Chapter 5

5.0 EFFECT OF SILICA FUME ON STRENGTH AND DURABILITY

5.1 General

Silica fumes are used many parts of the world to improve the desirable qualities of concrete such as strength, impermeability, abrasion resistance and pumpability. However, it has not been used in Sri Lanka so far in a significant scale. Therefore, it is useful to investigate the effect of silica fume with commonly used aggregate in Sri Lanka. With a detailed experimental study, it was shown that 5% to 10% silica fume by the weight of cement could improve the strength while reducing the sorptivity. Thus, silica fume could be used in Sri Lanka to enhance the desirable properties of concrete with commonly used aggregate.

5.2 The main objectives and methodology

The main objectives of the research study are the following:

1. To determine the strength enhancement that can be achieved with the silica fumes for selected concrete mixes.
2. To assess the effect of silica fumes on the long term durability of concrete.
3. To determine the appropriate percentages of silica fumes to obtain the desirable strength and durability characteristics.

The following methodology was adopted to achieve the above objectives:

1. A comprehensive literature review was carried out to gather as much details as possible about the application of silica fumes in low and high strength concretes.

2. A detailed experimental programme was carried out to determine the effect of silica fumes on strength characteristics. The effect on durability was also determined for the same concrete by using the sorptivity testing.

3. The above results were used to recommend suitable percentages for silica fumes to be used with concrete, specially with low strength concretes in the context of improving durability.

5.3 The experimental programme

The experimental programme was aimed to find out the effect of silica fumes on the strength of concrete. For this purpose, the cube test results of a number of mixes were used at the ages of 7 days and 28 days.

5.3.1 The experimental programme for strength

The principal factors that affect the properties of concrete are the mix proportions (especially the cement content), the slump achieved (primarily depend on water content), compaction during placing and curing after casting. In order to isolate the effect of cement content and the silica fume percentage, the trial mixes given in Table 5.1 were selected. It was found that 20% and 30% extra cement by volume in 1:2:4 (20mm) volume batched concrete could give Grade 25 and 30 concretes, respectively. Therefore, for this study, volume batched concrete with these mixes was used although the facilities were available to produce weigh batched concrete.

Mix	Proportion	Approximate cement content kg/m^3
M_1	1:2:4 with 0% extra cement by volume	310
M_2	1:2:4 with 10% extra cement by volume	325
M_3	1:2:4 with 20% extra cement by volume	350
M_4	1:2:4 with 30% extra cement by volume	380

Table 5.1: The trial mixes used for the experimental programme and the approximate cement contents

For these mixes, the silica fume was used with 0%, 5% and 10%. These are identified as S_0, S_1 and S_2 respectively. The coarse aggregate used is well graded nominal size of 20mm to 5mm and fine aggregate is well graded medium type of aggregate according to BS

882:1983. The full details of the mixes used for the experimental programme are given in Table 5.2.

Identification	Mix propotion	Approximate Cement content per m^3	Silica fume content per m^3	% increase of cement volume relative to 1:2:4 mix	% increase of silica fume (by weight)
M_1S_0	1:2:4	310	-	-	-
M_1S_1	1:2:4+5% SF	310	15	-	5%
M_1S_2	1:2:4 + 10% SF	310	30	-	10%
M_2S_0	1.1:2:4	325	-	10%	-
M_2S_1	1.1:2:4 +5% SF	325	16	10%	5%
M_2S_2	1.1:2:4 +10% SF	325	32	10%	10%
M_3S_0	1.2:2:4	350	-	20%	-
M_3S_1	1.2:2:4 +5% SF	350	17.5	20%	5%
M_3S_2	1.2:2:4 +10% SF	350	35	20%	10%
M_4S_0	1.3:2:4	380	-	30%	-
M_4S_1	1.3:2:4+5% SF	380	19	30%	5%
M_4S_2	1.3:2:4+10% SF	380	38	30%	10%

Table 5.2: The concrete mixes used for the study

5.3.2 The method used for concrete cubes

For all the mix proportions, as it was decided to ensure that the workability remain the same. A workability indicated by a slump of 50-60 mm was selected as it is sufficient for most of the concreting processes. Since, the water cement ratio that gives such a slump is not known, it is achieved in the following manner. First the constituent materials were initially fed to a tilting drum mixer with a water cement ratio of 0.4. The slump was measured after proper mixing. At this water cement ratio, the mix generally had almost zero slump. Then, the water was gradually sprinkled and then mixed to improve the workability. The slump was measured at suitable intervals. As soon as the slump reached

50-60 mm, the mix was used to cast concrete cubes. The additional quantity of water added was used to calculate the water cement ratio.

