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Mix Design Aspects of High Performance Concrete Comprised of Silica Fume and Fly Ash

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Abstract: With massive developments taking place in the construction industry, the demand for high performance concrete (HPC) is steadily increasing. It is possible to use industrial by-products such as silica fume (SF) and fly ash (FA) as supplementary cementitious materials (SCMs), to enhance the attributes of HPC. Although numerous investigations have been carried out to identify the optimum replacement levels of these SCMs, some inconsistences are noticed in the results. In this context, a study was conducted to look into the combined effect of SF and FA on the strength and workability of HPC. Four SF replacement levels: 5%, 10%, 12.5%, and 15%; and five FA replacement levels: 0%, 5%, 10%, 15% and 20% were proposed. A total of nineteen mix proportions were used including a control mix. Water-binder ratio was kept constant at 0.35. The mixes were tested for 7 and 28-day compressive strengths and for their workability. Results obtained revealed that the maximum 7-day compressive strength was in the mix with 10% of SF with no FA and the maximum 28-day compressive strength was in the mix with 12.5% of SF and 5% of FA. The workability increased with the addition of fly ash while the SF content kept below 10%. In terms of economy, the best strength to cost ratio was found in the control mix. The extension of the k-value concept for the water/binder ratio found in EN 206 for SF-FA combinations revealed that the existing parameters k_{SF} = 2.0 and k_{FA} = 0.4 show a good correlation with the experimental results.

Keywords: High Performance concrete, Silica Fume, Fly Ash, Compressive strength, Workability, k-value concept

1. Introduction

Concrete has become the most popular and widely used construction material in the world. With massive developments taking place in the field of construction, the demand for super quality concrete, namely high-performance concrete (HPC) is increasing. In comparison to normal concrete, HPC has a higher strength, higher stiffness, greater workability, higher durability etc. [01]. The American Concrete Institute defines HPC as a concrete with special performance and uniformity requirements that cannot be met by routine conventional concrete [02].

HPC always has a low water/cement ratio in the range 0.20 to 0.45 [03]. The use of high range water reducing admixtures in HPC is essential to attain workability. It is also found that the use silica fume (SF) as a supplementary cementitious material (SCM) in HPC is vital if the desired high strength is to be achieved. Fly ash (FA) is another SCM used optionally in HPC, mainly to enhance its workability and durability [04].

The large amount of CO_2 emissions generated during the production of OPC is a major contributor to global warming and greenhouse effect. Hence in terms of sustainability, minimum use of OPC for the production of any concrete is desirable. One potential option in this regard is to use SCMs appropriately. As discussed, SF and FA are commonly used in HPC. If the optimum usage of these SCMs can be identified, it can have a positive impact on sustainability.

Many investigations have been carried out to examine the behaviour of concrete with either SF or FA. There are also mix proportioning guidelines available in this regard. [05]. However, only a few studies have investigated the combined use of these two SCMs. This study therefore investigates, through an experimental procedure, the optimum combined use of SF and FA in the production of HPC. An experimental series comprised of nineteen HPC mixes in which SF and FA contents were each varied from 0% to 15% was conducted.

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2. Literature Review

2.1 Use of Silica Fume (SF)

Numerous investigations have looked into the possibility of replacing OPC with SF. The results of the studies made by Kadri et al. [06] showed that the optimum replacement level of cement with SF is in the range 10-15% for concrete having 28-day strength of over 100 MPa. Pradhan and Dutta [07] found that the maximum compressive strength is obtained with a 20% replacement of cement with SF. They also revealed that the workability of concrete decreases as the SF levels are increased from 0 to 20%. In contrast, Amudhavali and Mathew [08] revealed that the consistency of concrete increases to about 40% as SF is increased from 0 to 20%. The experiments carried out by Priyadarshana et al. [09] using both micro silica and nano silica found the optimum replacement quantities of cement to be 10% and 5% respectively for concrete having a 28-day compressive strength of 60 MPa. They also stated that nano silica is not commonly used due to high cost and non-availability.

