggregate (kg)	Water (Liter)	Extra Water (Liter)	Chemical Admixture
1	467	00	0	0.38	864	903	177.45	19.11	2.8% of PCE SP by weight of Cement
2	453	46	10		826	864	189.87	18.74	
3	439	92	20		789	825	202.29	18.38	
4	390	139	30		784	820	201.41	18.74	
5	364	185	40		757	792	209.39	18.62	
6	467	00	0	0.36	876	916	168.11	19.20	2.8% of PCE SP by weight of Cement
7	453	46	10		839	878	179.88	19.03	
8	439	92	20		803	839	191.65	18.69	
9	390	139	30		798	834	190.81	19.05	
10	364	185	40		772	807	198.37	18.94	
11	467	00	0	0.36	878	918	168.11	19.43	2.4 % of PCE SP by weight of Cement
12	453	46	10		842	880	179.88	19.08	
13	439	92	20		805	841	191.65	18.73	
14	390	139	30		800	836	190.81	19.09	
15	364	185	40		774	809	198.37	18.98	
16	467	00	0	0.36	880	920	168.11	19.45	2.2 % of PCE SP + VMA by weight of Cement
17	453	46	10		843	881	179.88	19.11	
18	439	92	20		806	843	191.65	18.76	
19	390	139	30		801	837	190.81	19.11	
20	364	185	40		775	810	198.37	19.00	

3.1 Effect on Flowability Index

The results of the various flowability tests of SCC with different percentage of FA are presented in Table 5. The viscosity of SCC mixtures was evaluated through the slump flow test. According to Nagataki and Fujiwara (40) and Khayat et al. (41), a slump flow ranging from 500 to 700 mm is considered as the slump required for concrete to be self-compacted. The stability of SCC mixtures was evaluated through the V- funnel test. Both the spread diameter and the V-funnel flow times are in good agreement to that of the values given by European guidelines (35) for a range of applications and different viscosity classes and were also within the specified range recommended in the literature (42). The L-box blocking ratio was also within the specified range laid down by EFNARC 2005 (34). The J-ring test extends common filling ability test methods to also characterize passing ability. It is also an estimation of susceptibility to blocking. The J Ring height for all SCC mixes was observed to be between 17-20 mm. The J-ring time was measured and is presented in Table 5. Slight bleeding and the noticeable aggregate pile were observed during the flowability test in few SCC mixes. Based on the visual of the flow tests, a visual stability index rating has been provided to all SCC mixes and is presented in Table 5.

At a higher dosage of PCE SP the spread diameter achieved was near maximum at same w/b ratio, in contrary, the spread diameter decreased with a reduction in w/b ratio for the same dosage of HRWR. At PCE SP dosage of 2.8% by weight of cement mass, the visual stability index achieved was 2 at both w/c ratios (0.38 and 0.36). High fluidity with bleeding was observed for SCC mixes with a PCE-SP dosage of 2.8% by weight of cement. The SCC mixes were unstable as a slight mortar halo was observed in the centre of concrete masses. Consistent viscosity with bleeding was observed in the case of mixes with PCE SP with VMA. As reported by Lachemi et al. (43), the mixes with an adequate concentration of PCE SP with VMA inhibits fluidity with increased viscosity. In such concrete mixes, the viscosity built up is promoted due to association and enlargement of polymer chains of VMA at the low shear rate. This property increases the stability of the concrete and reduces the risk of segregation.

When cement is partially replaced by FA, the superplasticizer dosage decreases without compromising the filling ability of the SCC mixes, this can be seen from the results presented in Table 5. Bouzoubaa et al. (44) reported similar results. Bleeding reduced noticeably when PCE SP with inbuilt VMA was used and further there was a slight increase in V–funnel time. A similar report has been published by Khayat (7) owing to the fact that VMAs, reduces the segregation and bleeding and increases viscosity as it absorbs some free water present in the mix. More or less similar reasons for the reduction in bleeding and increase in viscosity has also been cited by Khayat et al. (7). The VSI rating provided to all the FA-induced SCC mixes indicates that despite the use of PCE SP with inbuilt VMA, slight bleeding was observed along with air popping on the surface of concrete, but this effect was less when compared to SCC mixes without VMA.

Fig. 2 represents the combined influence of w/b ratio and dosage of PCE SP on both spread diameter and V-funnel time of SCC mixes. Both V-funnel time and spread diameter show a quadratic relation with the high correlation coefficient. Further Fig 3 and Fig 4 represent the effect of FA on V-funnel time and spread diameter of SCC mixes at w/b ratio 0.36. Here also both the flowability parameters viz., V- funnel time and spread diameter show a quadratic relation with FA replacement percentage with cement. From figures, it can clearly be interpreted that V- funnel time decreases with an increase in FA percentage, while spread diameter increases with an increase in FA percentage. Thus, concluding that FA lowers the viscosity of the SCC mixes. The SEM image shown in Fig 5 confirms the above finding that the increase in FA content increases flowability of SCC mixtures. The high fluidity of SCC having large FA content would be induced by the ball milling effect of FA particles, which is quite evident in Fig 5. The same findings have also been reported in the literature (44,45) and reasoned that due to its spherical shape, FA can disperse agglomeration of cement particles leading to a reduction in viscosity. From Fig 3 and 4, it can also be seen that the V funnel time and the spread diameter remained constant (the nature of the curve almost flattens) at replacement level more than 20%. Hence it can be concluded that the optimum level of fly ash replacement should be between 20% and 30%. The same has also been reported by Omar et al. 2018 (46).

The equation presented in the figures indicates that the cementing efficiency factor of FA, adopted in the presented work, restores the cementitious content in the mix. The increase in percentage replacement of FA has little or no impact on the spread and v funnel value as evident from the intercept value of the equation which is a 2nd order polynomial equation in the form

