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Influence of ca / fa Ratio on the Performance of Silica Fume Concrete

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***Abstract*—The objective of this paper is to study the influence of the ratio of coarse aggregate to fine aggregate (ca / fa) on the performance of silica fume concrete (SFC) with regard to cube compressive strength and cylinder compressive strength at 28 days. The investigation was carried out on 15
0 concrete mixes for various percentage replacement of cement with silica fume. Water – cementitious materials (w/cm) ratios adopted for the work were 0.26, 0.30, 0.34, 0.38 and 0.42. Keeping the total quantity of cementitious materials (cement + silica fume) and total aggregate constant, the work was divided into six modules with ca / fa ratios 1.55, 1.60, 1.65, 1.70, 1.75 and 1.80. The optimum value of ca / fa ratio is reported in this paper with possible reasons for the same.**

Key words*– *Silica fume concrete, ca/fa ratio, compressive strength, water – cement ratio.

I. Introduction

The usage and application of silica fume concrete (SFC) throughout the world has increased tremendously in the recent years. Many works are in progress to optimise the constituents of silica fume concrete to enhance the performance of concrete. With the advent of many supplementary chemical and mineral admixtures, the scope of enhancement has widened to a greater extent. Silica fume concrete can be produced with the addition of available supplementary cementitious materials to enhance the performance of concrete with reference to any quality or design criteria. The application of condensed silica fume as mineral admixture for making silica fume concrete with higher performance is common in the recent days and has attracted the attention of researchers throughout the world[1].

II. Related Work

Many works have been carried out on optimising various constituents of silica fume concrete. Shantanu Banja and Bratish Sengupta [1], Hooton [5], Khedr [6] and Yogendran [7] have done works on optimum replacement of cement with cementitious materials like silica fume, fly ash, ground granulated blast furnace slag, etc.

Myers [2], Sammy [3] and Karihaloa [4] attempted to find the optimum water – binder *(w-b)* ratio, optimum fineness modulus, optimum dosage of carrier fluidifying agent and optimum volume fraction of aggregates. However, researchers are yet to arrive at a unique conclusion with regard to the problem of optimising the constituents of silica fume concrete. Santanu Banja and Bratish Sengupta [1] reported that 15 to 25% of replacement of cement with silica fume gives maximum 28 – day compressive strength. Yogendran et al [7] and Hooton [5] confirmed that maximum 28 – day compressive strength was obtained at 15% replacement level for various w-b ratios and different dosages of high range water reducing admixtures (HRWRA). Khedr and Abou-Zeid [6] proved the same in their work with percentage replacement increasing for higher w-b ratio. It is found from the literature that similar works on optimising the replacement of cement with other materials give inconsistent results. The reason for this variation can be attributed to type, content, dosage of various constituents and the method of making silica fume concrete.

Canadian Portland Cement Association (1991) [8] also reported that for normal strength concretes, the optimal ratio of coarse to fine aggregate (for 14mm sized aggregates) is in the range of 0.9 to 1.4. The ratio of coarse to fine aggregates varies from 1.5 to 1.8 in works reported by Cook [9], Randall [11], Aitcin [12] and Burg [13]. However, Peterman and Carrasquillo [10] recommend an optimal value of 2.0 in their work. The present investigation aims to define the effect of ca / fa ratio on 28 – day compressive strength of cube and cylinder for various percentage replacement of cement with silica fume.

Generally the properties of concrete such as elastic modulus, tensile strength, flexural strength and shear strength are expressed as a function of uni – axial compressive strength at 28 days and this is the basis of design for most of the structures. Size of specimen, rate of loading and end conditions are a few variables that influence the compressive strength. Cook [9] along with other researchers conclude that smaller specimens exhibit a compressive strength 5% higher than bigger ones.