From each mix, 6 cubes were made using the standard method. The specimens being compacted on a vibrating table in three layers (until air bubble ceased to appear at each layer) into 150 mm cube moulds. Demoulding was done on the day after casting. Curing was carried out until the compressive strength was determined.

5.3.3 The sorptivity testing procedure

The nine mixes given in Table 5.1 were used for this programme as well. The moulds used for this programme were specially fabricated for casting concrete cylinders of 100mm diameter x 100mm length PVC moulds. A 6mm thick Perspex plate was secured to one end and given a coat of formwork release agent between the plate and cylinder. The concrete cast against the Perspex surface was used as the working surface. Inside of the cylinders was applied with mould oil to ease the removal of cast specimens. From each mix, two specimens were compacted into the moulds in two layers so that it is having medium level of compaction which gives a more realistic representation of the site practice. The time for the medium level of compaction was obtained by vibrating the quarter of the duration employed for higher compaction as used by Dias (1994). The time required for such a high compaction was obtained when the air bubble had ceased to appear at each layer. The casted cylinders are shown in Figure 5.1.

The demoulding procedure employed were identical to that of cube case. Dias (1991) has recommended a minimum of 7 days of moist curing for concreting in hot climates. Hence, in order to match site conditions, the specimens were cured for 7 days. After the above curing, all the specimens were kept in an oven for 48 hours at constant temperature of 50 ^{0}C until the moisture equilibrium was achieved. (ie. the specimen stopped loosing mass). After mass stabilization, the specimens were coated with two layers of an epoxy resin on their curved surface only, in order to ensure uniaxial water absorption. They were made to absorb water with their axes vertical, through sponges of 12mm placed in a shallow tray of water. Sponges were saturated in water and water level inside the tray was controlled such that half the thickness of sponges to promote the water absorption. Cast surface of specimens were used for sorptivity testing, because most surface of site cast concrete would be cast as opposed to free. The specimens at the sorptivity testing are shown in Figures 5.2 and 5.3.

The masses of the specimens were then taken after 1, 4, 9, 25 and 49 hours of absorption. The determination of mass was done by removing the specimens from their sponges, shaking off excess moisture and placing them with their dry surface on an electronic pan balance, so that absorbing surface would not be touched, and then return them to their sponges. It was assumed that no disturbance to the absorption process occur as weighing operation was completed in under 15 seconds.

The sorptivity was obtained by plotting the volume absorbed per unit wetted area aginst the square root of time (in $hr^{0.5}$). The absorbed masses were converted to volumes assuming a density of 1000 kg/m^3 for water. The slopes of the above line yielded the sorptivity of the specimens (in $mm/hr^{0.5}$).

