



Effect of Silica Fume on Permeability and Microstructure of High Strength Concrete

Satish Kumar Chaudhary^{a*}, Ajay Kumar Sinha^b

^a Research Scholar, Department of Civil Engineering, National Institute of Technology Patna, Bihar, India.

^b Professor, Department of Civil Engineering, National Institute of Technology Patna, Bihar, India.

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Abstract

The important concrete structure in the vicinity of industry, thermal power plant suffers deterioration by the acid rain cause due to combination of CO₂, SO_x and NO_x with rain water. A combined attack that is from acid as well as sulphate can be observed under impact of sulphuric acid. It attacks on Calcium hydroxide and form Calcium sulphate, which can be leached out easily and make Interfacial Transition Zone (ITZ) poor. The water retaining structure such as dam, weir should be impermeable and that can be achieved by binary cementitious blends, using Silica fume (SF). Silica fume a by product of silicon industry, proves very effective in improving the microstructure of concrete due to their finer particle size, approximately 100 times finer than cement particles. The SEM image of binary blended high strength concrete (HSC) with Silica fume shows the condensed packing of cement hydration product and a dense microstructure as compare to control mix. The water permeability test result reveals that there is about 87 percent reduction in the coefficient of permeability achieved by inclusion of 10% Silica fume (SF) by weight of cement. Rapid chloride penetration test (RCPT) has been performed to investigate the ingress of chloride ions into the concrete. There was significant reduction in chloride ions penetration recorded due to SF inclusion.

Keywords: Microstructure; Calcium-Silicate-Hydrate (C-S-H); Permeability; Interfacial Transition Zone (ITZ); Ca(OH)₂; Control Mix.

1. Introduction

Silica fume is extremely fine pozzolanic material with high silica content and hence is effectively use in high performance concrete. In the late sixty's and mid seventy silica fumes was simply emitted into the atmosphere. But due to the strict environmental law's its utilisation in concrete and other industries started. Through the research it has been proved that silica fumes in concrete induces high strength and reduces permeability and because of this, the silica fumes becoming the world most versatile mineral admixture. Concrete is virtually a permeable material. Permeability of concrete usually refers to the degree at which water or other aggressive substance (sulphates, chlorides ions, etc.) penetrates it, that plays a major role in the long-term durability of concrete. If the voids are interconnected, concrete becomes pervious. Permeability refers to the amount of water penetrate through concrete when the water is under pressure, and also to the ability of concrete to resist diffusion of any substance. This plays a significant role in durability because it controls the rate of entry of moisture that may contain aggressive chemicals and the movement of water during heating or freezing. Therefore, higher the permeability lesser will be the durability [1]. The partial replacement of cement with Supplementary Cementitious Material (SCM) such as SF decreases the permeability by the formation of C-S-H gel in the concrete mix which further put resistance against corrosion [2, 3]. SF is considered

* Corresponding author: satish.ce16@nitp.ac.in

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to produce low permeability concrete because of its high pozzolanic character and extreme fineness [4]. Moreover, the incorporation of SF appeared to fill the spaces between cement grains, this further leads to a reduction in water permeability and penetration of chloride ions [5].

The pozzolanic property of SF helps in the formation of C-S-H gel and as a result, there is a significant reduction in permeability [6]. An important parameter for evaluating the durability performance and service life of an existing concrete structure is permeability [7, 8]. There has not been much reporting on the permeability of HSC. Permeability of concrete is adequately explained by mainly four transport processes in concrete which are: transport of water under a hydrostatic pressure head; transport of water by capillary suction; diffusion of ions under a concentration gradient; and transport of ions by moving fluid [9, 10]. It is well accepted that permeability is a good indicator of durability potential [11]. It is known that the permeability controls deterioration of concrete in the aggressive environment. This is due to the fact that the transport processes in concrete govern the deterioration processes like carbonation, chloride attack and sulphates attack. Due to the application of fillers and pozzolanic materials to the concrete mix, strength and other properties of concrete get improved, as SF possesses both these property, due to which it improve the microstructure as well as make concrete impermeable [12]. Therefore, the blending of Portland cement with pozzolanic materials becomes an increasingly accepted practice in the construction of structures exposed to aggressive environments. There is drastic reduction in permeability of concrete when silica fume replacement level is equal to 8% by weight of cement. However, the permeability increases beyond this replacement level. Silica fume fineness is an important factor in permeability of silica fume concrete and further concluded that permeability decreases if silica fumes fineness increases [13]. The silica fume addition reduced the permeability of concrete by a very large value. The silica fume in concrete reduced the size of capillary pore and increases the probability of transforming continuous pores into discontinuous ones, as capillary porosity is related to permeability, thus permeability reduced [14].