III. Objectives & Overview Of The Proposed Mechanism

Materials

The proportioning of silica fume concrete consists of selection of suitable ingredients, cement, supplementary cementitious materials, aggregates, water and chemical admixtures, proportioning them and production of concrete under controlled conditions. Weston [14] and Task Force

Report No, 5 [15] stressed the importance of choice of cement for silica fume concrete. Mindess [16] concluded that there are only two requirements that any cement must meet: (i) it must develop the appropriate strength and (ii) it must exhibit the appropriate rheological behaviour. Perenchio [17] proved that cements with higher C_3A content leads to higher strength. Cement used for the present investigation is Portland Pozzolana (Fly ash – IS 1489 Part 1 of 1991) [24] Cement, having a 28 – day compressive strength of 53 MPa.

Choosing the right type of aggregate is very essential as it occupies nearly 60 to 80% of the weight of concrete. While factors like, shape, size, distribution and reactivity of the aggregate affect the performance of concrete, strength of aggregate plays a vital role in the development of strength of silica fume concrete. ACI Committee 363 [18] reported that contrary to the accepted fact that smaller size of coarse aggregate leads to better performance in relation to its compressive strength, by increasing the maximum size of aggregate from 13.2 to 26.5mm improves the strength of concrete. However, an aggregate of size 12.5mm and less was used in this work. High Strength Concrete, *Manual of Concrete Materials, Aggregates* [19] recommended that the shape of aggregates shall be clear, cubical, angular and completely crushed with a minimum of flat and elongated particles. The coarse aggregate used in this work was broken granite – crushed stone of nominal maximum size of 12.5mm. The specific gravity of coarse aggregate was 1.625 and water absorption 1%. The coarse aggregate was washed before using to clean loose materials and surface deleterious materials that would affect the performance of concrete.

Fine aggregate particles should be rounded, smooth textured as it reduces the demand for water [20]. The grading of fine aggregate is ensured to lie on the coarser side of the limits stipulated in relevant IS standards [21]. The fine aggregate used was natural river sand, clean and dry with specific gravity of 2.56 and fineness modulus 2.30. The mineral admixture that was used in this work was silica fume with the following chemical properties (Elkem Microsilica Grade 955-D):

ELEMENT	*Min. / Max.*	*%*
SiO_2	Min.	95.5
C	Max.	1.0
Fe_2O_3	Max.	0.3
Al_2O_3	Max.	0.7
CaO	Max.	0.4
MgO	Max.	0.5
K_2O	Max.	1.0
Na_2O	Max.	0.4
H_2O	Max.	1.0

The chemical admixture used for this work is CONPLAST SP 430, naphthalene based super plasticizer. Potable water was used for this work.

IV. Experimental Procedure

The experimental program included six modules. Each module consisted of 25 different mixes in which the w/cm ratio and the silica fume contents were varied. The dosages of silica fume were 10, 15, 20, 25 & 30% of the total cementitious materials. Each dosage was tested at w/cm ratios 0.26, 0.30, 0.34, 0.38 and 0.42. SFC can be produced in two ways: (i) by varying the super-plasticizer content to maintain constant slump and (ii) by maintaining constant super-plasticizer content irrespective of silica fume content. In the present study, super-plasticizer content was varied in order to maintain a constant slump. The slump of concrete produced is maintained at 50mm. It is reported that strength of both cement paste and concrete can be affected by the dosage of super-plasticizer [22]. Since the variation in the concrete strength is insignificant due to the variation in the dosage of super-plasticizer, it will not affect the objective of this study. The dosage of super-plasticizer adopted was 3.5% by weight of total cementitious materials for mixes with w/cm ratios 0.26 and 0.30, 2.25% for mixes with w/cm ratios 0.34 and NIL for mixes with w/cm ratios 0.38 and 0.42.

In each module, the total weight of cementitious materials were kept constant at 520 kg/cum. Total aggregate (coarse + fine) content was also kept constant at 1,813 kg / m^3. The ca/fa ratios adopted for six modules were 1.55, 1.60, 1.65, 1.70, 1.75 and 1.80.

