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EFFICIENCY OF SILICA FUME IN CONCRETE

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ABSTRACT

The use of silica fume as a mineral admixture for the production of high strength high performance concretes is gaining importance in recent years. The present paper is an effort towards a better understanding of the efficiency of silica fume in concrete. It was observed from an evaluation of the data available in literature that the efficiency of SF in concrete was not a constant at all percentages of replacement. It was proposed that the "overall efficiency factor" of SF can be assessed in two separate parts, the "general efficiency factor" - a constant at all the percentages of replacement and the "percentage efficiency factor" - varying with the replacement percentage. A comparison of the efficiencies obtained from the earlier data with studies on a "Lower Grade Silica Fume" in the laboratory show that the proposed values of efficiency are of lower bound and it is possible to achieve even higher efficiencies with proper mix proportioning.

Introduction

The use of pozzolanic admixtures in combination with chemical admixtures allowed the concrete technologist in recent years to taylor the concretes for many specific requirements. Amongst the pozzolanic admixtures condensed silica fume (SF), because of its finely divided state and very high percentage of amorphous silica, proved to be the most useful if not essential for the development of very high strength concretes and/or concretes of very high durability. It is recommended that for applications in concrete silica fume should confirm to certain minimum specifications such as - SiO_2 content of not less than 85%, spherical shape with a number of primary agglomerates with particles of size ranging from 0.01 to 0.3 microns (average of 0.1 to 0.2 microns), amorphous structure and a very low content of unburnt carbon [1].

Earlier studies on the utilisation of silica fume primarily adopted simple addition or partial replacement techniques, developed previously for pozzolans like fly ash. The effect of SF in concrete can be explained through the two mechanisms, namely the filler effect and the pozzolanic effect. Information available todate clearly indicates that the contribution of silica fume to the strength of concrete is not yet fully quantified. It is, however, recognised that this contribution of SF is not a constant determined entirely by its physical and/or chemical characteristics like cementitious compounds, fineness etc., but can also vary depending on the type of cement, water cement ratio and curing conditions [2]. The factors that maximize the contribution of silica fume to the strength of concrete are also not very clear. Earlier efforts regarding the use of silica fume in concrete, appropriately as explained later, were mostly limited to replacements in the range of about 10% by weight of cement for achieving the required strength [1]. However, it was reported that from the chemical considerations, the highest strength may be obtained at replacement levels of 30 - 40% [3]. In practice the silica fume contents were far less than this range due to the difficulties associated with the increased water demand to obtain a workable mix with such fine additives, though concretes with high SF content, large dosages of superplasticizers and extremely low water cement ratios are still a possibility for very special applications requiring high strength and durability. It was reported that by using silica fume and superplasticizers it is relatively easy to obtain compressive strengths of the order of 100 - 150 MPa in the laboratory [1]. The concretes containing silica fume were also found to be highly sensitive to the curing conditions in the initial period, and it is considered most appropriate to start the curing immediately after the final set. Also, it was reported that the rate of strength development in SF concretes will be significantly influenced by the curing temperature, which could be controlled by using either warm water for mixing and insulation or by applying heat. The accelerating effect due to elevated temperatures during the initial curing period is more on SF concrete compared to the same for normal concrete [1].

Studies todate show that the addition of SF to concrete will improve the durability of concrete - through a reduction in the permeability, refined pore structure leading to a reduction in the diffusion of harmful ions, reduced calcium hydroxide content which results in a higher resistance to sulphate attack etc. The improvement in durability will also improve the ability of SF concrete in protecting the embedded steel from corrosion. It is to be recognised that approaches resulting in maximum reduction in cement content, particularly through the use of SF in low/medium strength concretes, may however lead to a reduction in the period for the initiation of corrosion of steel in concrete [1].

Apart from the above, there have been several investigations relating to specific aspects of the behaviour of silica fume in concrete, most of them using silica fume confirming to the norms discussed earlier. These works have already been reviewed by a few [1 - 6], showing that concretes of very high strength and durability can be developed by using silica fume. In spite of all that is reported todate, a method for an exact evaluation of the efficiency of SF in concrete for predicting at least the compressive strength of the concrete containing SF is not yet available. This brief review shows that there is a necessity for a better understanding of the behaviour of silica fume in concrete for its effective utilisation. The primary objective of the present investigation is to look into the various parameters that influence the strength behaviour of concretes containing different percentages of silica fume.