2.2 Use of Fly Ash (FA)

The use of fly ash as a SCM is popular in the construction industry. There are two classes of FA, namely high calcium (Class C) FA and low calcium (Class F) FA, the latter being more widely used [01]. FA is a cheap material which significantly enhances the durability of concrete. It also generates a lower amount of heat than cement during hydration [11].

Muhit et al. [04] concluded that it is possible to reduce by more than 46%, the penetration of water through concrete by mixing it with 20% of FA. Priyadarshana et al. [09] showed that the replacement of cement with 10% of FA gives the maximum 28-day compressive strength.

2.3 Combined use of SF and FA

Goyal et al. [11] suggested that for a particular strength, the use of a SF and FA combination would be more effective than using each of them alone. They found that the combination of 5% of SF and 15% of FA gives the highest increase in strength. However, Jadhav and Chavarekar [12] concluded that the compressive strength would be optimum when cement is replaced with 2.5% of FA and 2.5% of SF. Magudeaswaran and Eswaramoorthi [13] stated that when cement is replaced with 5% of SF and 10% of FA, the compressive strength would increase by 13.9%. Thus, the conclusions made with regard to the use of optimum percentages of SF and FA are somewhat contradictory.

2.4 k-value Concept

EN 206-1:2000 [05] applies the k-value concept to design concrete mixes having either SF or FA. Different k-values have been defined for using only SF or FA with cement. However, the k-value concept has not yet been proposed for SF and FA combinations. For cement types CEM I and CEM II/A (except cements including SF), the *k*-value for Class 1 SF is set to be 2.0 when the SF to cement ratio is less than or equal to 0.11 [05]. Water to binder ratio is then defined as,

$$\frac{\text{Water}}{\text{Binder}} = \frac{\text{Water}}{\text{Cement} + (2\times\text{SF})} \quad \text{..... (1)}$$

The *k*-value for FA is defined as 0.4 for cement types CEM I and CEM II/A, when the FA to cement ratio is less than or equal to 0.33 by mass [05] with water to binder ratio defined as,

$$\frac{\text{Water}}{\text{Binder}} = \frac{\text{Water}}{\text{Cement} + (0.4\times\text{FA})} \quad \text{..... (2)}$$

3. Experimental Procedure

In the experimental procedure, nineteen mix proportions were tested for strength and workability. The amounts of SF, FA and OPC were varied while keeping the total mass of cementitious material constant at 550 kg m^{-3}. The coarse aggregate, fine aggregate, water and HRWRA mass were kept constant in all of the concrete mixes.

3.1 Material Specifications

Ordinary Portland cement (OPC) (strength class 42.5 N and Blaine fineness 3000 cm^2/g) was used as the main binder. The cement was reported to be comprised of 7.6% of C_3A, 2.3% of SO_3 and 2.1% of MgO with a lime saturation factor of 0.94. The coarse aggregate passing through a 14 mm sieve and retained on a 10 mm sieve and the fine aggregate passing through a 2.36 mm sieve were identified as the most suitable aggregates to achieve higher strength [07]. A high range water reducing admixture (HRWRA) was also used. Table 1 shows the chemical composition of the SF and FA used.

Table 1 - Chemical composition of FA and SF

Material	SiO_2	CaO	Al_2O_3	Fe_2O_3
FA (%)	52.03	5.55	32.31	7.04
SF (%)	90-98	0.2-0.7	0.4-0.9	1-2

3.2 Material Testing

Materials were tested in accordance with BS, EN and ASTM standards. The specific gravity of hydraulic cement was found to be 3.15, and the specific gravity of the coarse aggregate was found to be 2.76. The aggregate impact value (AIV) of the coarse aggregate was 34.17. The fine aggregate was analysed through sieve analysis and its fineness modulus when calculated was 3.16. Colour code 3 was observed for the fine aggregate in the organic impurity test.

3.3 Mix Proportioning

A mix design for the control mix targeted for a strength of 70 MPa with no SF and FA was carried out as set out in ACI Manual 211.4R-93 for a slump of 50 – 100 mm. The resulting mix proportions were 550 kg m^{-3} of cement, 1088 kg m^{-3} of coarse aggregate, 543 kgm^{-3} of sand, 194 kg m^{-3} of water and 1.2% of high range water reducing admixture. The required dosage of admixture was decided based on product specifications and by using trial mixes.