$$y = ax^2 + bx + c \quad (3)$$

Table 5: Flowability Test Results

Mix No.	w/b ratio	Chemical Admixture	% Fly Ash by weight of cement	Spread diameter mm	Slump Flow Test (time in sec)			J Ring Test (time in sec)			L Box Test	V Funnel Test	VSI
					300mm	500mm	700mm	300mm	500mm	700mm	H2/H1	time in sec	
1	0.38	2.8% of PCE SP by weight of Cement	00	743	0.8	3.2	6.2	1.0	3.8	6.6	0.84	9.4	2
2			10	748	1.1	3.1	7.2	1.5	4.6	7.8	0.88	9.1	2
3			20	752	0.8	2.5	6.9	1.2	4.3	7.5	0.85	8.6	2
4			30	755	0.6	2.3	6.4	1.1	4.1	7.1	0.84	8.4	2
5			40	760	0.5	2.4	5.9	0.8	3.9	6.7	0.83	8.2	2
6	0.36	2.8% of PCE SP by weight of Cement	00	732	1.0	3.2	6.6	1.4	4.2	7.1	0.82	9.6	2
7			10	734	1.3	3.2	7.5	1.6	4.9	8.1	0.87	9	2
8			20	741	0.9	2.9	7.0	1.4	4.5	7.9	0.80	8.4	1.5
9			30	745	0.8	2.7	6.2	1.3	4.3	7.5	0.98	8.4	1.5
10			40	747	0.7	2.3	6.0	1.1	4.2	7.1	1.00	8.2	2
11	0.36	2.4% of PCE SP by weight of Cement	00	715	1.7	3.5	7.9	1.8	5.9	9.1	0.85	10.5	1.5
12			10	720	1.5	3.0	7.8	1.7	5.7	8.7	0.88	9.2	1.5
13			20	724	1.4	3.2	7.5	1.7	5.4	9.2	0.90	9.0	1.5
14			30	732	1.3	3.0	6.9	1.5	5.2	9.4	0.87	8.5	1.5
15			40	729	1.1	2.8	6.4	1.4	5.1	9.6	0.89	8.6	1.5
16	0.36	2.2% of PCE SP + VMA by weight of Cement	00	652	1.5	4.4	-	1.7	5.6	-	0.84	11.4	1
17			10	700	1.3	3.9	7.6	1.6	5.3	8.0	0.85	10.9	1
18			20	710	1.0	3.7	7.0	2.0	5.0	9.0	0.84	10.5	0.5
19			30	705	1.0	3.4	4.0	1.0	6.0	8.8	0.88	10.4	0.5
20			40	725	0.8	3.3	5.0	1.9	6.0	8.4	0.90	10.2	1

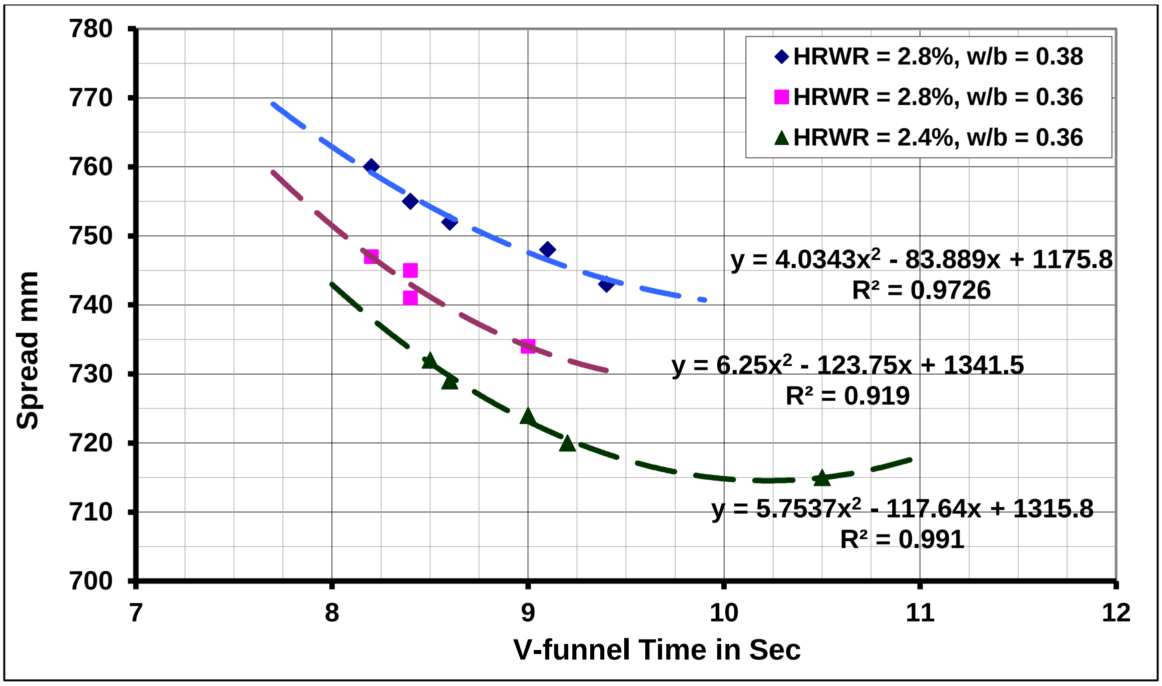


Fig 2: Combined Influence of w/b Ratio and Dosage of HRWR on both Spread Diameter and V-funnel Time

