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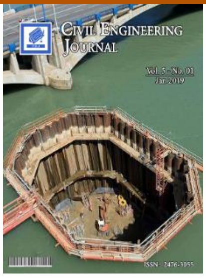

Efficiency Concepts and Models that Evaluates the Strength of Concretes Containing Different Supplementary Cementitious Materials

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Abstract

The usage of Supplementary Cementitious Materials (SCM) is very much acknowledged due to the several improvements possible in the concrete composites, and because of the general economy. Research work till date suggests that utilization of SCMs enhance a significant number of the performance characteristics of the hardened concrete. The idea of efficiency can be utilized for comparing the relative performance of different pozzolans when incorporated into concrete. The efficiency concept, which was initially developed for fly ash, can be effortlessly connected to other advantageous s as well, such as silica fume, slag and natural pozzolans. A quantitative understanding of the efficiency of SCMs as a mineral admixture in concrete is essential for its effective utilization. The paper reviews the literature pertaining to the different efficiency concepts and models present to date that evaluates the strength of concretes containing different SCMs. This short survey demonstrates that there is a need for a superior comprehension of the SCMs in concrete for its powerful usage. Also, it is an effort directed towards a specific understanding of the efficiency of SCMs in concrete.

Keywords: Fly Ash; Silica Fume; Cementing Efficiency Factor; Supplementary Cementing Material.

1. Introduction

Concrete is a mix of ingredient of cement, fine aggregate, coarse aggregate & water. It can be moulded into any shape in the plastic stage. The relative quantity of ingredient controls the property on concrete in the wet stage as well as in the hardened stage. Before two or three decades ago, the production of concrete for construction of building with ordinary Portland cement (OPC) with the ease of availability of ingredient of concrete irrespective of quality was in practice without considering the future of the concrete structure. Now with the passage of time in the modern era investigation since last two to three decades, the Engineers & scientists are keen to improve the strength, durability & other characteristics of concrete keeping in view the structural stability of structure. The demand for these characteristics derives the search for supplementary cementitious materials.

Supplementary cementitious materials (SCMs), such as Fly Ash (FA), Silica Fume (SF) or Ground Granulated Blast Furnace Slag (GGBS), are generally used to deliver mixed Portland concrete since they prompt a critical decrease in CO_2 outflow in the production phase compared to Portland cement [1,2]. The use of SCMs is gradually increasing due to technical, economic, and environmental benefits. SCMs are most commonly used in producing Ready-Mixed Concrete (RMC) and High Performance Concrete (HPC) [3–5]. In addition, SCMs contribute to the flow characteristics and cohesion required of Self-Compacting Concrete (SCC) [6–8] and also in production of sustainable concrete [9–11].

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The concept of efficiency factor (i.e. k-value concept) of the SCMs is one of the practical and the acknowledged way to assess the impact of SCMs to the strength of the hardened concrete. The efficiency factor (k) is defined as the part of the SCM in a concrete, which can be considered as equivalent to Portland cement. Although there are various investigations regarding efficiencies of FA, there is very few related to SCMs in this area.

Therefore, a quantitative understanding of the efficiency of SCMs as a mineral admixture in concrete is essential for its effective utilization. Many researchers developed a model known as efficiency factor (k value) for effective utilization and conservation of SCMs for future generations. The concept of an efficiency factor may be applied for comparing the relative performance of various SCMs (FA, SF, GGBS, natural pozzolans, etc.) as regards to Portland cement.

Despite all that is accounted for to date, a technique for a correct assessment of the efficiency of SCMs in concrete for estimating compressive strength of the concrete with SCM is yet not presented. This short survey demonstrates that there is a need for a superior comprehension of the SF in concrete for its powerful usage. The essential target of the present literature review is to explore the different Efficiency concepts and models present to date that evaluates the strength of concretes containing different percentages of SCMs.

2. Efficiency Concept – A Historical Perspective

2.1. Strength Definitions for the Water to Cementitious Materials Ratio

The key works of Feret, Abram's, Bolomey and other researchers determined wide application in the pragmatic innovation of the water-cement (w/c) law (rule) and based on it computation formulas. Feret, 1896 [12] recognized first the influence of the water-cement ratio of concrete strength,

$$f_c = \alpha_f f_{mc} \left[\frac{v_c}{v_c+v_w+v_a}\right]^2 \quad (1)$$

Where f_c is the resistance of the concrete to the considered expiry; f_{mc} is the normal resistance of cement to the same expiry; v_w and v_a the respective volumes of cement, water and entrained air brought back to the volume of the concrete; α_f is a coefficient.