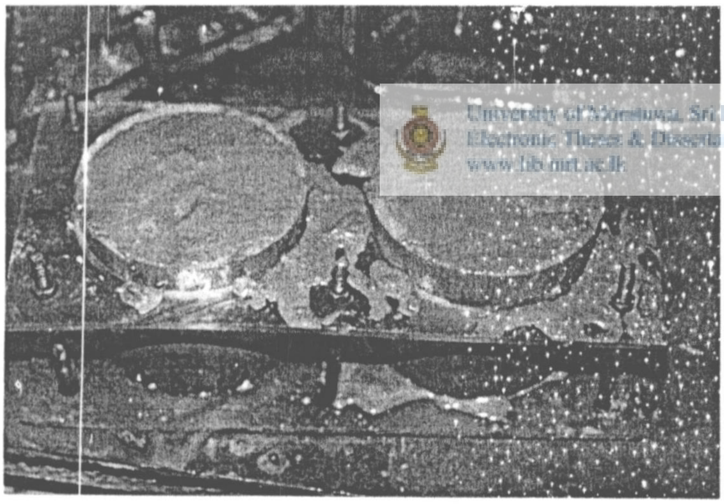

Figure 5.1: The casted cylinders for sorptivity testing

Figure 5.2: The sorptivity testing specimens

Figure 5.3: The sorptivity testing is in progress

5.4 The results of the experimental study

The water cement ratio is generally considered as the factor with dominant influence on workability and strength of concrete. This term is applicable only when cement and water is used. As soon as silica fume is used, it introduces an additional material that can contribute to the strength. Therefore, the term called water-binder ratio could be introduced. For a concrete with 325 kg of cement, and 16 kg of silica fume, the water cement ratio that gives 50-60mm slump is 0.45 (about 146 kg of water). The corresponding water to binder ratio is 0.43. This value is obtained by dividing the water content by total cementious material (i.e. cement + silica fume, 146/(325+16)).

Mix	Water cement ratio	Water binder ratio
M_1S_0	0.51	0.51
M_1S_1	0.50	0.48
M_1S_2	0.52	0.47
M_2S_0	0.49	0.49
M_2S_1	0.45	0.43
M_2S_2	0.46	0.42
M_3S_0	0.47	0.47
M_3S_1	0.44	0.42
M_3S_2	0.46	0.42
M_4S_0	0.44	0.44
M_4S_1	0.44	0.42
M_4S_2	0.47	0.43

Table 5.3: The water cement ratio and water binder ratios for a constant workability (Slump value of 50-70mm)

The water to cement (w/c) ratio and water to binder (w/b) ratio used for the experimental programme are given in Table 5.3. This table indicates that the use of silica fume has reduced the water to binder ratio in most of the mixes. This may support the fact that the presence of silica fume improves the workability

Under compressive loads, failure in normal concrete occurs either within the hydrated cement paste or along the interface between the cement paste and aggregate particles. This interface is a weak area in normal concrete. In order to improve the strength, it is necessary to strengthen this weak area. Reducing the water binder (w/b) ratio by using supplementary cementitious material like silica fume tends to strengthen the weaker zone. The calcium silicate hydrate produced as a result of the reaction between silica fume and $Ca(OH)_2$ produced as a result of hydration of cement could improve the strength and impermeability (Joshi, 2001).

The average strength recorded for slump between 50-70 mm for different mixes are given in Table 5.4. The detailed cube strength results with silica fume is given in Appendix E. The mixes M_3S_0 and M_4S_0 recommended for Grades 25 and 30 gave a current margin in excess of 13 N/mm^2 at 28 days.

Mix	7 days compressive strength in N/mm^2	Average 7 days compressive strength in N/mm^2	28 days compressive strength in N/mm^2	Average 28 days compressive strength in N/mm^2
M_1S_0	19.10 18.20 18.23	18.51	29.21 29.43 29.35	29.33
M_1S_1	22.58 22.30 22.5	22.46	33.71 33.52 33.57	33.60
M_1S_2	21.41 21.83 21.77	21.67	36.52 36.71 36.63	36.62

Mix	7 days compressive strength in N/mm^2	Average 7 days compressive strength in N/mm^2	28 days compressive strength in N/mm^2	Average 28 days compressive strength in N/mm^2
M_2S_0	22.78 22.53 22.85	22.72	35.81 35.43 35.56	35.60
M_2S_1	24.20 24.12 24.31	24.21	36.71 37.79 37.49	37.63
M_2S_2	23.21 22.98 23.11	23.10	36.82 37.24 37.24	37.10
M_3S_0	26.17 26.41 26.35	26.31	38.93 39.51 39.46	39.30
M_3S_1	30.10 29.21 29.04	29.45	46.21 45.84 45.74	45.93
M_3S_2	27.52 27.79 27.70	27.67	45.72 45.59 45.73	45.68
M_4S_0	27.84 27.90 28.17	27.97	47.61 47.72 47.59	47.64
M_4S_1	28.42 28.19 28.26	28.29	47.79 47.71 47.84	47.78
M_4S_2	28.17 28.32 28.14	28.21	47.49 47.61 47.58	47.56