Efficiency Concepts

The simple addition or replacement methods were not found to be suitable for a general understanding of the behaviour of concretes with pozzolans. Rational methods were expected to take into account the characteristics of the pozzolan which are known to influence the fresh and hardened state properties of the concrete. A rational method of proportioning fly ash concrete was first proposed by Smith [7], in which the "fly ash cementing efficiency factor" (k) was defined in such a way that the strength to water cement ratio relation for the normal concretes is also valid for the fly ash concretes with the modification that the cement content is replaced by the effective cementitious materials content, as given by $[w/(c + k.f)]$.

Similar to the above, research efforts in recent years were directed towards obtaining the activity of SF in concrete in terms of the amount of cement replaced through its "cementing efficiency factor" (k). This efficiency factor for SF in concrete can also be defined as the number of parts of cement that may be replaced by one part of silica fume, without changing the property being studied, normally the compressive strength. The efficiency of SF can also be evaluated based on other properties like durability, since there is a considerable improvement in the durability properties of SF concretes compared to the normal concretes. As there could be several different durabilities that could be defined depending up on the parameter being investigated (resistance to sulphate/acid, chloride diffusion, freeze-thaw etc.), it is possible to arrive at more than one durability factor. But it is generally accepted that the compressive strength of concrete is a reasonable indicator of the durability for most concretes without major chemical modifications and hence the efficiency of SF concrete is always defined with respect to the compressive strength of its control.

Many of the publications related to SF concretes contain data on the compressive strength but only a few of them contain sufficient information to allow the calculation of efficiency factors. It was reported [1] that Loland found the "k" value to be 2.0 for SF concretes with 300 kg/m^3 or higher cement content and for leaner concretes the "k" value to be 3.0. In contrast Sellevold and Radjy [8] reported that the "k" values ranged between 2.0 and 4.0 with higher values for richer mixes. It was also reported [1] that Sorensen found the "k" factors to be ranging from 2.0 to 5.0, with values increasing for richer mixes and decreasing with higher SF contents. Studies of Maage [9] on the efficiency of SF in concretes containing normal and blended cements also showed that the efficiency factor "k" increases for the higher strength grades. This study also included the evaluation of efficiencies based on curing conditions, permeability, carbonation and chloride diffusion.

Sellevold [8] also proposed another efficiency factor "k_w" which takes into account the water demand for a given mix (strength) and termed it as the efficiency factor at constant slump. He also discussed the relationship between the two efficiency factors. The factor "k_w" takes into account the different water demands in the two types of concretes and as such it will depend on the characteristics of cement, SF and also the different chemical admixtures (in particular the type and amount of superplasticizer). The above discussions clearly prove that the cementing efficiency factor "k", based on the fundamental relationship of strength to water cement ratio (and not the "k_w" which depends on the different water demands of a mix) is only the most appropriate.

In a recent evaluation on concretes containing different cements and fly ashes (another pozzolan), Schiessl [10] defined the reduction (Δw) in water cementitious materials ratio of fly ash concrete [w/(c + f)] as compared to the water cement ratio of reference concrete [w/c_o] and termed this as the "Δw concept". Also, it was already seen that "k" is defined in such a way that the water cement ratio of the reference concrete [w/c_o] and the water to effective cementitious materials ratio [w/(c + k.f)] of fly ash concrete are the same. Adopting a very similar methodology "Δw" the difference in water cement ratio of the control concrete and the water cementitious materials ratio of the SF concrete will be :

$$\Delta w = (w/c_o) - \{w/(c+s)\} = \{w/(c+k.s)\} - \{w/(c+s)\}$$

$$= (w/c)\,[1/\{1+k(s/c)\} - 1/\{1+(s/c)\}]$$

The above formulation clearly indicates that this reduction depends not only on the value of the efficiency factor (k), but will depend additionally on the water cement ratio and more importantly the cement and silica fume contents in the concrete mix.

Evaluation of Efficiency

As already stated a comprehensive evaluation of all the results available for even the compressive strength characteristics of SF concretes was difficult because of the vast variation in the concretes and the parameters studied. To bring about a common basis for these discussions, the authors scanned over 100 references, primarily dealing with the strength

TABLE. 1.