Mindess and Young [16] pointed out that it is necessary to pay careful attention to all aspects of concrete production, viz., selection of materials, mix design, handling and placing of concrete. During the experimental work, care was taken to keep these aspects uniform. The mix details of all modules are given below in Table 1:

Table 1: Mix Details for Different Mixes

Module no. *	ca / fa ratio	Coarse aggregate (kg / cum)	Fine aggregate (kg / cum)
1	1.55	1102.02	710.98
2	1.60	1115.69	697.31
3	1.65	1128.85	684.15
4	1.70	1145.97	667.03
5	1.75	1153.73	659.27
6	1.80	1165.5	647.50
For all modules Total cementitious content = 520 kg/cum; and Total aggregate content = 1,813 kg/cum. * - Each module involves w-cm ratios 0.25, 0.30, 0.34, 0.38 and 0.42 and various percentage replacement of cement with silica fume 10%, 15%, 20%, 25% and 30%			

All the specimens were moist cured under water at room temperature around 29 to 31^{o}C and relative humidity ranging from 50 to 70%. Tests for cube compressive strength and cylinder compressive strength were carried out in accordance with relevant IS standards [25, 26, 27]. Since it was reported that the performance of silica fume concrete is inferior when the silica fume replacement was less than 10%, during this study, silica fume replacement below 10% was not adopted [5, 6, 7].

V. RESULTS AND DISCUSSIONS

Cube compressive strength and cylinder compressive strength were found for all mixes at the end of 28 – days. The experimental results were analysed and the findings are in line with the general accepted conclusion that the mechanical properties of silica fume concrete – average cube and cylinder compressive strength were superior for lower w/cm ratios. This was proved beyond doubt in all modules of various ca/fa ratios. Other results are discussed below:

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.55		0.26	39.90	31.92
1.55		0.30	36.19	29.94
1.55	10	0.34	34.30	27.83
1.55		0.38	33.28	27.72
1.55		0.42	31.25	23.44
1.55		0.26	44.28	35.42
1.55		0.30	42.87	34.28
1.55	15	0.34	38.61	30.98
1.55		0.38	36.19	27.97
1.55		0.42	32.26	25.81
1.55		0.26	39.68	31.74
1.55		0.30	38.37	30.93
1.55	20	0.34	35.02	27.43
1.55		0.38	33.57	26.85
1.55		0.42	31.12	24.86
1.55		0.26	37.06	29.64
1.55		0.30	34.44	28.01
1.55	25	0.34	32.26	26.01
1.55		0.38	30.08	23.87
1.55		0.42	29.21	24.68
1.55		0.26	36.84	28.92
1.55		0.30	34.74	27.83
1.55	30	0.34	31.83	25.64
1.55		0.38	28.20	22.66
1.55		0.42	26.60	21.73

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.6		0.26	41.13	39.83
1.6		0.30	33.87	36.65
1.6	10	0.34	32.99	34.54
1.6		0.38	29.36	31.62
1.6		0.42	27.47	29.57
1.6		0.26	42.73	42.69
1.6		0.30	36.73	40.58
1.6	15	0.34	42.15	37.67
1.6		0.38	37.64	33.94
1.6		0.42	33.86	31.85

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.6		0.26	41.05	37.83
1.6		0.30	33.57	35.68
1.6	20	0.34	29.07	33.19
1.6		0.38	28.56	32.59
1.6		0.42	26.81	28.53
1.6		0.26	38.37	36.39
1.6		0.30	34.66	34.29
1.6	25	0.34	29.00	31.52
1.6		0.38	25.72	29.83
1.6		0.42	25.72	28.77
1.6		0.26	Mix was too harsh due to higher specific area of the ingredients	
1.6		0.30		
1.6	30	0.34	27.68	29.66
1.6		0.38	25.95	27.51
1.6		0.42	23.98	26.86