Hence, in this study, effect of silica fume addition in concrete mix on microstructure of concrete have been investigated with the help of scanning electron microscope (SEM) image and try to investigate the mechanism behind reduction in pores and interconnected voids present in concrete matrix. The other objective of this study is to study the influence of SF inclusion on permeability of high strength concrete.

2. Experimental Program

2.1. Materials

The constituent material used for this study were Ordinary Portland Cement (OPC) 43 Grade, nano silica, fine aggregate of zone III, 20 mm graded coarse aggregate and super plasticizer Structuro 203 (polycarboxylic based). The OPC 43 conforming to [15] used in this study has specific gravity 3.15, fineness 0.225 m²/g and soundness (outoclave expansion) 0.8%. The Silica fume used in the experiment satisfied the requirement of Indian Standard [16] is purchased from Elkem South Asia Pvt. Ltd. The chemical composition of cement has been shown in Table 1 and the properties of SF have been shown in Table 2.

River sand from Sone river bed was used as fine aggregate and after sieve analysis confirms to zone III as per Indian standard. Locally available crushed stone "with maximum graded size of 20 mm have been used as coarse aggregate The sieve analysis conducted on coarse aggregate sample and confirmed to 20 mm graded size as per Indian standard [17]. The physical properties of fine and coarse aggregates have been reported in Tables 3 and 4 respectively.

Table 1. Chemical composition of OPC

Chemical composition by mass (%)							
SiO ₂	K ₂ O+Na ₂ O	Al ₂ O ₃	SO ₃	CaO	Fe ₂ O ₃	MgO	Loss on ignition
22.11	1.09	5.2	3.46	64.34	3.45	2.61	1.45

Table 2. Properties of Silica fume

Sl. No.	Parameters	Specification	Analysis
1	Silicon dioxide, SiO ₂	Min 85%	87.01%
2	Moisture content	Max 3%	0.57%
3	Loss of ignition	Max 6%	0.99%
4	Physical requirement (>45mm)	Max 10%	1.13
5	Pozzolanic activity index	Min 105%	132
6	Specific surface (m ² /g)	Min 15m ² /g	19.4
7	Bulk density (Kg/m ³)	500-700Kg/m ³	616

Table 3. Physical property of Fine aggregate

Specific gravity	Fineness modulus	Water absorption
2.66	2.506	1.35%

Table 4. Physical property of Coarse aggregate

Aggregate Crushing value	Aggregate Impact value	Specific gravity	Water absorption
24%	29%	2.72	0.76%

2.2. Mix Proportion

Twelve mixes were prepared for M60 concrete by different permutation and combination of constituent materials and following IS code [18] with six replacement ratio of silica fume, viz. 0%, 2%, 4%, 6%, 8% and 10% by weight of cement and two level of w/b ratio, viz. 0.36 and 0.40. The Reduction in water-cement ratio to achieve higher strength is going to reduce the workability, but the advent of HRWR (High rate water reducer) allows it up to 0.36. The mix proportion for M60 concrete has been summarized in Table 5. Proper mixing of the concrete constituents is necessary for attaining the maximum strength.

Table 5. Different mix proportion for M60 concrete

Mix Code	%SF	w/b ratio	C (kg)	SF (kg)	W (kg)	FA (kg)	CA (kg)	HRWR (kg)
L-S0N0	0	0.36	377.78	0	135.68	782.24	1205.84	7.56
L-S2N0	2	0.36	370.22	7.56	135.68	782.24	1205.84	7.56
L-S4N0	4	0.36	362.67	15.11	135.68	782.24	1205.84	7.56
L-S6N0	6	0.36	355.11	22.67	135.68	782.24	1205.84	7.56
L-S8N0	8	0.36	347.56	30.22	135.68	782.24	1205.84	7.56
L-S10N0	10	0.36	340	37.78	135.68	782.24	1205.84	7.56
H-S0N0	0	0.40	349.8	0	139.92	801.87	1199.64	7
H-S2N0	2	0.40	342.81	6.99	139.92	801.87	1199.64	7
H-S4N0	4	0.40	335.81	13.99	139.92	801.87	1199.64	7
H-S6N0	6	0.40	328.81	20.99	139.92	801.87	1199.64	7
H-S8N0	8	0.40	321.82	27.98	139.92	801.87	1199.64	7
H-S10N0	10	0.40	314.82	34.98	139.92	801.87	1199.64	7