Ranges of Constituents in the Silica Fume Concretes Evaluated [8,11-20]

S. NO.	Reference	Year	% Replacement Studied	SF Characteristics		Concrete Characteristics			
				SiO_2 (%)	L.O.I (%)	Cement Content (Kg/m^3)	w/(c+s)	Slump (mm)	Comp. str. (MPa)
1	Sellevold [8]	1983	8,16%	94-98	1.2-3.5	200-300	----	120-130	22-99
2	Sorensen [11]	1983	10,20,40%	86-92	2.0-4.0	144-318	0.38-0.60	70-130	27-64
3	Jahren [12]	1986	3,6,9%	88-98	NA	NA	0.34-0.59	10-90	35-81
4	Sandvik [13]	1986	5,10,20%	92.1	0.8	240-300	0.70	60-150	30-44
5	Maage [14]	1986	5,10%	94.7	1.6	250-345	0.61-0.70	100-150	42-54
6	Skjolsvold[15]	1986	5,10,13,20%	NOT AVAILABLE		180-494	0.37-1.06	100-190	23-79
7	Malhotra [16]	1986	5,10,15,30%	94.0	2.50	240-431	0.40-0.60	75-216	36-71
8	Yamoto [17]	1986	5,10,20,30%	88-91	2.50	238-500	0.25-0.55	75-110	28-83
9	Marusin [18]	1986	5,10,15,20%	94.0	2.50	283-395	0.29-0.38	70-130	38-56
10	Yogendran[19]	1987	5,10,15,20,25%	NA	NA	354-502	0.28-0.47	0-55	40-68
11	Yamato [20]	1989	10,20,30%	90-94	NA	224-320	0.55	69-92	20-47
12	Authors	1990	10,15,20,25%	72-75	7.0-10.0	230-353	0.33-0.61	0-55	61-112

characteristics of SF concretes. A data base was then created for concretes containing ordinary Portland cement (OPC) and silica fume only (without any other pozzolanic addition) from the earlier investigators [8,11 - 20]. Finally, around 160 concretes (about 100 with SF addition and another 60 of the corresponding control concretes by the same investigators) with strength ranges from 20 - 100 MPa were chosen for the evaluation of efficiency of SF in concrete. Table.1 presents a brief summary of the ranges of SF replacement, characteristics of both SF and the concretes studied by these investigators. Many of these concretes contain some quantity of superplasticizers to counteract the effect of higher water demand for wetting the increased surface area due to SF addition. While choosing the different mixes for this evaluation the authors limited these to concretes containing 0 - 2% superplasticizer. This was done to see that the effect of superplasticizers (through the concretes containing very high dosages of superplasticizer resulting in significantly higher strengths at very low water cement ratios) does not influence the results of this investigation.

An evaluation of the efficiency of SF, as presented later, clearly indicated that for some of the concretes the values of efficiency obtained were far too low (more than 50% below the average) and these concretes were not included in the later evaluations. In all a total of 68 concretes containing SF at the different replacement levels ranging from 3 - 40% and another 44 of the corresponding control concretes by the same investigators were finally considered for an evaluation of the efficiency of SF in concrete at present. In general, it was seen that as the SF replacement percentage and the water cement ratios increase, the strength of concrete decreases. It was also evident that while concretes of the order of 90 MPa could be produced with replacements ranging from 8 - 16% silica fume, replacement of 40% could still lead to concretes of 40 MPa, through minor adjustments in water cement ratio and other concrete constituents.

The variations of the 28 day compressive strength with the parameter [w/(c + s)] at the different percentages of replacement for all concretes considered were presented in Fig.1. The curves presented were the best fits for each of the different percentages of replacement. It can be clearly seen that all these concretes with replacements even up to 40% show strengths