Table 5.4 : The average compressive strength of concrete at 7 days and 28 days

These results indicate that 5% silica fumes could give strength enhancement for concrete mixes such as 1:2:4 (20mm) and 1:2:4 (20mm) with 10% and 20% more cement. This is consistent with the observations reported by the other researchers in literature. When 20 % and 30 % more cement were used, the silica fume did not give an enhancement of strength. This is not the expected result. It could be that the ratio of fine to coarse aggregate of 1:2 may not be working in this strength range. This should be investigated in future research. However, the results for M_4S_0 shows that the mix with 30% extra cement could be used for Grade 30 concrete with a lot of confidence. The current margin given is about 17.5 N/mm^2

The sorptvity test results are given in Table 5.5. The detailed sorptivity test results are given in Appendix F. These results indicate a significant reduction in sorptivity for all the mixes with extra cement and 5% and 10% of silica fume. For example, the sorptivity achieved by using 5% silica fumes with 20% extra cement is approximately equal to the sorptivity of concrete with 30% extra cement and no silica fume. Thus, the reduction in sorptvity that is achieved with extra cement could be achived by using about 5% silica fumes. Even a better reduction can be achieved with 10% silica fumes.

Specimen	Sorptvity ($mm3/hr^{0.5}$)	Sorptivity as a ratio of concrete with 0% silica fume
M_1S_0	1.037	1.00
M_1S_1	0.529	0.51
M_1S_2	0.528	0.51
M_2S_0	0.747	1.00
$M2S_1$	0.392	0.52
M_2S_2	0.250	0.33
M_3S_0	0.300	1.00
M_3S_1	0.244	0.81
M_3S_2	0.147	0.49
M_4S_0	0.229	1.00
M_4S_1	0.152	0.66
M_4S_2	0.098	0.43

Table 5.5: Sorptvity results of the mixes

Based on the results given in the Table 5.5, the following could be summarized:

1. When the cement content is increased in concrete as in M_1S_0, M_2S_0, M_3S_0 and M_4S_0, the sorptvity reduces. This means, the durability of concrete can be improved by increasing the cement content.

2. When cement content is low, 10% silica fume has not given much advantage. This may be that the amount of $Ca(OH)_2$ produced is not sufficient to react with all silica fume.

3. In all other mixes (M_2, M_3, M_4), 10% silica fume has given a lower sorptivity than 5% silica fume. The use of 5% silica fume has given a lower sorptivity than concrete without silica fume.

4. Therefore, it is reasonable to suggest that silica fume could be used in Sri Lanka even with low Grades of concrete such as 20 or 30 to improve the durability. This would be particularly useful in situation such as irrigation channels and factory buildings since silica fumes could improve the abrasion resistance under both wet and dry condition. It could also be used in highway bridges since the long term durability of concrete is often could be a problem in coastal roads.

It would also be possible to use silica fumes in buildings especially when the fair finish is given with the formwork without plastering. It is reported that the concrete containing silica fume could give much better finish due to improved workability and reduced bleeding and segregation. With these encouraging results, it is prudent to pursue further applications of silica fumes specially with respect to the ready mix concrete since it could enhance the pumpability in addition to the other benefits.

5.4 Summary

The strength and durability are important properties of concrete. The strength of concrete could be improved by using extra cement. It is shown with the experimental study that the sorptivity of concrete containing higher cement content will be lower. This means, the concretes containing higher cement contents could be used for enhanced durability.

Silica fume, when used with 5% by weight of cement, could enhance the strength of concrete. It could lower the sorptivity of concrete as well. When 10 % silica fume are used, the sorptvity could be lowered further. This means, with the fine and coarse aggregate used in Sri Lanka, silica fume could give higher strength with enhanced durability. This is an important finding. Thus, it will be useful to explore the benefits of using silica fume for ready mix concrete as well, either to achieve better quality wet or hardened concrete. This will need further detailed research since silica fume is expensive and hence benefits should be justified with respect to the cost.