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.65		0.26	52.47	43.70
1.65		0.30	51.30	41.20
1.65	10	0.34	50.29	38.70
1.65		0.38	43.45	32.46
1.65		0.42	40.84	28.72
1.65		0.26	54.93	48.69
1.65		0.30	52.76	49.94
1.65	15	0.34	51.15	42.45
1.65		0.38	46.22	37.46
1.65		0.42	42.87	33.71
1.65		0.26	52.47	46.20
1.65		0.30	49.65	39.95
1.65	20	0.34	43.31	33.71
1.65		0.38	38.57	28.72
1.65		0.42	39.96	29.97
1.65		0.26	47.81	42.45
1.65		0.30	44.47	37.46
1.65	25	0.34	44.37	34.96
1.65		0.38	38.36	28.72
1.65		0.42	35.01	26.22
1.65		0.26	Mix was too harsh due to higher specific area of the ingredients	
1.65		0.30		
1.65	30	0.34	39.10	29.97
1.65		0.38	35.02	26.22
1.65		0.42	34.44	24.97

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.7		0.26	42.94	38.70
1.7		0.30	39.68	34.96
1.7	10	0.34	38.37	29.97
1.7		0.38	36.33	28.72
1.7		0.42	35.61	25.60
1.7		0.26	43.97	39.95
1.7		0.30	42.58	37.46
1.7	15	0.34	44.03	32.46
1.7		0.38	44.03	29.97
1.7		0.42	39.10	27.47
1.7		0.26		37.46
1.7		0.30	40.40	31.21
1.7	20	0.34	39.68	29.97
1.7		0.38	38.52	27.47
1.7		0.42	35.90	24.97

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.7	25	0.26	39.68	38.70
1.7		0.30	42.73	27.47
1.7		0.34	37.50	26.22
1.7		0.38	40.11	23.72
1.7		0.42	34.01	26.22
1.7	30	0.26	Mix was too harsh due to higher specific area of the ingredients	
1.7		0.30		
1.7		0.34	40.41	28.72
1.7		0.38	35.46	26.22
1.7		0.42	38.51	24.97

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.75	10	0.26	40.19	36.54
1.75		0.30	38.16	32.83
1.75		0.34	36.67	27.68
1.75		0.38	35.12	26.32
1.75		0.42	34.08	24.18
1.75	15	0.26	41.23	37.98
1.75		0.30	40.82	35.59
1.75		0.34	40.16	31.48
1.75		0.38	40.12	28.79
1.75		0.42	36.10	25.65
1.75	20	0.26	40.16	35.48
1.75		0.30	38.54	30.77
1.75		0.34	36.68	26.23
1.75		0.38	34.52	25.85
1.75		0.42	32.89	24.66
1.75	25	0.26	36.73	33.89
1.75		0.30	37.18	29.84
1.75		0.34	35.14	25.34
1.75		0.38	33.78	24.18
1.75		0.42	31.47	23.80
1.75	30	0.26	Mix was too harsh due to higher specific area of the ingredients	
1.75		0.30		
1.75		0.34	34.51	25.15
1.75		0.38	31.02	23.87
1.75		0.42	29.34	27.78

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.8	10	0.26	33.79	28.01
1.8		0.30	29.79	24.45
1.8		0.34	28.34	21.33
1.8		0.38	26.89	22.51
1.8		0.42	24.70	20.98
1.8	15	0.26	43.17	35.22
1.8		0.30	38.80	29.24
1.8		0.34	36.77	28.41
1.8		0.38	33.69	27.41
1.8		0.42	31.10	24.33
1.8	20	0.26	41.64	32.21
1.8		0.30	38.80	20.51
1.8		0.34	38.08	31.25
1.8		0.38	36.48	30.41
1.8		0.42	33.86	28.54
1.8	25	0.26	33.36	27.98
1.8		0.30	32.41	24.34
1.8		0.34	31.10	23.54
1.8		0.38	27.76	23.04
1.8		0.42	25.87	21.65

ca/fa	% rep of cement with silica fume	w-cm	σ_{cube}	σ_{cyl}
1.8	30	0.26	Mix was too harsh due to higher specific area of the ingredients	
1.8		0.30		
1.8		0.34	30.81	24.31
1.8		0.38	27.61	23.54
1.8		0.42	29.36	22.95

A. Cube Compressive Strength

Percentage Replacement of Cement with Silica Fume: Fig 1 shows the variation of average cube compressive strength with respect to percentage replacement of cement with silica fume for various w/cm ratios when ca/fa ratio was 1.55. Fig 2 shows the similar variations for ca/fa ratio of 1.80. From these figures it can be seen that the average cube compressive strength is maximum when the silica fume replacement is 15%. The same trend is observed for other ca/fa ratios also. Hence, it can be concluded that performance of silica fume concrete with regard to cube compressive strength is maximum at 15% replacement of cement with silica fume.