The eighteen mix combinations proposed for SF and FA are shown in Table 2. The notation SxFy stands for x% replacement of cement with SF and y% replacement of cement with FA both by weight.

The mix combinations were categorized into four silica fume series, namely S5, S10, S12.5 and S15. For an example, S5 would stand for 5% of OPC replaced with SF. In each of the SF series, the FA content was set at 0%, 5%, 10%, 15% and 20%. The total mass of the cementitious material was kept constant at 550 kg m^{-3}. The amounts of coarse aggregate, fine aggregate, water and HRWRA were also kept constant in all of the mix combinations at 1088 kg m^{-3}, 543 kg m^{-3}, 194 kg m^{-3} and 6.6 L m^{-3} respectively.

Table 2 – Mix proportion

Sample	Cement (kg m^{-3})	Silica Fume (kg m^{-3})	Fly Ash (kg m^{-3})	Sample	Cement (kg m^{-3})	Silica Fume (kg m^{-3})	Fly Ash (kg m^{-3})
S0F0	550.0	00.0	00.0	S10F20	385.0	55.0	110.0
S5F0	522.5	27.5	00.0	S12.5F0	481.3	68.8	00.0
S5F5	495.0	27.5	27.5	S12.5F5	453.8	68.8	27.5
S5F10	467.5	27.5	55.0	S12.5F10	426.3	68.8	55.0
S5F15	440.0	27.5	82.5	S12.5F15	398.8	68.8	82.5
S5F20	412.5	27.5	110.0	S15F0	467.5	82.5	00.0
S10F0	495.0	55.0	00.0	S15F5	440.0	82.5	27.5
S10F5	467.5	55.0	27.5	S15F10	412.5	82.5	55.0
S10F10	440.0	55.0	55.0	S15F15	385.0	82.5	82.5
S10F15	412.5	55.0	82.5				

Cubes of size 150×150×150 mm^3 were cast and tested for their 7-day and 28-day compressive strengths in accordance with BS 1881-116:1983 using the Auto-test Compression Testing Machine 3000.

Slump test was carried out for all mix combinations in accordance with ASTM C143 guidelines and the variation of the workability was observed.

4. Results and Discussion

Test results were analysed for workability, 7-day compressive strength and 28-day compressive strength. In addition, the economic feasibility of mix combinations and the *k*-value concept were also explored.

4.1 Compressive Strength and Workability

Table 3 shows the results for the average compressive strengths of the nineteen mix combinations including the control mix.

Table 3 – Avg. compressive strength results

Sample	7-Day (MPa)	28-Day (MPa)
S0F0(Control)	49.4	65.1
S5F0	50.4	66.1
S5F5	49.4	71.1
S5F10	46.8	70.8
S5F15	45.5	66.4
S5F20	45.0	62.9
S10F0	53.1	69.7
S10F5	51.3	70.6
S10F10	48.7	68.7
S10F15	43.8	67.4
S10F20	40.0	65.6
S12.5F0	49.5	69.9
S12.5F5	47.2	72.1
S12.5F10	45.8	70.1
S12.5F15	44.2	65.8
S15F0	46.7	64.4
S15F5	44.3	65.8
S15F10	40.5	63.0
S15F15	37.3	61.2

The values obtained for 7-day and 28-day compressive strengths are illustrated in Figures 1 and 2. Different hatching patterns have been used to distinguish each of the four silica fume series of S5, S10, S12.5 and S15. Figure 3 shows the slump test results.