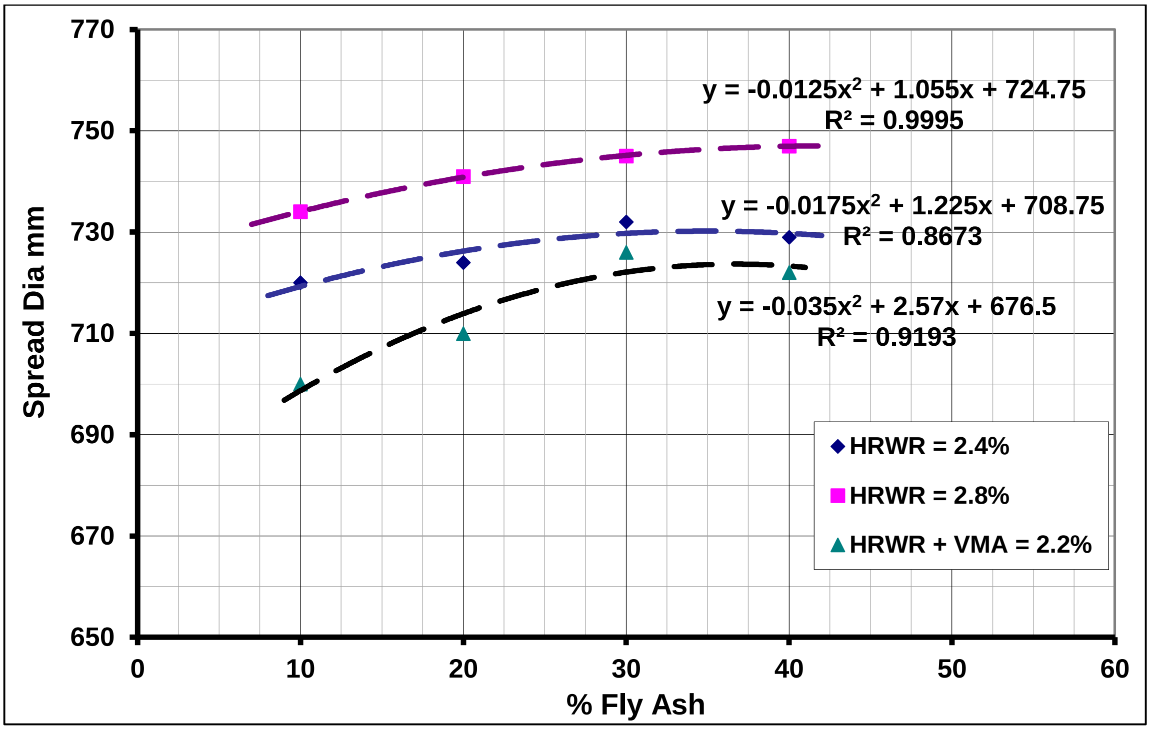


Fig 3: Influence of Fly Ash Percentage on Spread Dia at w/b = 0.36

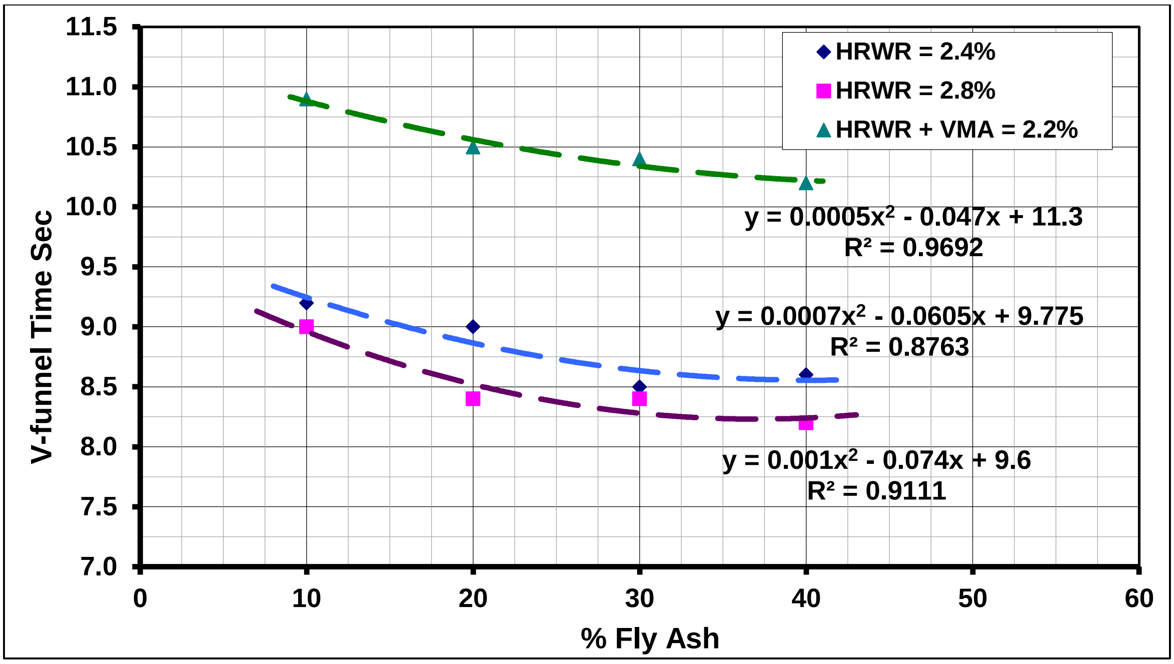


Fig 4: Influence of Fly Ash Percentage on V-funnel Time at w/b = 0.36

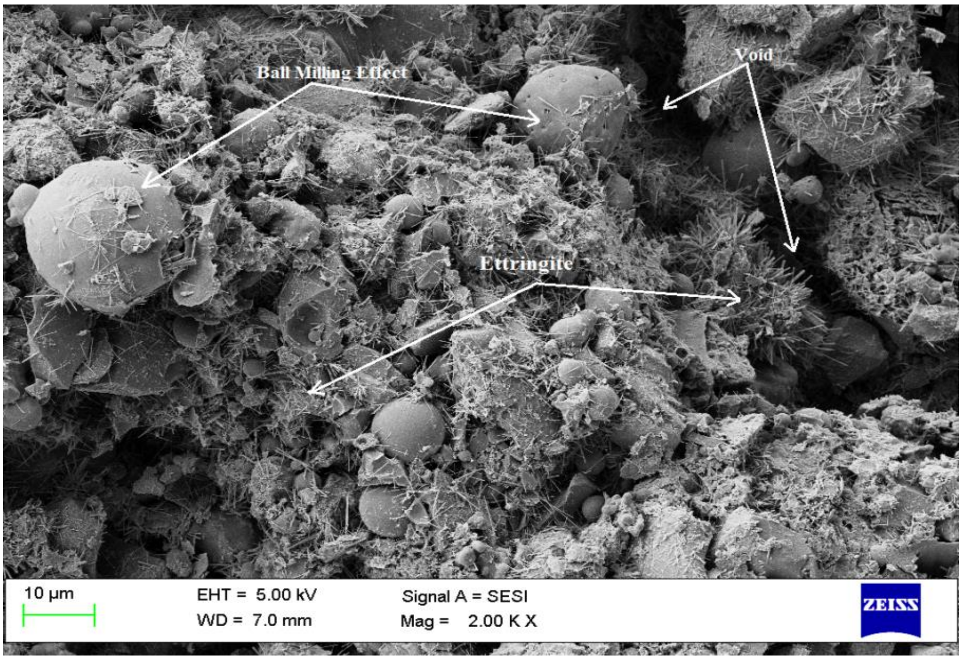


Fig 5: SEM Image Showing Ball Milling Effect of FA particles in SCC Mixture

3.2 CORRELATION BETWEEN FLOWABILITY INDEX

The test methods described in (34) are devised specifically for SCC and are mainly definitive. No correlation has yet been developed between the different flowability parameters to standardize these test methods. Many researchers in the past have used T-500 and V- funnel time as an indicator of viscosity in case of self-compacting concrete, and have indicated co-relations between these two parameters. Through the different flowability test results, an effort has been made to develop a correlation between different flowability parameters using regression analysis in MINITAB software. All 20 experimental data irrespective of w/b ratio and dosage of superplasticizers were used to develop the correlation between different flowability parameters. A good correlation exists between V-funnel time and T-500 time for all SCC mixes with a correlation coefficient R^2=0.84, as indicated in Fig 6. Relationship between V-funnel time and T-500 time has also been reported in the past and is presented in Table 6.

Table 6: Correlation equation between T-500 and VF time

Author	Correlation equation	R^2 value
Beton & Wüstholz (47)	$T_{500} = 0.261 \times VF_{Time} + 0.523$	0.77
Felekoğlu & Sarıkahya (48)	$VF_{Time} = 2.83 \times (T_{500})^{2.05}$	0.87
Safiuddin, Salam, & Jumaat (49)	$VF_{Time} = 2.7614 \times T_{500} + 0.6247$	0.92
Savić & Aškrabić (50)	$VF_{Time} = 1.666 \times T_{500} + 7.457$	0.86
Present work	$VF_{Time} = 6.073 + 0.403 \times T_{500} + 0.2025(T_{500})^2$	0.84

Most of the authors have presented a linear correlation between V- funnel time and T-500 time however in the present work both quadratic and linear models were tried, and both the models were statistically significant with 95% confidence level (p<0.05). However, the quadratic model was chosen in the present work as the regression coefficient was more as compared to the linear model. The prediction plot at a 95% confidence interval is shown in Fig 7.