2.3. Methodology

The guidelines of IS: 3085-1965 [19] has been followed in this study, to measure the permeability of concrete cube of different mix proportion in the laboratory. In the laboratory to measure the coefficient of permeability of test specimen, 'concrete permeability test apparatus' (AIM-381) manufactured by Aimil Ltd. has been used. For water permeability test, cubical concrete specimen of size 150mm were caste in the mould and coefficient of permeability has been find at 28 days of water curing. Chloride ion penetration was measured at various ages using the rapid chloride permeability test in accordance with AASHTO T 277 (recently adopted as ASTM C 1202-91). This test does not offer diffusion constant, but rather an index, which has been found useful in comparative studies [20]. For RCPT cylindrical specimen of diameter 100mm and height 50 mm have been casted in lab and test were done at 56 days of water curing. The microstructural studies have been done with the help of SEM photograph of control concrete and silica fume concrete at 7 days and 28 days.

3. Results and Discussion

The results of water permeability test and rapid chloride penetration test obtained from this study have been summarized in Table 6.

Table 6. Permeability test result for all mix code

Mix Code	% SF	w/b ratio	RCPT (coulomb)	Coefficient Of permeability (cm/s)
H-S0N0	0.0	0.40	2425	4.87E-09
H-S2N0	2.0	0.40	2232	4.25E-09
H-S4N0	4.0	0.40	2080	1.288E-09
H-S6N0	6.0	0.40	1752	1.127E-09
H-S8N0	8.0	0.40	1360	8.35E-10
H-S10N0	10.0	0.40	1138	6.15E-10
L-S0N0	0.0	0.36	2390	4.52E-09
L-S2N0	2.0	0.36	2132	4.12E-09
L-S4N0	4.0	0.36	1986	1.195E-09
L-S6N0	6.0	0.36	1692	1.072E-09
L-S8N0	8.0	0.36	1285	7.36E-10
L-S10N0	10.0	0.36	1088	5.18E-10

3.1. Water Permeability Test Result

The variation in coefficient of permeability of cube specimens with varying percentage of silica fume and w/b ratio has been shown graphically in Figure 1. The variation in coefficient of permeability shows that as percentage of silica fume increases permeability reduces and for same percentage of SF, as w/b ratio reduces the permeability also reduces. From the result obtained it is clear that the coefficient of permeability is maximum for the control mix compared to all other mixes and as the percentage of silica fume increases, the permeability reduces. Concrete with silica fume shows good resistance against water permeation, it can be attributed to the high specific surface area of silica fume which results in greater pozzolanic activity and due to its finer size it fills the void between cement particle.

3.2. Rapid Chloride Penetration Test Result

The variation in charge passed through specimen in six hours with varying percentage of silica fume and w/b ratio has been shown graphically in Figure 2. From the graph it is infer that as percentage of silica fume increases, the ingress of chloride ions reduces and for same percentage of SF, as w/b ratio increases the charge passed increases. From the result obtained it is clear that the charge passed is maximum for the control mix compared to all other mixes and as the percentage of silica fume increases, the ion penetration reduces.