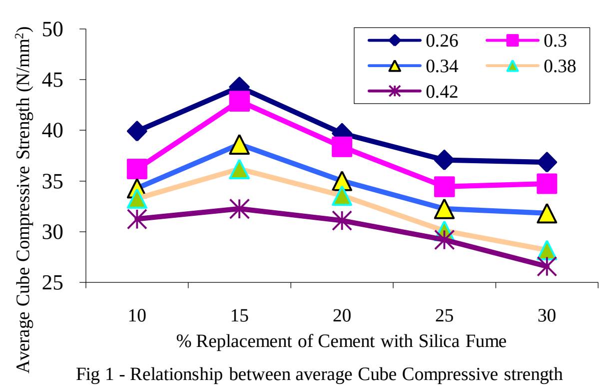

Fig 1 - Relationship between average Cube Compressive strength and percentage Replacement of cement with silica fume for various w/cm ratios (ca/fa ratio = 1.55)

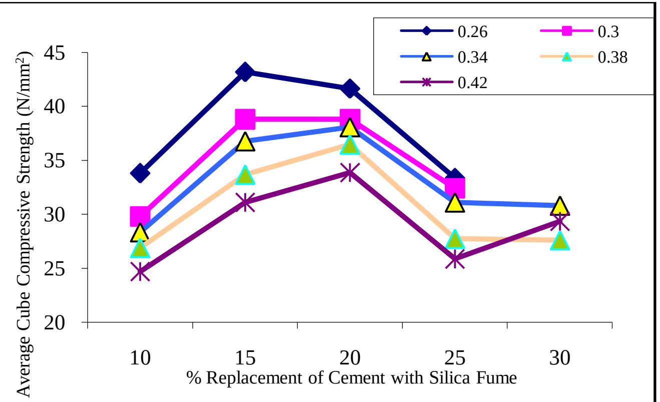

Fig 2 - Relationship between average Cube Compressive strength and percentage Replacement of cement with silica fume for various w/cm ratios (ca/fa ratio = 1.80)

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Ca/fa ratio

The effect of ca/fa ratio on the compressive strength of concrete has not widely been discussed by many researchers. This ratio is important since it decides the quantity of fines that is present in the mix. For a given quantity of total aggregate, the percentage of fines decreases as the ratio increases. Thus any variation in ca/fa ratio affects the compressive strength of concrete which in turn affects other physical properties. During the course of this work, extensive study is made on the effect of ca/fa ratio on the performance of silica fume concrete.

Fig. 3 shows the variation of average cube compressive strength with respect to ca/fa ratio for various percentage replacements of cement with silica fume for w/cm ratios 0.26. Fig. 4 shows the similar variation for w/cm ratio 0.42. From these figures it can be seen that the average cube compressive strength is maximum when the ca/fa ratio is 1.65. The same trend is observed for other w/cm ratios also. Hence, it can be concluded that performance of silica fume concrete with regard to cube compressive strength is maximum at ca/fa ratio 1.65.