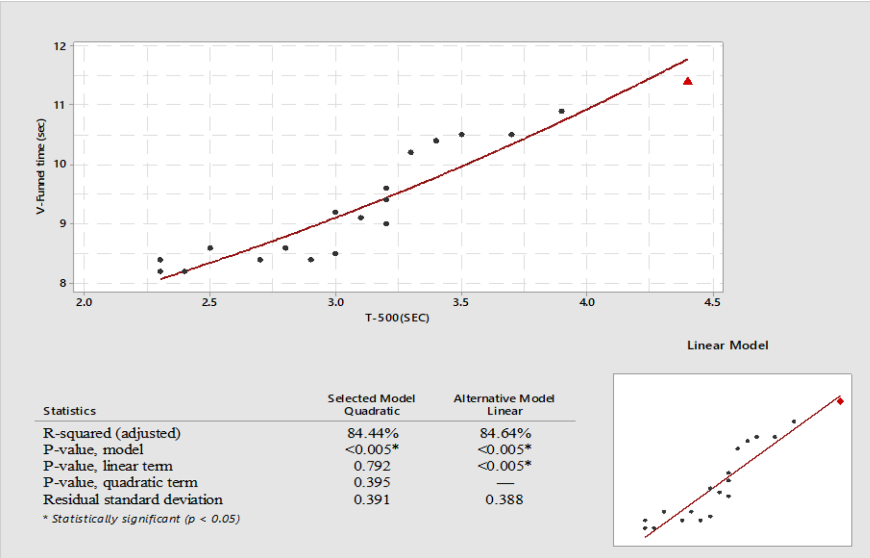


Fig 6: Correlation between T500 and V Funnel Time

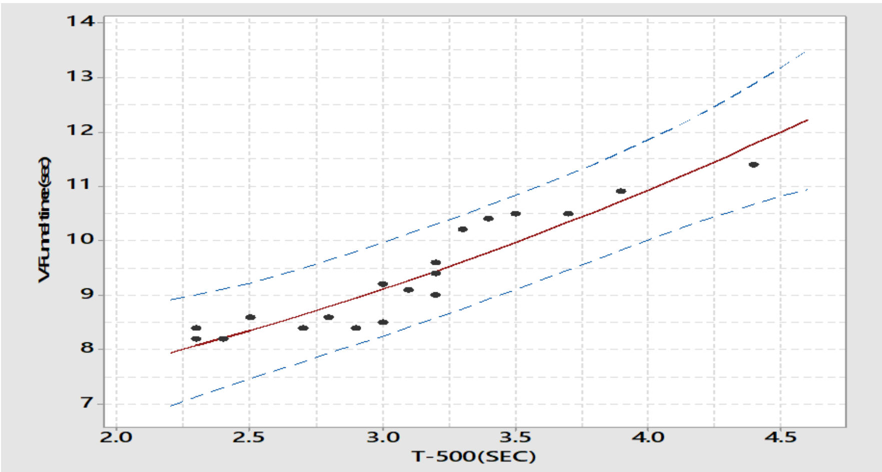


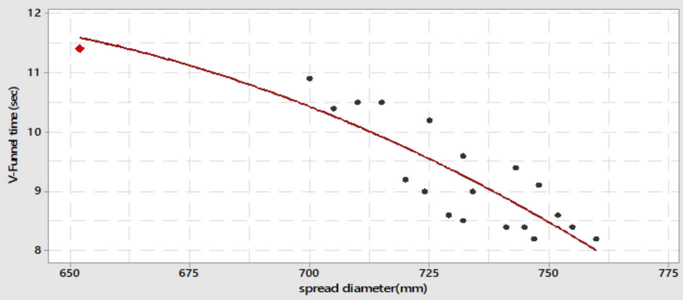
Fig 7: Prediction Plot for V Funnel Time

Spread diameter, in the present work, has also been considered as an indicator of viscosity in case of self-compacting concrete; hence correlation between spread diameter and V-funnel time and spread dia and T-500 time has also been developed and is shown in Fig 8 and Fig 9 respectively. Second order polynomial equation fitted best with high correlation coefficient.

$$VF_{Time} = -\,41.43 \;+\; 0.1796\ \text{Spread dia} \;-\; 0.000151\ (\text{Spread dia})^2 \quad \ldots\ldots\ldots\ldots (4)$$

$$\text{Spread dia} = -20.43 + 0.08695T_{500} - 0.000075(T_{500})^2 \quad \ldots\ldots\ldots\ldots (5)$$

Similar expressions between spread diameter and V- funnel time have been reported in the literature (16,51,52). The prediction plot at a 95% confidence interval is shown in Fig 10 and Fig 11, respectively.



Statistics	Selected Model Quadratic	Alternative Model Linear
R-squared (adjusted)	73.36%	72.71%
P-value, model	<0.005*	<0.005*
P-value, linear term	0.329	<0.005*
P-value, quadratic term	0.247	—
Residual standard deviation	0.511	0.518

* Statistically significant ($p < 0.05$)

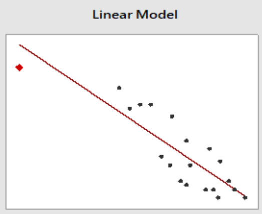
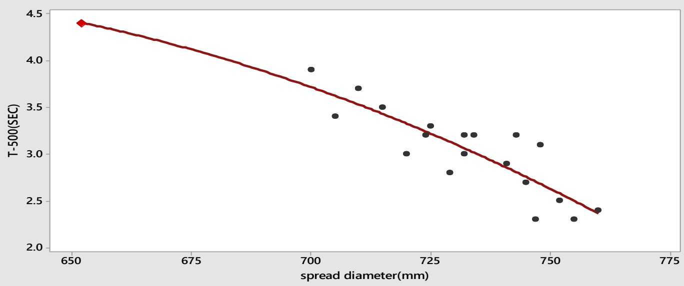


Fig 8: Correlation between V Funnel Time and Spread Diameter



Statistics	Selected Model Quadratic	Alternative Model Linear
R-squared (adjusted)	80.58%	79.86%
P-value, model	<0.005*	<0.005*
P-value, linear term	0.307	<0.005*
P-value, quadratic term	0.214	—
Residual standard deviation	0.236	0.241

* Statistically significant ($p < 0.05$)