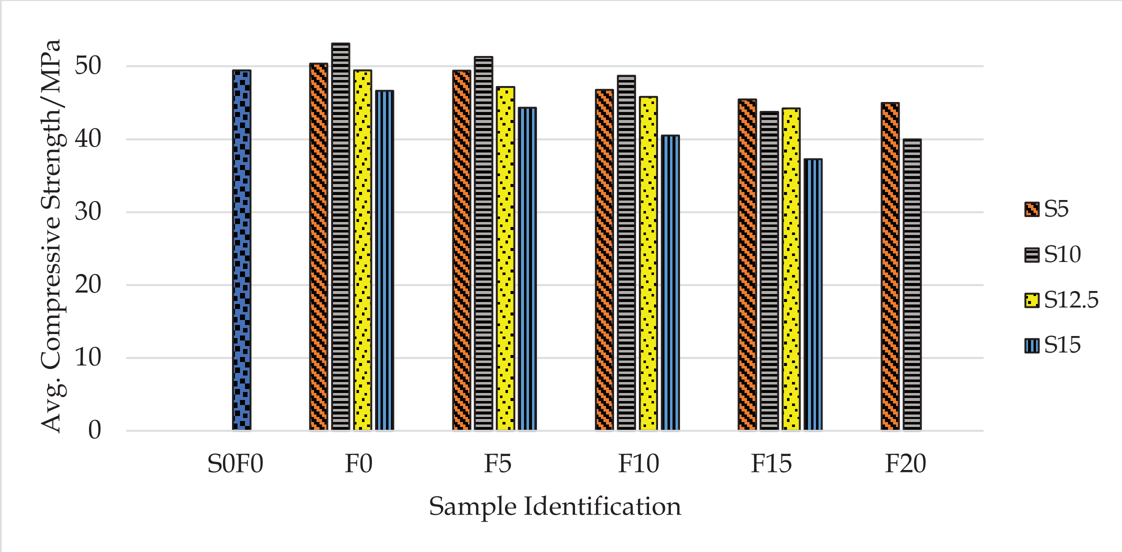


Figure 1 – Compressive Strength at 7-days

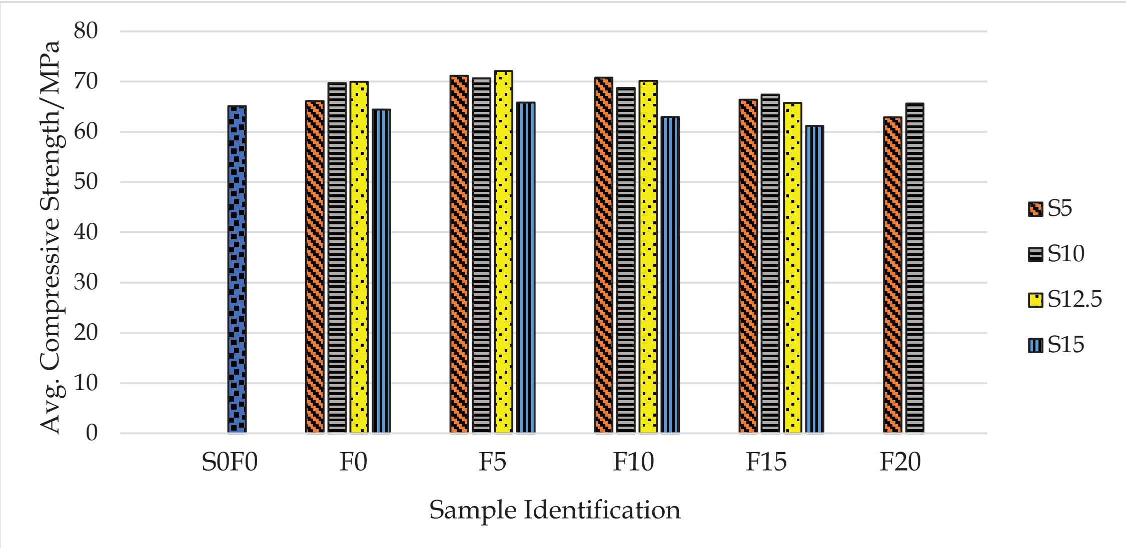


Figure 2 – Compressive strength at 28-days

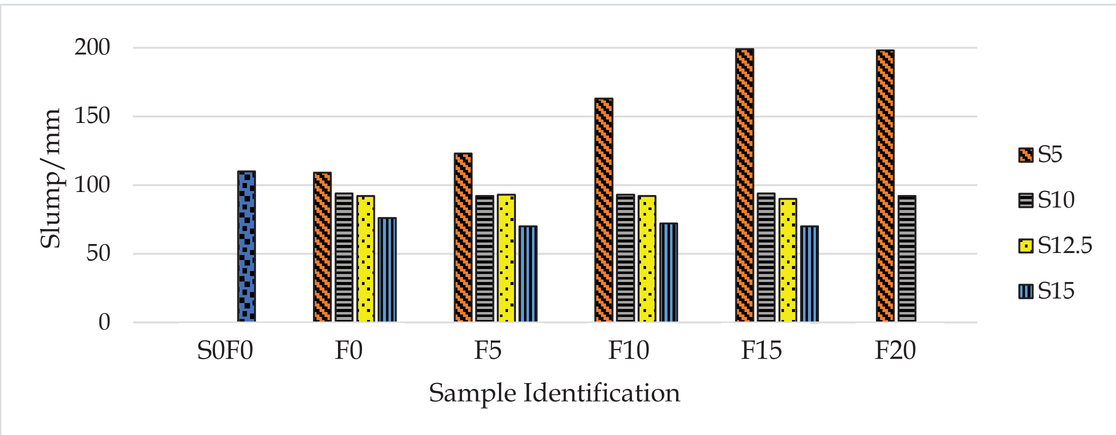


Figure 3 – Workability

Figure 1 shows that the 7-day compressive strength of each of the SF series gradually decreases as the amount of FA used is increased from 0% to 20%. It also reveals that the highest 7-day compressive strength in each of the series is present in the combination with no FA. The maximum compressive strength of 53.1 MPa is found in S10F0.

As can be seen from Figure 2, the 28-day compressive strengths of the mix combinations have followed a trend different from that of the 7-day compressive strengths. In each of the SF series, the highest strength has been given by the mix having a 5% replacement of cement with FA and the maximum compressive strength of 72.1 MPa has been shown by the S12.5F5 combination. This mix is 10.8% stronger than the control mix. It is also clearly observed that the compressive strength begins to decrease in each of the SF series as OPC is replaced with 10%, 15% and 20% of FA.