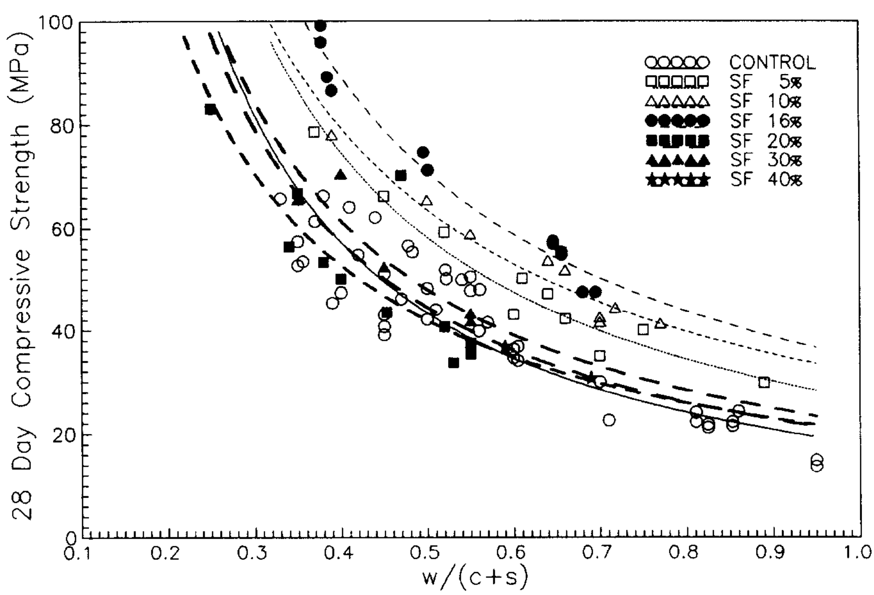

FIG. 1
Variation of Compressive Strength with [w/(c + s)]

higher than that of the control. The improvements in strength at the different percentages of replacement at any water cement ratio were also varying over a wide range.

Presently, the evaluation of the efficiencies of these concretes was attempted based on the " Δw concept" discused earlier. Fig.2 presents a conceptual diagram of the relationship between the compressive strength and water cementitious materials ratio for the control as well as the silica fume concretes. This shows that the silica fume concretes in general have strengths higher than the control concretes. The point "A" represents the water cementitious materials ratio of the SF concrete at some percentage of replacement for a typical strength, while the point "N" represents the water cement ratio of the control concrete at the same strength. The method now tries to bring the [w/(c + s)] ratio of the SF concrete nearer to that of the control concrete by applying the cementitious efficiency of silica fume "k". Now the figure is replotted to check whether a unique value of "k" can help in bringing "A" to "N" or in other words, the correction (Δw) required can be achieved through a unique (overall) cementitious efficiency factor "k" at all percentages of silica fume replacement. It was observed that this was not possible, as the range of percentage replacements considered were far too wide. To start with a unique value of "k" was first chosen so that this brings the concretes at all percentages of replacement as close to the normal as possible, with the lowest percentages being still only slightly higher and the highest percentages being slightly lower. This value of "k" which is generally applicable for all the replacement percentages is from henceforth defined as the "general efficiency factor" (k_e). This means that the point "A" now shifts to its revised location "B" due to the application of the general efficiency factor (k_e) with the axis as [w/(c + k_e.s)].

Thus the original point "A" has shifted to the point "B" by a distance of " Δw_1" (according to " Δw concept"). The correction still required for bringing "B" to "N" is ($\Delta w - \Delta w_1 = \Delta w_2$) and this factor was assumed to be the effect of the different percentages of replacement. To counteract this effect, an additional "percentage efficiency factor" (k_p) has been evaluated (as a multiplication factor to k_e) for each of the percentages of replacement in a way similar to that adopted earlier. These two corrections together will now bring the point "A" to "N" so