Bolomey [13] based on Feret dependence determined a formula:

$$f_c = \alpha_f \left(\frac{c}{w} - 0.5\right) \quad (2)$$

Where f_c = strength of concrete; $\frac{c}{w}$ = cement-water ratio; α_f = coefficient.

The Bolomey equation has been used for relating the cement–water ratio to compressive strengths of concrete containing normal weight aggregate. This is basically a linear equation, not considering explicitly the parameters relating to coarse aggregates.

Abram's'[14] classical w/c ratio law proposed in 1918, is still reckoned as a milepost in the history of concrete technology.

$$f_c = \frac{A}{B^{\frac{w}{c}}} \quad (3)$$

Where f_c is the strength of concrete, w/c is the water-cement ratio, A and B are the constants. This formulation 1narrating the inverse proportionality between water-cement ratio and intensity level of concrete has been knocked a number of times by various researchers as not being a fundamental law, but yet it is accepted that w/c is the greatest single factor that regulates the effectiveness of concrete is the water-cement ratio. However, Abram's' water-cement ratio law is not directly applicable to concrete containing admixtures like FA or silica fume. The SCM play an important role in the strength development. Thus the Abram's' law, which relates the compressive strength only to the water-cement ratio, requires necessary modifications based on extensive experimentation.

To gauge the efficiency of FA as well as different pozzolans the above three equations (Equations 1 to 3) have been varied and modified by Gopalan et al 1985, Ganesh Babu et al 1996, Wong et al 2005 and Rajamane et al 2007 [15–18].

2.2. Fly Ash Cementing Efficiency Factor

"An efficiency factor (k) is characterized as the fraction of SCM in pozzolanic concrete, which can be viewed as comparable to Portland cement (PC) that produces the similar properties as concrete without SCM (k=1 for PC). Different researchers introduced the concept of 'k' and 'efficiency Model' to evaluate the comparative performance of SCM and PC. Smith[19] was the first to propose a judicious model for the water to cementitious ratio through the introduction of a 'FA cementing efficiency factor' (K).To evaluate the efficiency factor Smith[19]utilized compressive strength as a basis for estimation of the k value since it is a basic and predictable industrial test. The cementing efficiency k of FA is characterized as a mass of FA which is equivalent to a mass kFA of cement in terms of strength development. The k factor is the difference between influence of PC and FA to the development of strength". The model was of the form

$$\frac{w}{c_m} = \frac{w}{(c+kFA)} \tag{4}$$

The k factor is calculated by equating the w/c of Portland cement concrete to the w/c_m of Portland cement/fly ash concrete, provided the two concretes have the same workability and the same 28-day compressive strength. Results from Smith's experiment indicated that K is not constant for a particular FA, but a value of 0.25 for K was suitable for use in preliminary mixture proportioning. For practical applications, the method is reported to be complex[20].

Ghosh [21]equated the strength of cement and cement/fly ash concretes in the form

$$\frac{w}{(c+FA)} = M + N\left(\frac{w}{c}\right) \tag{5}$$

Where, *M* and *N* are constants. Using laboratory measurements and linear regression, the empirical constants M and N were calculated and found to vary with the level of FA replacement.

In another study Mills [22] justified the Smiths model of efficiency factor based on the equivalent maturity of concrete in terms of the response to different curing regimes.In 1988, the Building Research Establishment (BRE) [23] in the United Kingdom adopted Smith's definition of K, the cementing efficiency factor, in their guide to the design of concrete mixtures. It assumes that a Portland cement/fly ash concrete will have the same strength as a Portland cement concrete of similar workability if w/(c + kFA) = w_1/c_1, where w, c, and FA are the weights of the free water, cement and FA respectively, and w_1 and c_1 are the weights of the free water and cement in the Portland cement concrete. The guide recognizes that this k factor may vary from 0.2 to 0.45 for most European FA, which is mostly Class F.