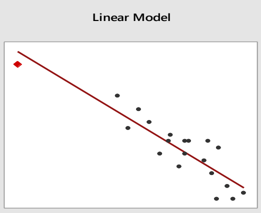


Fig 9: Correlation between T-500 and Spread Diameter

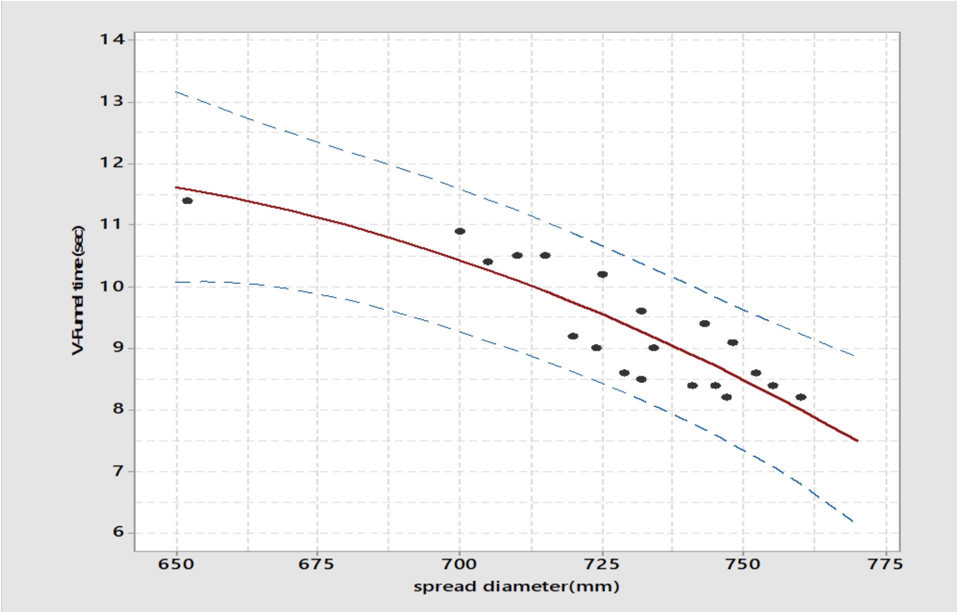


Fig 10: Prediction Plot for V Funnel Time with Spread Diameter

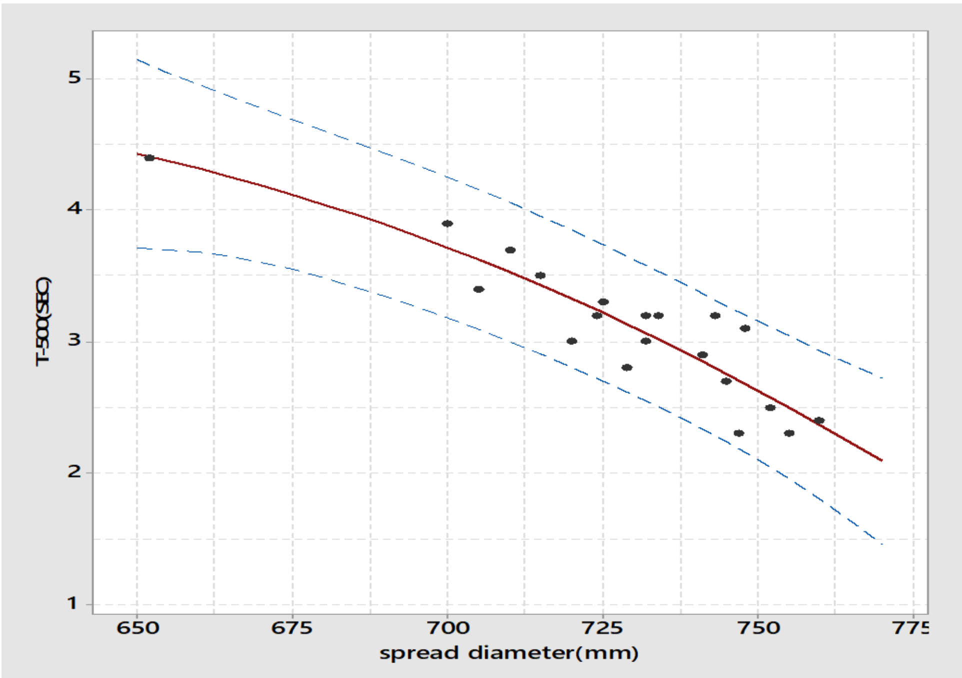


Fig 11: Prediction Plot for T 500 with Spread Diameter

3.3 EFFECT ON COMPRESSIVE STRENGTH

Three different sets of mix proportion were cast to study the influences of the different parameter on the fresh and hardened properties of SCC. Table 7 presents the descriptive statistics of all 60 cube specimens prepared to evaluate the compressive strength at 28 days.

Table 7: Descriptive Statistics of the Test Samples

w/b	PCE-SP By Weight of Cement	Sample Number	Mean	Std Dev	Normality Test	P Value
0.38	2.80%	15	44.65	1.24	Pass	0.842
0.36	2.80%	15	47.40	1.74	Pass	0.685
0.36	2.40%	15	48.07	1.94	Pass	0.107
0.36	2.20%	15	52.79	1.11	Pass	0.515

The comparative analyses of the results of the cube compressive strength test at 14 days, 28 days and 56 days are presented in Table 8. The compressive strength increased with a decrease in the percentage of the fly ash and the water-to-binder ratio. These observations are in agreement with the findings of Zhao et al. (53) and Güneyisi et al. (20). In case of the first set of experiments, where, the dosage of PCE SP was fixed at 2.8% by weight of cement, the cube compressive strength is on a higher side of w/b ratio 0.36 as compared with w/b ratio 0.38 at both 28 and 56 days. Further, it can be inferred that in the same water to binder ratio, there was an increase in compressive strength when PCE SP with VMA was used in the trial mixes. The increase observed was almost 10% as compared to the strength of the trial mixes were only HRWR was used.

From the results, it can be seen that at 56 days, the increase in compressive strength for all the mixes is almost 25% as compared to that at 28 days strength. This may be due to the slower pozzolanic reaction of the FA with the $Ca(OH)_2$ of the hydrated cement at an early age. It has been reported (54,55) that at the age of 56 days, about 15% FA undergoes pozzolanic reaction, forming a gel-like calcium silicate hydrates (CSH) and consequently results in about 20% increase in compressive strength. From Fig 12 it can also be inferred that at 30% replacement of FA with cement, the compressive strength increased by about 7% as compared to 20% replacement of FA by weight of cement. However, the compressive strength increase is nominal at 40% replacement of FA as compared to 20% replacement of FA by weight of cement, i.e. the strength decreases by about 3% as compared to 30% replacement of FA with cement. The same conclusions were drawn in all three sets of experiments.

Table 8: Strength Test Results

Mix No.	w/b	Chemical Admixture	% of Fly Ash by Weight of Binder	Compressive Strength (MPa)		
				14 Days	28 Days	56 Days
1	0.38	2.8% PCE SP by wt of Binder	0	38.50	46.38	57.85
2	0.38		10	25.60	43.12	55.32
3	0.38		20	24.80	44.26	56.25
4	0.38		30	27.59	44.85	62.19
5	0.38		40	26.15	44.63	58.26
6	0.36	2.8% PCE SP by wt of Cement	0	38.92	47.97	58.63
7	0.36		10	28.20	45.17	57.55
8	0.36		20	29.60	46.32	59.80
9	0.36		30	31.72	49.76	63.80
10	0.36		40	27.60	47.79	61.20
11	0.36	2.4% PCE SP by wt of Cement	0	36.36	47.48	61.34
12	0.36		10	33.67	47.12	59.92
13	0.36		20	33.90	47.37	60.23
14	0.36		30	35.10	51.26	65.26
15	0.36		40	33.50	47.13	60.12
16	0.36	2.2% PCE SP with VMA by wt of Cement	0	37.87	53.26	67.52
17	0.36		10	35.56	51.52	67.82
18	0.36		20	35.77	51.82	68.56
19	0.36		30	36.72	53.86	68.97
20	0.36		40	36.65	53.46	67.76

Test results revealed that the main factor affecting the compressive strength of SCC was the w/b ratio. The incorporation of VMA did not affect compressive strength development. The results presented in Fig 12 shows that the SCC mixes with PCE-SP with VMA resulted in the least reduction in compressive strength as compared to SCC mixes with only PCE-SP. This may be attributed to the higher air content of the modified mixes. The same has been reported by Isik et al. 2014 (56).