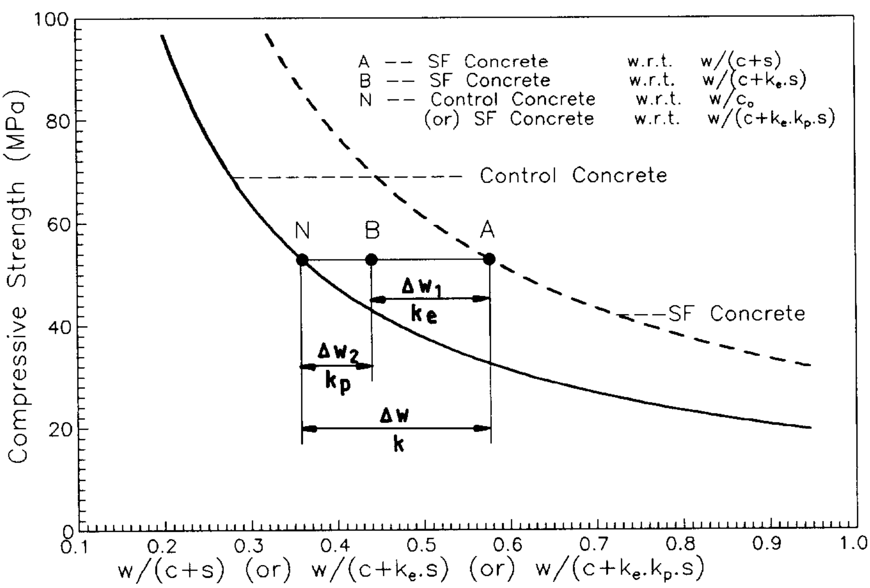

FIG. 2
Conceptual Diagram Showing Effect of Efficiency Factors

that the water cement ratio of the control concrete and the "water to the effective cementitious materials ratio" of the silica fume concrete [$w/(c + k_e.k_p.s)$] will be the same for any particular strength at all percentages of replacement. This methodology thus finally results in the evaluation of the "overall efficiency factor" ($k = k_e.k_p$) for any particular concrete at any particular replacement. A similar procedure was successfully adopted to predict the efficiency of fly ash in concrete earlier at both 7 and 28 days [21,22]. The basic concepts of this development and its use in the design of concretes with pozzolans was presented earlier [23].

Results and Discussions

Using the above methodology, at first the authors studied the effect of the variation of "general efficiency factor" (k_e) on the strength to water cementitious materials ratio at different percentages of SF replacement. Based on the efficiency factors reported earlier, the value of "k_e" was assumed to be varying between 2.0 and 5.0 for all replacement levels. As already discussed, a single value of "k_e" at all the percentages of replacement was not sufficient to correct the water cementitious materials ratio of SF concretes to the water cement ratio of the control. A value of 3.0 was found to be most acceptable for the "general efficiency factor" (k_e), representing the correction "Δw_1", as the concretes containing replacements up to 16% showed strengths higher than the control concretes while those containing replacements above 16% showed lower strengths than the control concretes (Fig.3). This means that instead of using only one "overall efficiency factor" (k) at all the replacement percentages of SF like the earlier researchers, here only the "general efficiency factor" (k_e) was kept constant for all the percentages of replacement.

The difference between the water cementitious materials ratio including the effect of general efficiency factor (k_e) for SF concrete and that of the control concrete (the value of "Δw_2" which represents the correction required for the percentage replacement effect) was now computed for the individual mixes. This effect of the percentage replacement was then calculated by applying an additional "percentage efficiency factor" (k_p). Finally, considering the average of the "k_p" values for the each different percentages of SF replacement, the

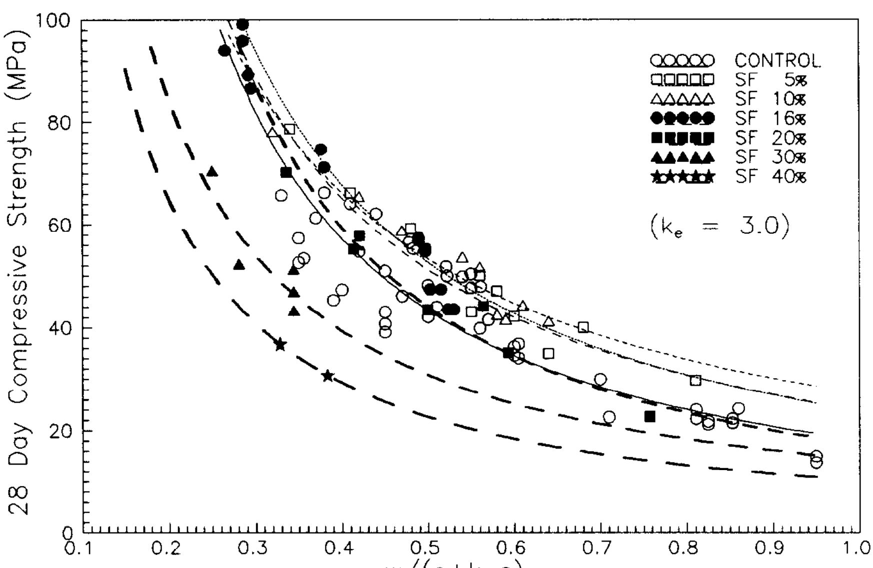

FIG. 3

Variation of Compressive Strength with [$w/(c + k_e.s)$]