Hedegaard and Hansen[24]proposed a model relating the strength of FA concrete to cement to water ratio and a FA to water ratio.

$$s_f = A\left(\frac{c}{w}\right) + B\left(\frac{FA}{w}\right) + E \tag{6}$$

This equation is a modified form of the equation introduced by Bolomey [25] many years earlier. where s_f = strength of concrete, *c*, *FA* and *w* are the cement, fly ash and the free water content of concrete respectively and A, B and E are constants forgiven materials, age and curing conditions. Hedegaard and Hansen's equation can be rearranged in a format similar to that of Smith [19]:

$$s_f = A\left(\frac{c+k*FA}{w}\right) + E \tag{7}$$

Where; $k = \frac{B}{A}$.

Using A and B values generated from their experiment, the pozzolan efficiency factor k was calculated to be 0.18. This is lower than suggested by BRE [23].

In 1992, ACI published a revised ACI 318 report [13] which replaced the traditional W/C values with W/CM ratios, without changing numerical values of the two ratios. However, the corresponding 28-day compressive strengths were increased by only 6%. ACI defined the w/c_m ratio as w/(c + FA.).Recently in their guide for selecting proportions for high strength concrete with cement and FA, ACI Committee 211 [20] presents a proportioning method that utilizes w/c_m ratios. The resulting concrete is essentially proportioned by the simple replacement method. As for ASTM standards covering the use of FA, there has been no major change in recent years. ASTM 618 [26] still classifies FA based on its source and physical or chemical characteristics rather than its performance in concrete, while ASTM C 311 [27] is still missing a strength evaluation test to judge the quality of FA. The only test that attempts to measure the strength potential of FA is the pozzolanic activity index test.

To obtain the k- value for FA, Hassablallah and Wenzel (1995) [28] compared the compressive strength of two concrete mixtures (control and blended) having the similar functionality and consequently proposed a "strength based model" represented by Equation 8. The 28 days compressive strength of control mix (f_c) and blended mix (f_b) differs by contribution of FA. According to this method, strength improvement is indicated when k value is positive while strength loss indicates negative value.

$$k = \frac{f_b - f_c}{f_c} \quad (8)$$

Babu and Rao (1996) [29] proposed that the “overall efficiency factor” of FA can be assessed in two separate parts, the “general efficiency factor” –assumed regular at all replacement level and the “percentage efficiency factor” - varying at all replacement level. The “overall efficiency” (k) was a two-way interaction between “general efficiency factor” (k_e) and the “percentage efficiency factor” (k_p) i.e. $k = k_e * k_p$. The authors modified the smith model as given in Eq. (3) and transformed in the form presented in Equation 9.

$$\frac{w}{c_0} = \frac{w}{C + kf} = \frac{w}{C + k_e f + k_p f} \quad (9)$$

Where; $\frac{w}{c_0}$ = the effective water/cement ratio, w = the water content in kg/m^3, C = cement content in kg/m^3 and f = FA content in kg/m^3.

In light of the relationship of compressive strength with w/c ratio, percentage of replacement and age, Babu and Rao[16] again in 1996 re-ascertained the efficiency factor for FA by reassuring the experimental results of earlier researchers with FA. They concluded that a single value cannot adequately represent the overall cementing efficiency factor k of FA.

Oner et al, 2004 [30] used the Bolomey and the Ferret equation to calculate equivalent cement content C′ and c′ that is expected to supplant the FA in the FA mixed concrete, keeping in mind the end goal to achieve the equivalent compressive strength. To achieve the above objective the equations are presented in the form established in Equations 10 and 11.The actual cement content is shown as C and c while the equivalent cement content are shown as C′ and c′ in kg/m^3

$$f_c = K_B \left(\frac{c + c'}{W + h} - a \right) \quad (10)$$

$$f_c = K_F \left(\frac{c + C'}{C + C' + w + h} \right)^2 \quad (11)$$

where $f_c$represents the concrete compressive strength in N/m^2, Bolomey and Ferret coefficient are represented as K_B and K_F, W is the water content in concrete (kg/m^3), w is the amount of water (absolute volume, m^3/m^3), h is the air content in concrete (m^3/m^3),and a is a coefficient depending mainly on time and curing.