The lower w/b ratio, together with the PCE SP with VMA to obtain adequate flowability, favours a more compact and homogeneous transition zone, which in turn, improves the microstructure of the concrete matrix and thus enhances the mechanical characteristic of the concrete. The SEM image of SCC mixture with FA shown in Fig 13 confirms the above observation. With the addition of FA, the mix becomes cohesive after the hydration, and after subsequent symbiotic pozzolanic action, the voids created during leaching was arrested with FA after the formation of C-S-H gel. Also, the formation of voids is avoided since, in SCC, there is no need to apply external vibration, during pouring (57).

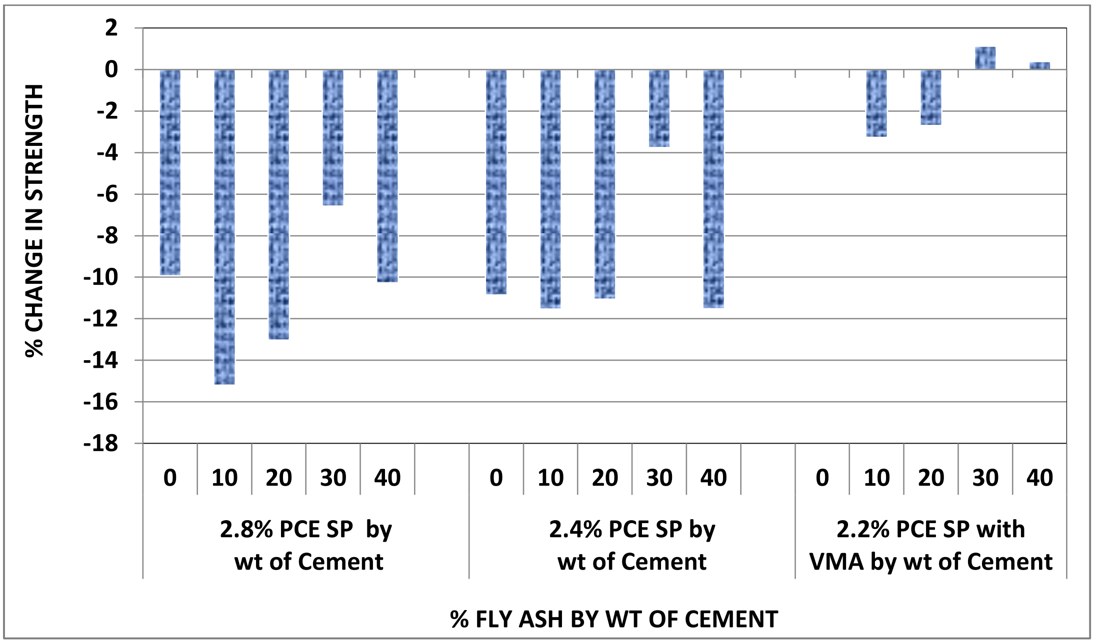


Fig 12: Percentage Increase or Decrease in Strength at Same w/b Ratio

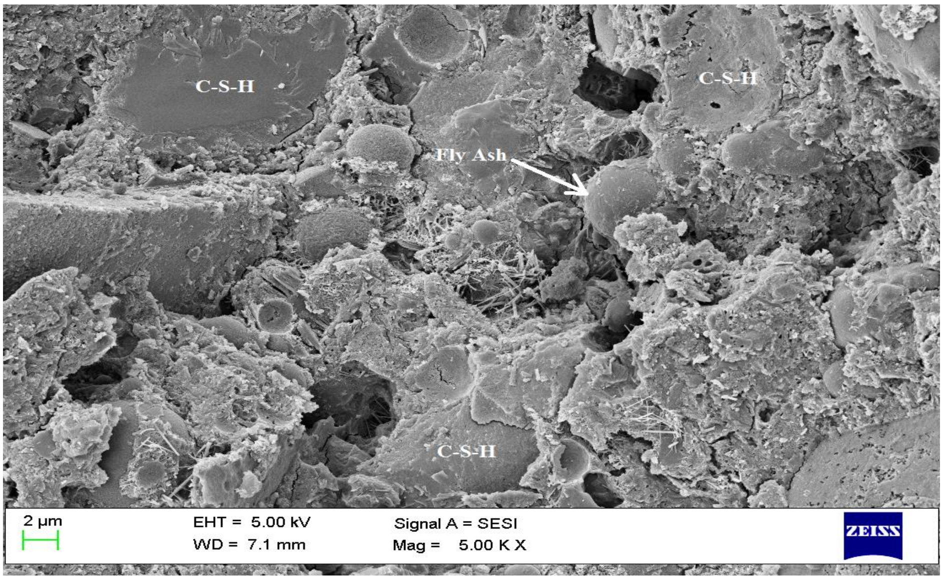


Fig 13: SEM Image Showing Formation CSH Gel in SCC Mixture with 30% FA

3.4 EFFECT ON SPLIT TENSILE STRENGTH

In the present study, the splitting tension of all SCC mixes was assessed, and the results are shown in Fig 14. It clearly indicates that split tensile strength increases with a decrease in w/c ratio. The effect of VMA was most prominent on split tensile strength test results as VMA helped in increasing the cohesiveness of the SCC mixes. This is attributed to an improved bond between the aggregates and the paste in the SCC mixtures (57).