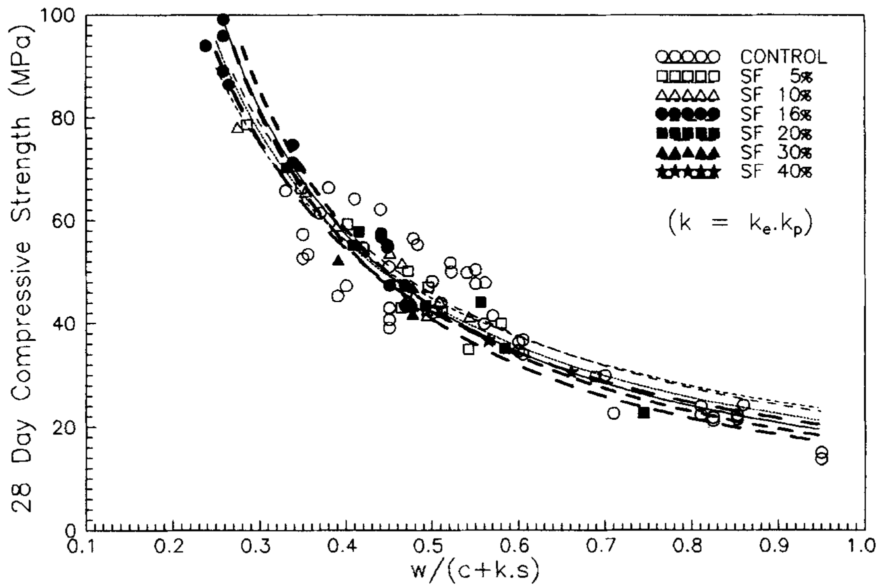

FIG. 4
Variation of Compressive Strength [w/(c + k .s)]

variation of compressive strength with the parameter [$w/(c+k_e.k_p.s)$] was presented in Fig.4. It can be clearly seen that this has resulted in a reasonably close agreement with the control concrete strengths at all the 9 different percentages of replacement ranging from 3 - 40%.

The variation of this average "k_p" with the percentage of replacement ("p_r", the percentage of SF in the total cementitious materials), at a constant general efficiency factor (k_e) of

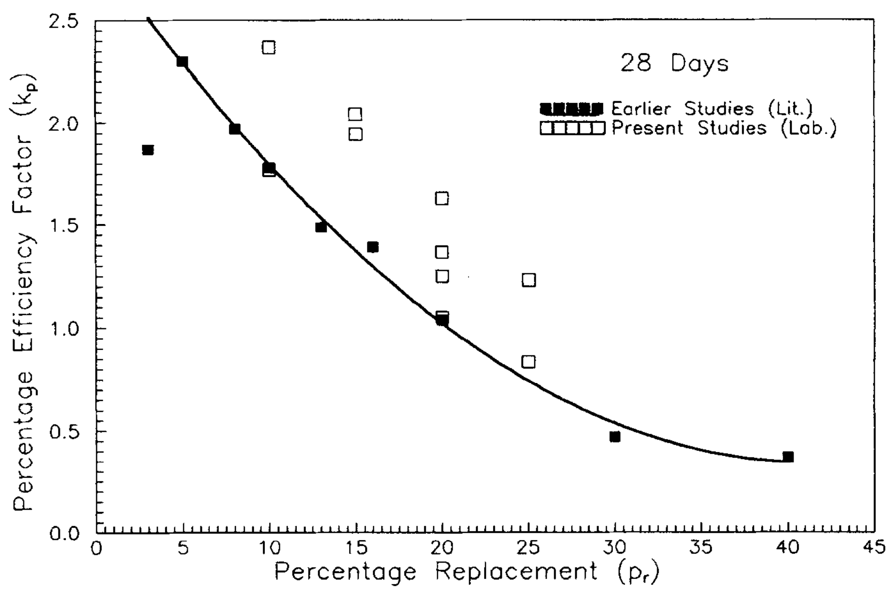

FIG. 5
Variation of Percentage Efficiency with Silica Fume Replacement

3.0, was presented in Fig.5. It can be seen that the values of "k_p" evaluated showed a continuous decrease from around 2.28 to 0.37 for the replacement percentages varying from 5 - 40% and is represented by the relationship :