In another research [18], the compressive strength (f_c) of concrete with SCM was predicted with the application of both Bolomey and the Smith model. The model developed by the author is as follows:

$$f_c = A \times \{([1 - p \times (1 - k)]/wb) - 0.5\} \quad (12)$$

$$f_c = A \times \{([1 + m \times p_s \times s \times k]/wc) - 0.5\} \quad (13)$$

Where A is a coefficient dependent on age of concrete, p_s represents the fraction of sand in concrete is replaced by FA, the sand fraction s in concrete is represented as ratio of sand to cement and m represents the addition factor for fly ash. Their study indicated logarithmic variation of ‘k’ with FA fraction, p, in binder portion.

$$k = a + b \times \log_e(100 \times p) \quad (14)$$

Where, p = fraction of FA in binder = F/B = F / (F + C) and constants ‘a’ and ‘b’ of Eq. (14) can be evaluated by the data on concretes with and without FA.

2.3. Silica Fume Cementing Efficiency Factor

Prior reviews on the use of SF principally adopted straightforward expansion or incomplete substitution methods, established earlier for pozzolans like FA. The straight forward addition or substitution techniques were not observed to be reasonable for a general comprehension of the conduct of concretes with pozzolans. Rational strategies were relied upon to consider the qualities of the pozzolana which are known to influence the fresh and hardened properties of the concrete.

Similar to the above discussion in the previous section, research endeavours in the past were coordinated towards acquiring the action of SF in concrete regarding the measure of cement replaced through its “cementing efficiency factor” (k). The term "efficiency factor" for condensed SF in concrete can be defined as “the number of parts of cement that may be replaced by one part of SF without changing the property studied”. Many of the results reported on the use of silica fume, pertain to discussions on various effects on compressive strength, either for the purpose of cement substitution or as a medium for strength increase but only a few of them contain adequate data to permit the estimation of efficiency factors.

Limited research [31,32] has been done in past on SF to obtain its activity compared to cement. This factor is called: - activity index, efficiency index or substitution index. Value for this factor in the literature have ranged from 2 to 5, specifically 2 to 4 by Loland, K.E. [31] and 3 by Fagerlund, G. [32].

P. Jahren,[33] used the expression efficiency index = k, where k expresses the efficiency of SF(s) compared to cement (c) in the relationship similar to Smith model for FA. The author calculated and plotted 51results from 7 series from 5 different laboratories. 7 out of 51 results give k > 4 while 7 out of 51 results give k < l. The areas are shown in Figure 1. Figure 2 represents the Dependence of the Dosage of SF on the strength Ratios

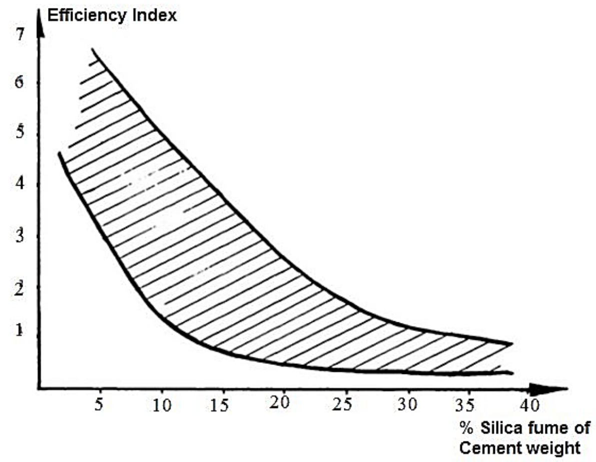

Figure 1. The Efficiency Factors in Terms of SF Content [33]