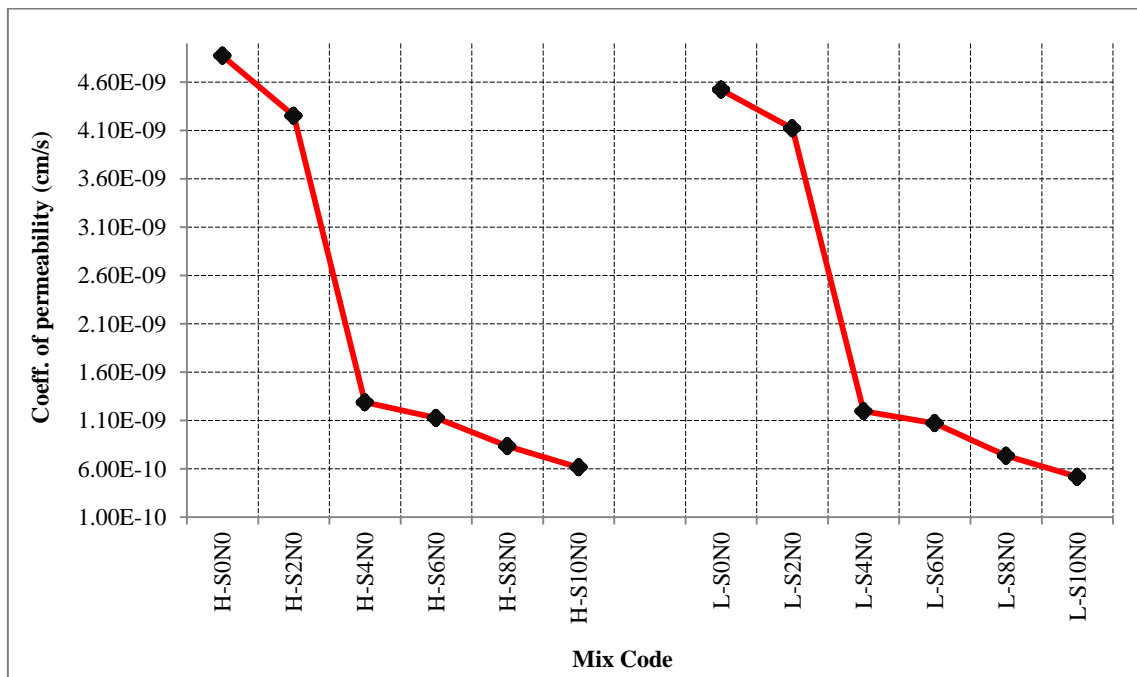


Figure 1. Water permeability test result for different mixes

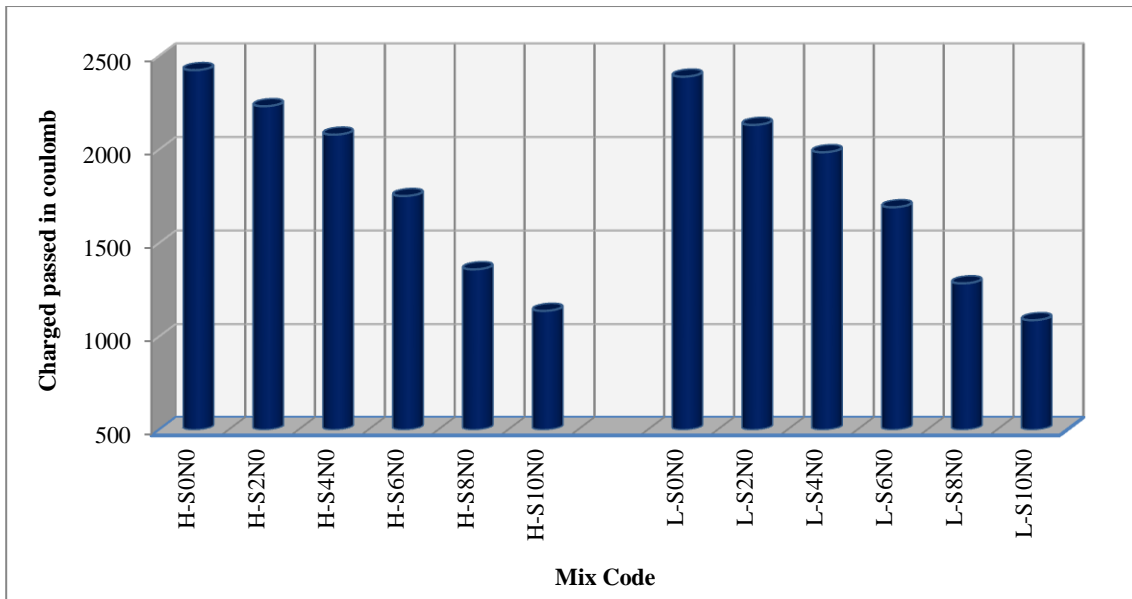
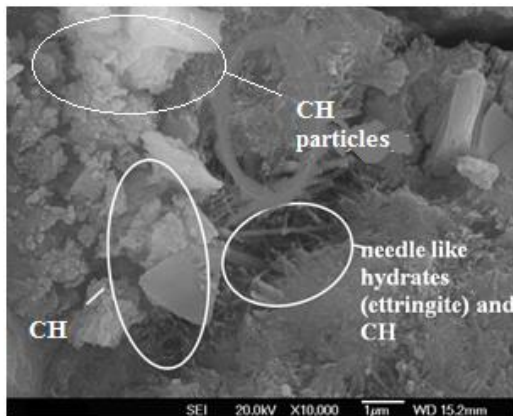


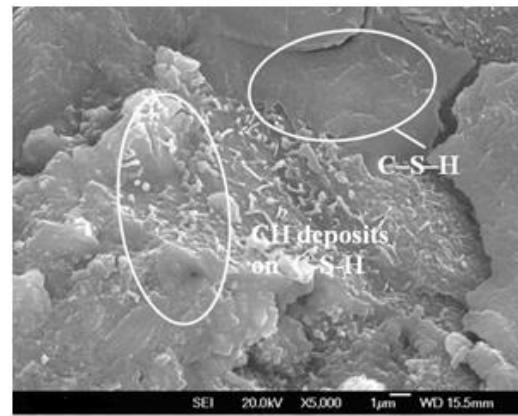
Figure 2. Rapid chloride penetration test result for different mixes

3.3. Scanning Electron Microscope (SEM) Test Result

After the permeability test result, it has been prove that the concrete shows best resistant against water and ion permeation at 8% replacement level of silica fume and w/b ratio 0.36. So in this study the SEM study has been done for Mix Code L-S8N0. To understand the changing occurs in the microstructure of concrete matrix by the application of SF, we firstly investigate the microstructure of Control Mix at 7 days and 28 days of curing and SEM photograph of control mix have been shown in Figure 3. The SEM photographs of SF concrete have been shown in Figure 4.