$$k_p = 0.0015p_r^2 - 0.1223p_r + 2.8502$$

The variation of the overall efficiency factor ($k = k_e.k_p$) was presented in Fig.6. It can be stated that one can choose a marginally different value for "k_e" which would only have changed the values of "k_p" slightly. These evaluations show that the total/overall efficiency (k) of silica fume to be decreasing with increasing percentage replacement. In particular, the compressive strength improvement is decreasing with either an increase in water cementitious materials ratio, as in the case of normal concretes, or with an increase in the replacement percentage. Also, the decrease in the efficiency of SF is higher at the lower percentages of replacement (with "k" decreasing from a value of 6.85 for 5% replacement to about 5.0 and 3.11 for 10% and 20% replacements respectively) and is lower at higher percentage replacement (with "k" decreasing from a value of 3.11 at 20% replacement to about 2.0 and 1.11 for 30% and 40% replacements respectively). Similar to "k_p" the relationship between the overall efficiency factor "k" and "p_r" was observed to be :

$$k = 0.0045p_r^2 - 0.3671p_r + 8.5552$$

It is quite clear from both Figs. 5&6, that the efficiency of SF appears to be decreasing at percentages lower than 5%, as can be seen at 3% (being the average of four concretes from ref. 12). This can be attributed to the fact that, firstly the high efficiency expected for this low percentage of replacement would result in considerable reduction in the available cementitious materials (which particularly in lower strength concretes will not be sufficient to coat all the aggregates for effective binding) and secondly the small quantity of SF at this low percentage will be completely utilised in the filler effect without much material being available for additional pozzolanic strength development. The above evaluation also clarifies the diverse views expressed by the earlier investigators [2,9] and shows that these interpretations

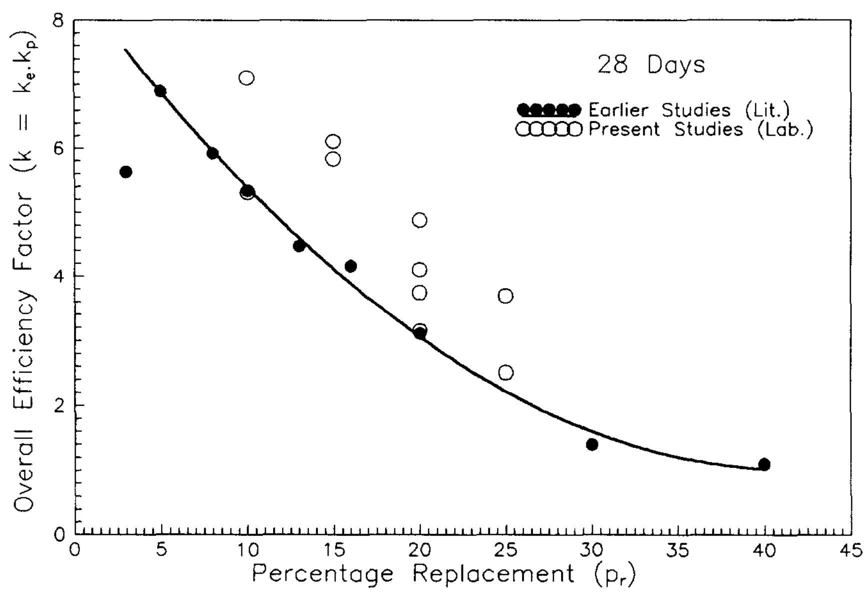

FIG. 6
Variation of Overall Efficiency with Silica Fume Replacement

were primarily due to the fact that they were the conclusions based on the limited experimental investigations and did not comprehensively look into the efficiency of SF in concrete the different percentages of replacement.

At this stage it was also felt essential to study the overall effect of the different efficiencies evaluated (k_e and k_p resulting in k). This was achieved by a comparison of best fit curves for the strength to water cement ratio relation of normal concretes with the corresponding strength to water-to-effective cementitious materials ratio, [$w/(c+k_e.k_p.s)$] of SF concretes combined at all percentages of replacement as presented in Fig.7. This figure clearly shows that predictions are almost perfect, and an analysis of the correlation coefficients for both these sets showed that the correlation coefficient for the SF concretes (a value of 0.98 for the 68 SF concretes considered for evaluation) was better than even that obtained for normal concretes (a value of 0.95 for the 44 corresponding control concretes from the same investigators).