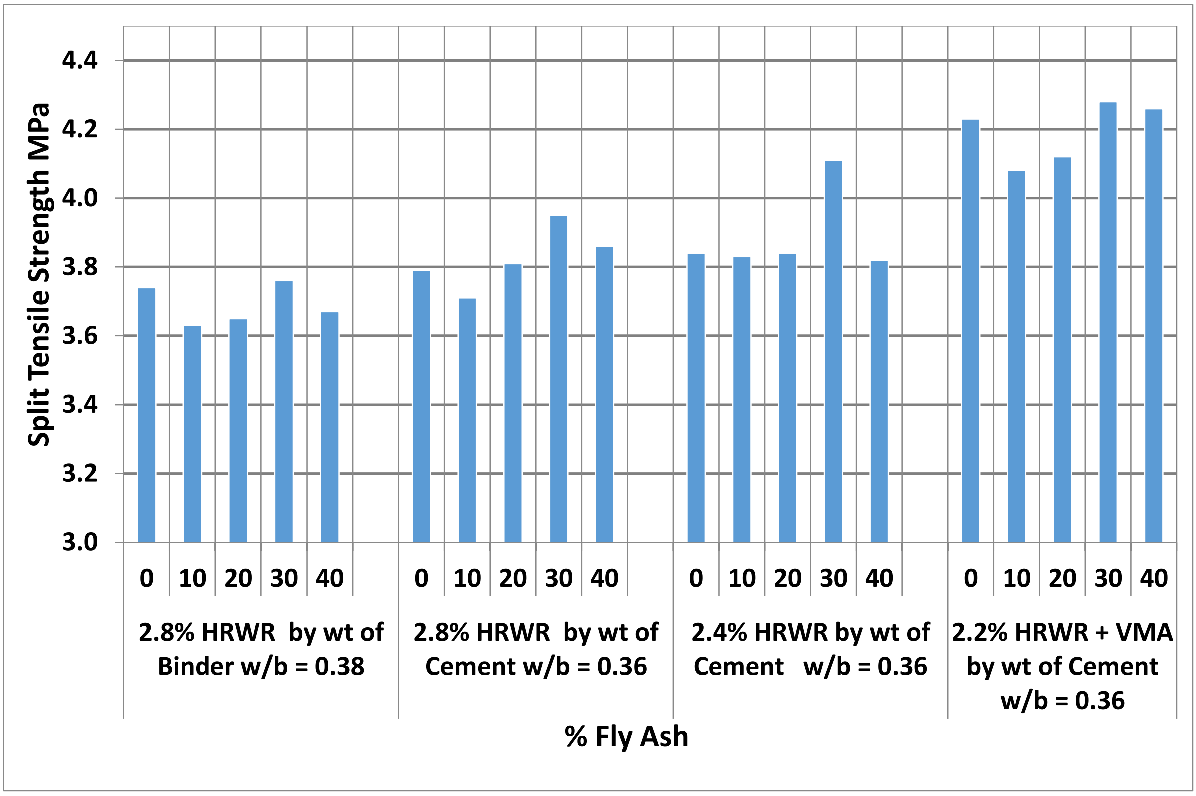


Fig 14: Split Tensile Strength Test Results

3.4.1 Relationship between Split Tensile Strength and Compressive Strength

For serviceability of RC structures, the direct or indirect tensile strength of concrete should be used as an indication of cracking in concrete. The American standard test method (ASTM), (58,59) suggests an indirect method (splitting tensile strength) to measure tensile strength, however, ASTM has no recommendations for direct tension test for concrete, as it is challenging to ensure that uniaxial stress along the specimen is evenly applied. Further, in accordance with MC 2010 and EC 2 (60) the direct tensile strength (f_{ct}) can be converted into the splitting tensile strength(f_{ts}) by using a conversion factor Asp, presented in Eq. (6):

$f_{ct} = A_{sp} \times f_{ts}$ ………………………………………………………………………….………..……….. (6)

With:

A_{sp} = 0.9 for all concrete grades according to EC 2.

A_{sp} = 1.0 for all concrete grades, according to MC 2010.

However, it is not quite clear whether these conversion factors can still be used for SCC. In the present work splitting tensile strength has been recorded in the lab and to establish the relationship between splitting tensile strength and cube compressive strength no conversion factor have been considered. Moreover, changes that affect SCC, such as variations in the mix design or higher fines content in the Cement-Fly or the placing of concrete, can also modify this relationship (61).

The correlation between splitting tensile strength and cube compressive strength for SCC is reported in several kinds of literature (3,62–69). Different concrete institutes and researchers have summarized the correlation between $f_{ts}$and cube compressive strength (f_{ck}) by the following general equation:

$f_{ts} = a_0(f_{ck})^{a_1}$………………………………………………………..…………………………….………………… (7)

where f_{ck} and f_{ts} are in MPa; a_0 and a_1 are regression coefficients. Logarithmic transformation was applied as the dependency in equation 6 is nonlinear. Equation 7 and equation 8 presents the relationship between f_{ck} and f_{ts} obtained after linear regression.

$$\log_{10}(f_{ts}) = -0.6925 + 0.760\log_{10}(f_{ck}) \quad (8)$$

Equation 7 was transformed into a single variable power equation in the form

$$f_{ts} = 0.205(f_{ck})^{0.76} \quad (9)$$

The proposed empirical formula (equation 8) to express the relationship between f_{ck} and f_{ts} of SCC is presented in Table 9. Table 9 also presents the correlation proposed by ACI 363R -92 (70), ACI 318-95 (71) and CEB-FIP (72).

Table 9: Proposed Empirical Relationship between Split Tensile Strength and Compressive Strength for SCC

Sl. No.	Authors	Correlation proposed	Remarks	Filler material
1	ACI363R -92 (70)	$f_{ts} = 0.59(f_{ck})^{0.5}$	Normal concrete	-
2	CEB-FIP (72)	$f_{ts} = 0.301(f_{ck})^{0.67}$	Normal concrete	-
3	ACI 318 -95 (71)	$f_{ts} = 0.56(f_{ck})^{0.5}$	Normal concrete	-
4	Felekoglu et al. 2007 (73)	$f_{ts} = 0.43(f_{ck})^{0.6}$	SCC	Limestone
5	Parra et al. 2011 (74)	$f_{ts} = 0.28(f_{ck})^{0.67}$	SCC	Limestone
6	Nikbin et al. 2014 (61)	$f_{ts} = 0.49(f_{ck})^{0.5}$	SCC	Limestone
7	Aslani and Nejadi (62)	$f_{ts} = 0.251(f_{ck})^{0.712}$	SCC	Fly ash
8	Kim (75)	$f_{ts} = 0.52(f_{ck})^{0.5}$	SCC	Fly ash
9	Present work	$f_{ts} = 0.205(f_{ck})^{0.76}$	SCC	Fly ash

Fig 15 displays the fitted line plot of equation 7 at a 95% confidence interval. The residual plots shown in Fig 16 validate the proposed relation. Fig 17 compares the formulae proposed by different codes and researchers with Equation 8 proposed in the present work. The comparison demonstrates that the relation proposed in the present work is in the vicinity of the relations proposed by CEB-FIP (72), ACI 318 (71), ACI 363 (70) codes. Vilanova et al. (57) reported that ACI 318 relations can predict the values of the tensile strength of SCC with acceptable precision. From the results of this limited study, this code shows a noticeable underestimation of the SCC tensile strength when compared with the normal concrete.