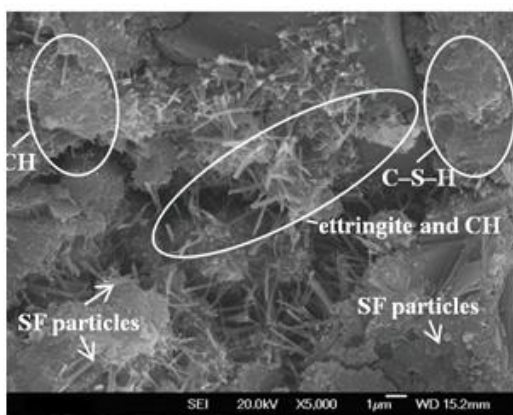


a) Microstructure of Control mix at curing age of 7 days

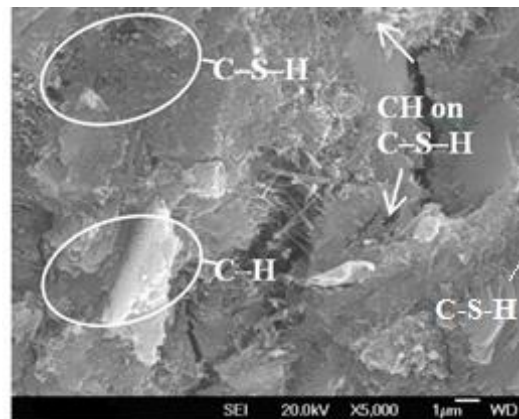


b) Microstructure of Control mix at curing age of 28 days

Figure 3. SEM photograph of Control concrete



a) Microstructure of Mix L-S8N0 at curing age of 7 days



b) Microstructure of Mix L-S8N0 at curing age of 28 days

Figure 4. SEM photograph of Silica fume concrete

From the SEM image of control mix (L-S0N0) it can be seen that there is a heterogeneous distribution of C-S-H, CH grains and needle like ettringite crystals. There are some micro cracks are visible within structure. From the SEM image of control mix L-S0N0 at 28 days of curing, it can be seen that the deposit of small and large size CH crystals are dispersed in the hardened state. It is pertinent to mentioned that, there is an insignificant growth of C-S-H gel recorded from 7 days to 28 days of curing.

The SEM image of SF concrete at 7 days of curing, shows the condensed packing of cement hydration products. The mineral particle of SF is arbitrarily dispersed throughout the hydrated cement products. The Figure 4(a) shows the CH and Ettringite needle formations crystals found between the C-S-H crystals, which contribute in the strength development. From the Figure 4(b), it is evident that although the incomplete reaction of SF due to controlled hydration, the formation of $\text{Ca}(\text{OH})_2$ is less in comparison with Portland cement hydration and efficiency of its utilisation is improved with the presence of silica oxide. So a dense micro structure is evident in the SEM image presented in Fig 4(b), due to the filler effect of SF also. So increment in durability observed through the water permeability test and RCPT tacitly conform through the images.

4. Conclusion

On the basis of the experimental results, it can be infer that as the percentage of silica fume increases in concrete mix, the water and ion permeability reduces, but the rate of reduction in permeability reduces after 8% silica fume inclusion. So the 8% SF replacement level proves optimum dose for best resistance against water and ion permeation, this finding is in line with the observation of Song et al. (2010) [13]. It can also be concluded that as the w/b ratio reduces, the permeability also reduces. But when we reduces w/b ratio beyond 0.36, the concrete became unworkable.

From the microstructural study, it may be attributed to the fact that SF not only improves the pore structure in cement mortar but also improves the cement mortar/aggregate interface. Further, SF makes the cement mortar and transition zone dense and homogeneous due to its micro filler and pozzolanic effect by arresting the calcium hydroxide produced during hydration process of Portland cement and formation of C-S-H gel, this observation is in accordance with the findings of Khayat et al. (1997) [6], thereby making concrete almost impermeable.

5. Conflicts of Interest

The authors declare no conflict of interest.

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