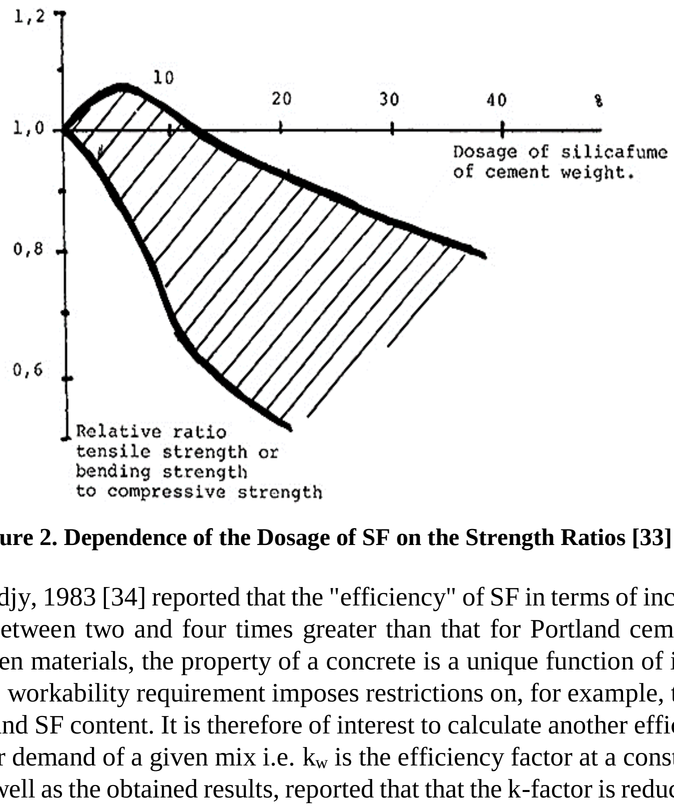

Figure 2. Dependence of the Dosage of SF on the Strength Ratios [33]

In contrast Sellevold and Radjy, 1983 [34] reported that the "efficiency" of SF in terms of increasing the compressive strength was calculated to be between two and four times greater than that for Portland cement and is based on the general assumption that, for given materials, the property of a concrete is a unique function of its w/c-ratio. The author also reported that in practice the workability requirement imposes restrictions on, for example, the w/c-ratio which may be obtained with given cement and SF content. It is therefore of interest to calculate another efficiency factor (k_w) which also takes into account the water demand of a given mix i.e. k_w is the efficiency factor at a constant slump. The authors, based on general experience as well as the obtained results, reported that that the k-factor is reduced for higher SF dosage is probably significant as well as the result that SF is more efficient with the less efficient standard Portland cement. They further reported that the k-factor expresses the strength potential of the SF. In practice, it is necessary to produce a workable concrete, and k_w is the relevant factor in this connection since it also takes into account the water needed to produce a given slump. The relationship between the two efficiency factors has also been discussed taking into consideration that both the types of concrete takes into account the different water demand. The authors further reported that k_w will depend on cement type, production and origin of SF and finally on the type of chemical admixture. Figure 3 shows the relationship between w/c ratio and 28 days strength for mixes with cement and different amounts of SF and water reducing agent. Using the plot shown in Figure 2 the authors calculated the cementing efficiency factor (k) for SF as follows:

$$\left(\frac{w}{c}\right)_R = \left(\frac{w}{c+kS}\right)_S \tag{15}$$

The subscripts Rand S indicate reference and SF concrete, respectively. *w*, *c* and *S* are the amounts of water, cement and SF, respectively, in units of kg/m^3. Equation 15 is based on the general assumption that, for given materials, the property of a concrete is a unique function of its w/c-ratio. The k-factor expresses the cement replacement value of the SF to maintain a given property unchanged. It may also be presented in a reorganized form:

$$k = \frac{(w/c)_S - (w/c)_R}{(s/c)\cdot(w/c)_R} \tag{16}$$

Equation 17 defines k_w as the difference in cement contents needed to produce equal strengths in a reference and SF concrete with the same slump, divided by the SF content.

$$k_w = \frac{c_R - c_S}{s} \tag{17}$$

k and k_w may be related by combining Equations 16 and 17 in the Equation 18:

$$k_w = k - \frac{\Delta w}{s}\cdot\frac{c_R}{w_R} \tag{18}$$

Where; $\Delta w = w_S - w_R$ is the increase or decrease in the water demand when SF is used. The cementing efficiency factor (k) of the SF is shown in Figure 4 for the three cement types at two dosage levels of SF.