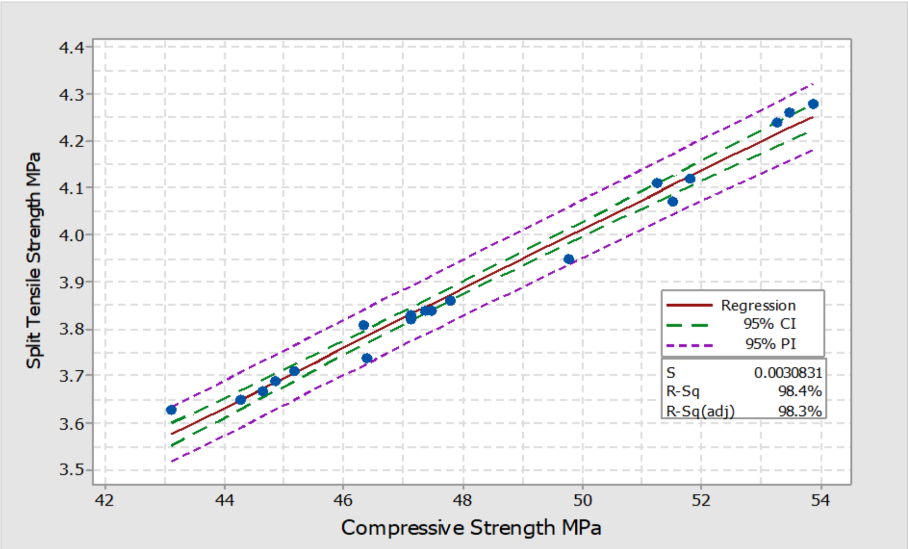


Fig 15: Relationship between Split Tensile Strength and Compressive Strength

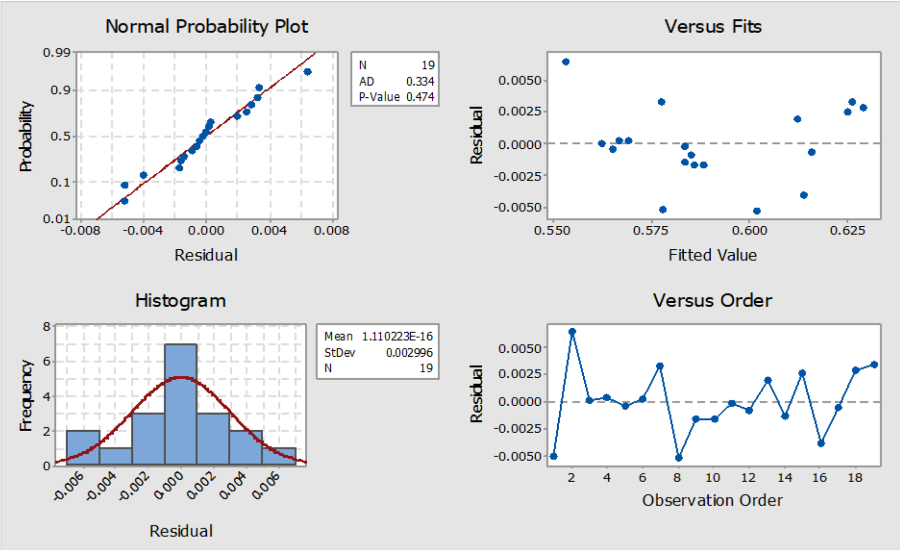


Fig 16: Residual Plots for Proposed Relation

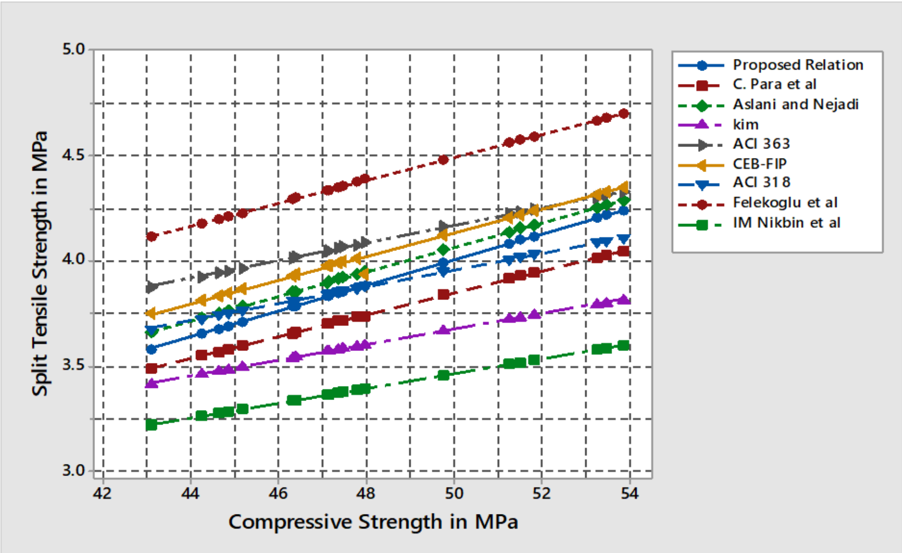


Fig 17: Comparison of the Proposed Relation with ACI 363R -92 and CEB-FIP

4. CONCLUSIONS

Based on the results of this experimental work, the following conclusions can be drawn:

1. The combined influence of w/b ratio and dosage of PCE SP on both spread diameter and V-funnel time of SCC mixes showed a quadratic relation with a high correlation coefficient. At a higher dosage of PCE SP the spread diameter achieved was near maximum at same w/b ratio, in contrary, the spread diameter decreased by a reduction in the w/b ratio for the same dosage of PCE SP.
2. The cementing efficiency factor of FA, adopted in the presented work, restored the cementitious content in the mix. The effect of FA on spread diameter and V-funnel time also showed a quadratic relation with FA replacement percentage with cement which clearly indicated that V- funnel time decreases with increase in FA percentage, while spread diameter increases with increase in FA percentage. Thus, concluding that FA lowers the viscosity of the SCC mixes which results in segregation.
3. Bleeding reduced noticeably when PCE SP with inbuilt VMA was used. The mixes with an adequate concentration of PCE SP with VMA inhibited fluidity with increased viscosity. In such concrete mixes, the viscosity built up is promoted due to association and enlargement of polymer chains of VMA at the low shear rate. This property increases the stability of the concrete and reduces the risk of segregation.
4. A good correlation existed between V-funnel time and T-500 time for all SCC mixes with a correlation coefficient. Correlation between spread diameter and V-funnel time and spread diameter and T-500 time

has also been proposed. Although the models are based on a given set of materials, they can be easily used to predict the flowability parameters with low scattering between the measured and predicted values.

5. The compressive strength increased with a decrease in the percentage of the fly ash and the water-to-binder ratio. With the addition of fly ash, it can be seen that the compressive strengths of the SCC mixes were either almost the same or below that of the control mixes.
6. The cube compressive strength was on a higher side at w/b ratio 0.36 as compared with w/b ratio 0.38 for both 28 and 56 days at same PCE SP content. For the same w/b ratio there was an increase in compressive strength when PCE SP with VMA was used in the trial mixes. The increase observed was almost 10% as compared to the strength of the trial mixes were only PCE SP was used. This may be attributed to the fact that lower w/b ratio, together with the PCE SP with VMA, favours a more compact and homogeneous transition zone, which in turn, may have improved the mechanical characteristic of the concrete.
7. The empirical formula proposed in the present work to express the relationship between compressive strength and split tensile strength of SCC is in close relation with the empirical relations proposed by different codes. The Residual Plots for Proposed Relation indicates that the proposed equation is a pretty good fit for the data. However, the values of split tensile strength achieved with the proposed equation were under predicted because of the effect of FA addition in the SCCs mix.
8. Proposed splitting tensile strength model for SCC mixtures show that there are small differences between proposed SCC models with normally vibrated concrete.

Based on experimental investigations carried out on self-compacting concrete it is recommended to produce SCCs with FA, and HRWR with VMA coupled with w/b ratio 0.36. The use of fly ash as replacement of cement may be used up to 30% by weight of cement in SCC effectively. It is further recommended to concurrently use FA with other cementitious material like silica fume to achieve early gain in strength. Moreover, the higher powder content in SCC compared to normally vibrated concrete provides an opportunity to replace the Portland cement with different types of cementitious materials which can have potential economic and environmental advantages.

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