It can be observed from Figure 3 that the workability of S5 series increases as OPC is replaced with 0% to 20% of FA. However, such a variation cannot be observed in S10 and S12.5 series as the amount of FA is increased. A sudden drop in the workability can be observed which further dropped in the S15 series.

4.2 Strength / Cost Ratio

An economic analysis was carried out for the strength/cost ratio of the mixes. For this, the material prices used were as follows:

Cement - Rs. 17.40/kg; SF - Rs. 133.00/kg; FA - Rs. 3.50/kg; Coarse aggregate - Rs. 2.00/kg; Fine aggregate - Rs. 3.55/kg; and HRWRA admixture - Rs. 333/*l*.

Material cost and strength /cost ratio for each mix are tabulated in Table 4. Figure 4 illustrates the resulting strength / cost ratio for each combination.

Table 4 - Cost of 1 m³ of concrete

Sample	Cost for 1 m³ (Rs)	Strength / Cost (MPa/RS) ×1000
1. S0F0	26,046	2.50
2. S5F0	29,861	2.21
3. S5F5	29,402	2.42
4. S5F10	28,944	2.44
5. S5F15	28,485	2.33
6. S5F20	28,026	2.24
7. S10F0	33,676	2.07
8. S10F5	33,217	2.13
9. S10F10	32,759	2.10
10. S10F15	32,300	2.09
11. S10F20	31,841	2.06
12. S12.5F0	35,583	1.97
13. S12.5F5	35,125	2.05
14. S12.5F10	34,666	2.02
15. S12.5F15	34,207	1.92
16. S15F0	37,491	1.72
17. S15F5	37,032	1.78
18. S15F10	36,573	1.72
19. S15F15	36,115	1.69