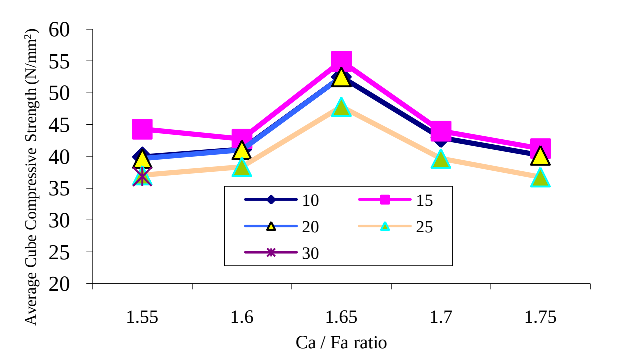

Fig 3 - Relationship between Average Cube Compressive strength and ca/fa ratio for various Percentage Replacement with Silica Fume (for w/cm - 0.26)

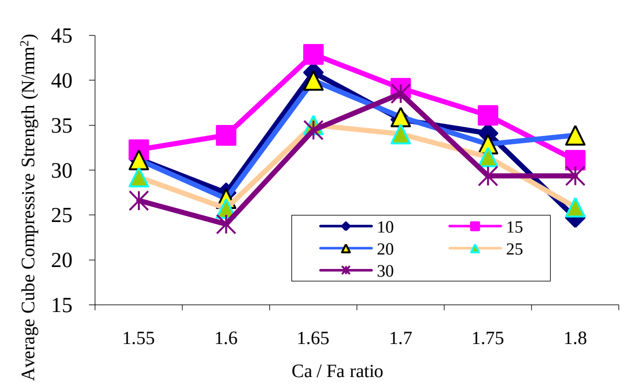

Fig 4 - Relationship between Average Cube Compressive strength and ca/fa ratio for various Percentage Replacement with Silica Fume (for w/cm - 0.42)

Cylinder Compressive Strength

Percentage Replacement of Cement with Silica Fume

Fig. 5 shows the variation of average cylinder compressive strength with respect to percentage replacement of cement with silica fume for various w/cm ratios when ca/fa ratio was 1.65. Fig 6 shows the similar variations for ca/fa ratio of 1.75. From these figures it can be seen that the average cylinder compressive strength is maximum when the silica fume replacement is 15%. The same trend is observed for other ca/fa ratios also. Hence, it can be concluded that performance of silica fume concrete with regard to cube compressive strength is maximum at 15% replacement of cement with silica fume.

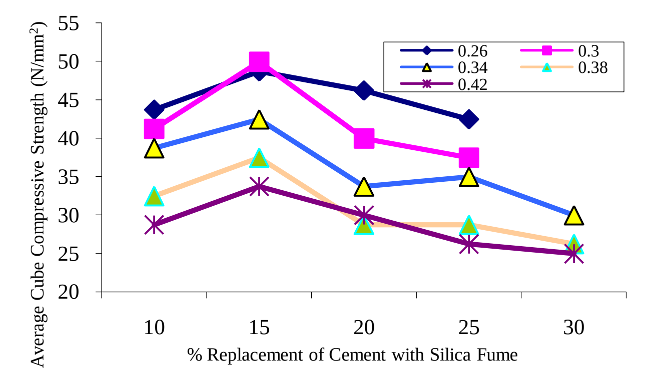

Fig 5 - Relationship between average Cylinder Compressive strength and Percentage Replacement of cement with silica fume for various w/cm Ratios (ca/fa ratio = 1.65)

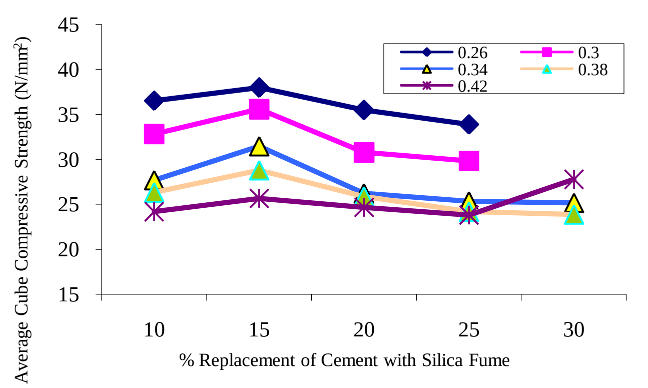

Fig 6 - Relationship between average Cylinder Compressive strength and Percentage Replacement of cement with silica fume for various w/cm Ratios (ca/fa ratio = 1.75)

Ca/fa ratio: Fig. 7 shows the average cylinder compressive strength with respect to ca/fa ratio for various percentage replacements of cement with silica fume for w/cm ratios 0.30. Fig. 8 shows the similar variation for w/cm ratio 0.34. From these figures it can be seen that the average cube compressive strength is maximum when the ca/fa ratio is 1.65. The same trend is observed for other w/cm ratios also. Hence, it can be

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concluded that performance of silica fume concrete with regard to cube compressive strength is maximum at ca/fa ratio 1.65.