Finally, to study the validity of the evaluations reported so far, a set of results from a large experimental programme which is presently being conducted at the laboratory were reported here. One important deviation is that these investigations related to the efficiency of a lower grade (70 - 75% SiO_2) silica fume available, at replacement levels ranging from 5 - 25%. The silica fume utilised also contained a substantial amount of unburnt carbon. Even so, it was possible to obtain concretes in the range of 60 - 120 MPa by effectively utilising these lower grade silica fumes. The values of both the "percentage efficiency factors" (k_p) and the "overall efficiency factors" (k) were superimposed on the relations obtained earlier (Figs. 5&6). This clearly indicates that the average values of "k_p" and "k" obtained from the earlier investigators were certainly the lower bound values and it is possible to obtain even higher efficiencies with proper mix proportioning. Also, the lowest values (close to the proposed relationships) reported were all for the concretes of very high strength (over 120 MPa attempted) or for the higher percentages of replacement.

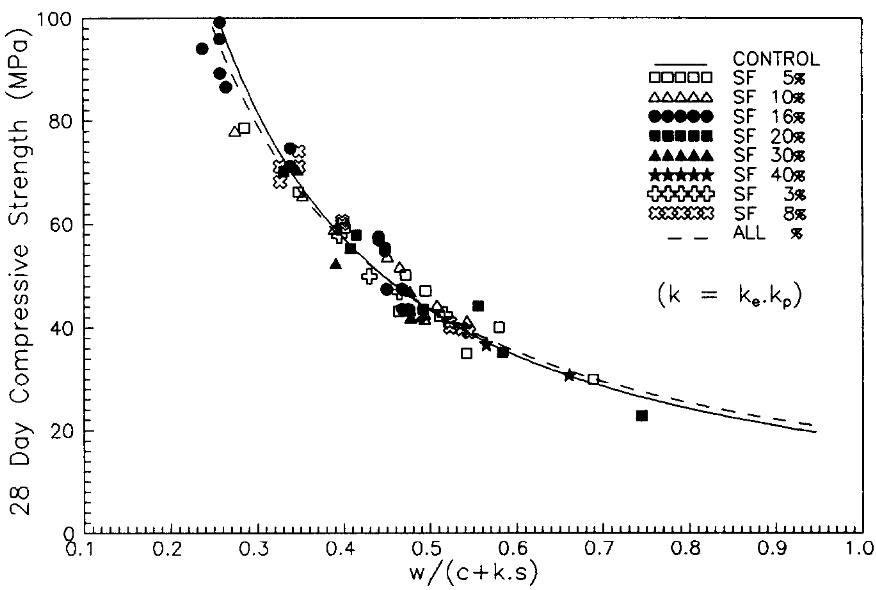

FIG. 7
Variation of Compressive Strength with [$w/(c+k.s)$]

Conclusions

The present paper primarily is an effort to understand the strength behaviour of concretes containing silica fume. The evaluation of the efficiency of SF concrete, was attempted through the data available in literature. The efficiencies evaluated were also verified through an experimental study using the available "Lower Grade Silica Fume". These studies have lead to the following conclusions.

1. An evaluation of the data available indicates clearly that the "overall efficiency of Silica Fume" (k) is not a constant at all the replacement percentages (3-40%) studied.

2. The overall efficiency (k) was found to be a combination of the "general efficiency factor" (k_e) - a constant at all percentages of replacement and the "percentage efficiency factor" (k_p) - varying with the percentage of replacement. The "general efficiency factor" (k_e) was found to be 3.0 at all replacement percentages for the 28 day cube compressive strengths considered. It was found that the values of "k_p" and "k" ranged from 2.28 to 0.37 and 6.85 to 1.11 respectively for the percentage replacements varying from 5-40%.

3. Studies in the laboratory using the available "Lower Grade Silica Fume" show that the above proposed variations of "k_p" and "k" are the lower bound values and it is possible to achieve even higher efficiencies with proper mix proportioning.

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