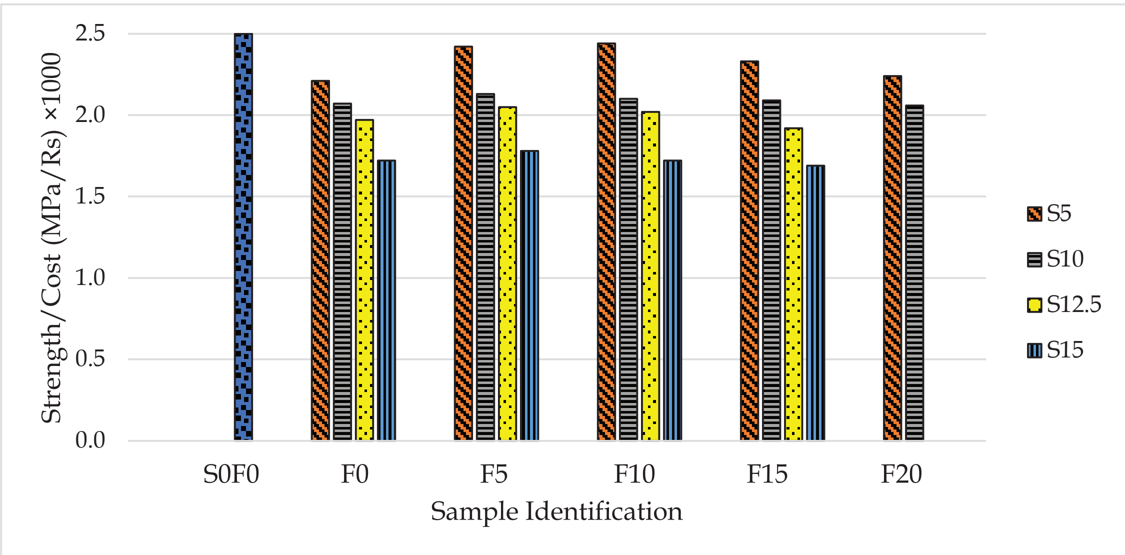


Figure 4 - Variation of strength to cost ratio

It can be noted from the figures in Table 4 that when SF is added, the cost of concrete increases. Interestingly, the control mix has the best strength/cost ratio. Of the combinations having strengths closer to 70 MPa, it is the S5F10 mix that has the maximum strength/cost ratio. The ratio of S5 series appears to be generally better than that of each of the other combination series. It has to be noted that even with the inclusion of material cost inflation, these trends would remain.

4.3 k-value Concept for SF-FA Combinations

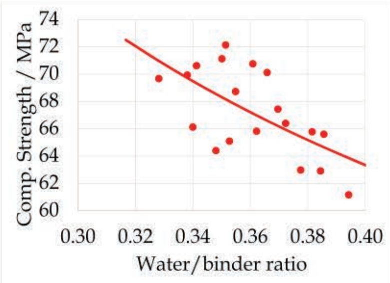
Although in all of the nineteen mixes, water/binder ratio was kept constant (=0.35), the resulting strengths were notably different. Thus, the use of an appropriate k-value is necessary to facilitate SF-FA mix designs. As a first step, the k-values given in EN 206-1:2000 [05] was studied. k-values are defined for OPC replacements with only SF or FA [05]. However, it is not clear how k values have to be used when both SF and FA are present. It was therefore decided to examine the suitability of the k-value concept, the equation for which is in the form of,

$$\frac{\text{Water}}{\text{Binder}} = \frac{\text{Water}}{\text{Cement} + (k_{SF} \times SF) + (k_{FA} \times FA)} \quad \text{.... (3)}$$

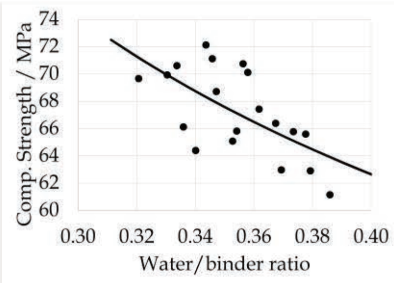
where, k_{SF}: k-value for silica fume
k_{FA}: k-value for fly ash

In this analysis, the k value of one SCM was kept constant while varying the k values of the other. When k_{SF} was kept constant while varying $k_{FA,}$ no significant outcome was noticed. Hence, k_{FA} was kept at 0.4 (k-value for individual addition of FA) while varying k_{SF} from 1.50 to 2.75 in 0.25 increments and the compressive strengths obtained were plotted against the water/binder ratios. The graphs obtained for k_{SF} values of 1.75, 2.00 and 2.25 are shown in Figures 5 (a), (b) and (c) respectively. It is to be noted that, to comply with EN206, the silica fume/cement ratio was kept at less than or equal to 0.11.