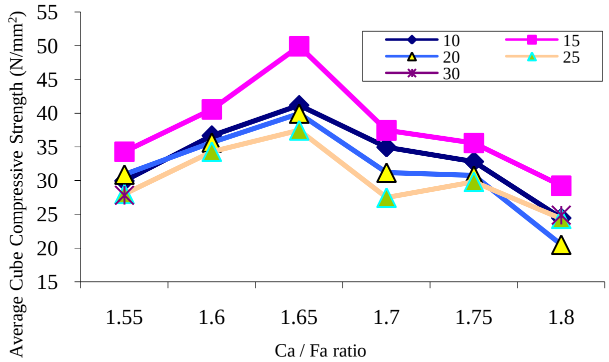

Fig 7 - Relationship between average Cylinder Compressive strength and ca/fa ratio for various Percentage Replacement of cement with silica fume (for w/cm - 0.30)

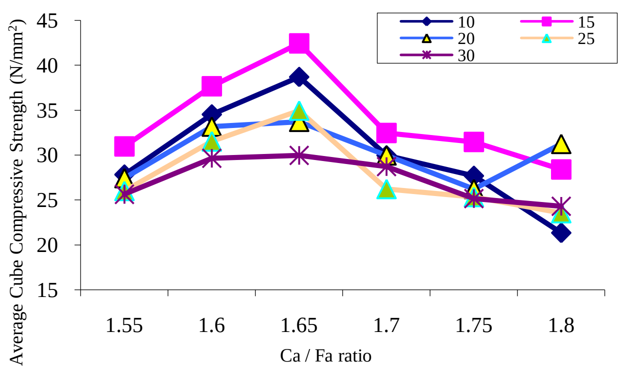

Fig 8 - Relationship between average Cylinder Compressive strength and ca/fa ratio for various Percentage Replacement of cement with silica fume (for w/cm - 0.34)

Optimum Percentage Replacement of Cement with Silica Fume

The analysis of the results indicates that the performance of silica fume concrete with regard to the cube and cylinder compressive strength is superior when the percentage replacement of cement with silica fume is 15%.

The reason for this when analysed, it was found that, as the percentage replacement of cement with silica fume increases, the quantity of silica fume that participates in the pozzalonic activity decides the performance of concrete. In the case of 10% replacement it can be concluded that majority of the silica fume content have participated in the chemical reactions while still a portion of it taking part in the filling effect. As the percentage of replacement of cement with silica fume increases, it was noticed that the performance enhanced till 15% replacement. When the percentage replacement was further increased, it was noticed that the performance of concrete became inferior relatively. This may be due to the fact that as percentage of replacement increases beyond certain limit, a major portion of the silica fume content may remain as filler. This will result in the increase of specific surface, thus leading to more demand of water.

Ca/fa ratio

During this work, it was found that the performance of mechanical properties of silica fume concrete viz., cube and cylinder compressive strength is relatively best when ca/fa ratio was 1.65.

VI. CONCLUSION

The following conclusions were derived based on the experimental investigation:

1. The silica fume high performance concrete has maximum cube compressive strength and cylinder compressive strength when the replacement of cement with silica fume is 15%.
2. The silica fume high performance concrete has maximum cube compressive strength and cylinder compressive strength when the ca/fa ratio is 1.65.
3. The ratio of cylinder compressive strength to cube compressive strength decreases as the w/cm ratio increases for all replacement levels of cement with silica fume.
4. The volume of voids in the coarse aggregate and fine aggregate is found to have a minimum value when the ca/fa ratio is 1.65.

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