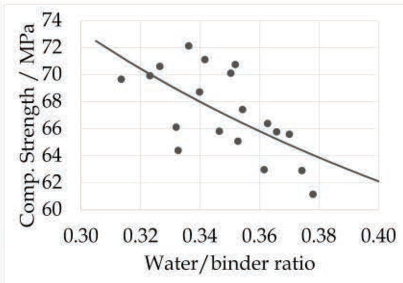
A statistical analysis in terms of R^2 values was conducted to identify the line that best fits the data shown in Figure 5, and Figure 6 illustrate the resulting R^2 values. It is observed that the best fit would be for k values of 2.25 and 0.4 for SF and FA respectively. However, the k values recommended in EN 206-1:2000 [05] for using only SA or FA which are 2.0 and 0.4 respectively also show good agreement with the experimental results. Therefore, to avoid confusion and for simplicity, the authors recommend to use the stipulated k values when using only SA or FA as well as when they are used together. Further studies in this area are matter for future work.



(a)



(b)



(c)

Figure 5 - Variation of compressive strength with water/binder ratio: (a) k_{SF}=1.75; (b) k_{SF}=2.0; (c) k_{SF}=2.25

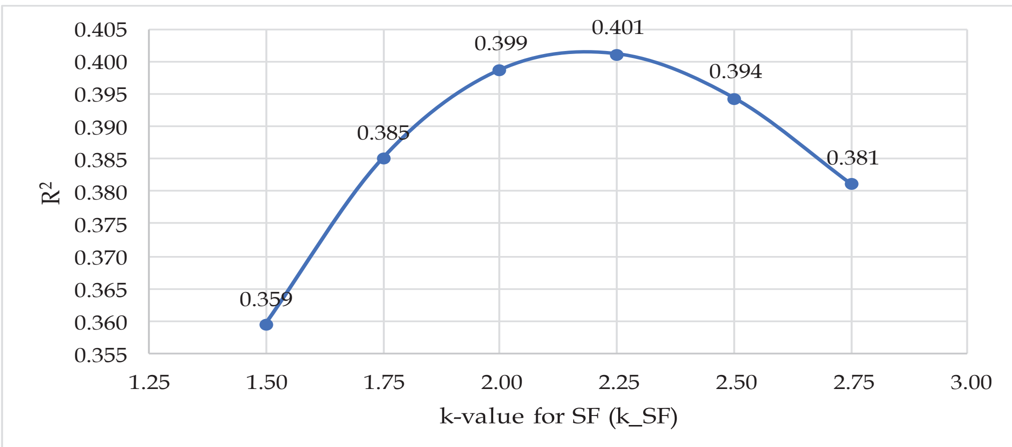


Figure 6 - Variation of R^2 values with k_{SF}

5. Conclusions

Based on the results of this study, the following conclusions could be made:

1. Maximum 7-day compressive strength is found in the mix combination of 10% of SF and no FA.

2. Maximum 28-day compressive strength is found in the mix combination of 12.5% of SF and 5% of FA.

3. 28-day compressive strength begins to decrease as FA is increased to 10%, 15%, and 20%.

4. An increase in the workability is noted as the fly ash dosage is increased in the S5 series. However, irrespective of whether fly ash is present or not, the workability of all other mixes comprised of silica fume is lower than that of the control mix.

5. In terms of economy:
   - control mix provides the best strength to cost ratio;
   - amongst the combinations having strengths closer to 70 MPa, the best strength to cost ratio is found in the mix with 5% of SF and 10% of FA.

6. K-value concept stated in EN 206-1:2000 [05] for the water/binder ratio shows a good correlation with the results for the combined use of SF and FA.

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