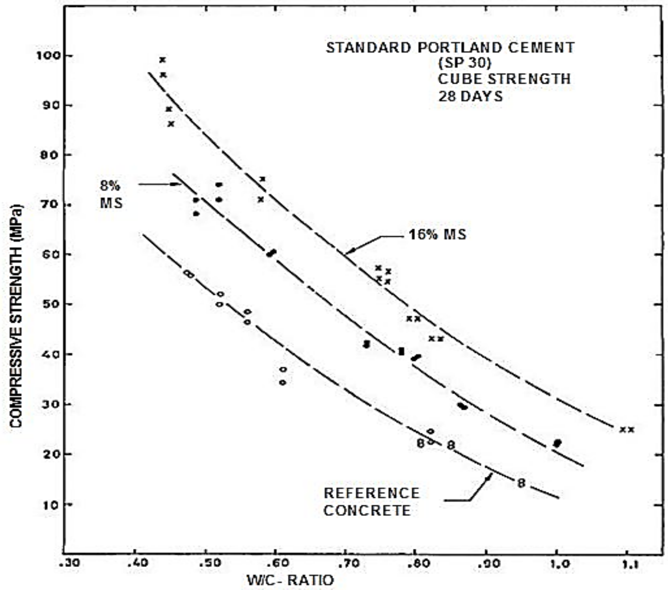

Figure 3. 28-Day Compressive Strength vs. w/c-Ratio for Concrete [34]

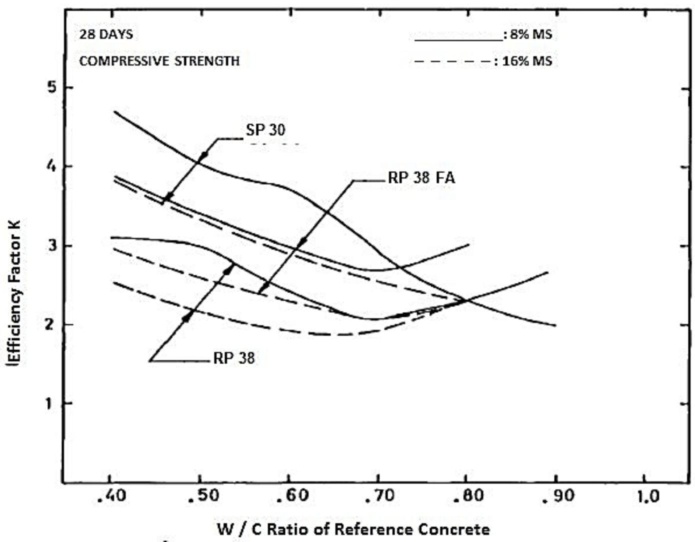

Figure 4. The Cementing Efficiency Factor of SF with Different Cement Types [34]

Malhotra and Carette, 1983 [35] stated that "SF is a very efficient pozzolan and, like other pozzolanic materials, it is generally more efficient in concretes having high water-cement ratios. Research in Norway and Canada indicates that in concretes with a water-cement ratio of about 0.55 and higher, the SF has an efficiency factor of 3 to 4. This means that (within the usual 0-to-10-percent range of replacement) 1 pound of SF can replace 3 to 4 pounds of cement in concrete without changing the compressive strength".

In general, the addition of SF reduces the permeability of hydrated cement paste as well as the porosity of the transition zone between the cement matrix and aggregate. The efficiency factor of SF in reducing the permeability of concrete is greater than the efficiency factor in increasing the strength [36]. This is especially the case when SF is added in small concentrations to low-strength concrete. The author [36] used thin concrete discs to measure the relative diffusion coefficient of concretes containing 0, 8, and 16% SF. It was found that the efficiency factor with respect to the drying of concrete containing SF ranged between 6 and 8**.**

Maage, 1989 [37] utilized the reorganized form of efficiency model proposed by Sellevold and Radjy and presented in Equation 16 to determine the efficiency factor of SF in concrete mixes. Studies of Maage,1989 [27] on the efficiency of SF in concretes showed that this efficiency factor is not a constant. Among other factors, it varies depending on the property studied, the curing time and temperature, the concrete strength, and the quantity of SF used. This study also included the examination of the efficiency factor of condensed SF in concrete both for compressive strength anddurability and investigated the influence of a number of variables upon these parameters including permeability, carbonation and chloride penetration.The results show that the uncertainty in such calculations is relatively high. A 90 % confidence interval was shown by assuming a standard deviation of 3 MPa for strengths over 30 MPa and 10 % of the mean strength for strengths lower than 30 MPa (Figure 5). Figure 6 shows the efficiency factor for condensed SF on concrete strength and also shows the effect of the cement type used and the quantity of SF. From Figure 6 it was again made clear that the k-factor is calculatedwith a very high degree of uncertainty.

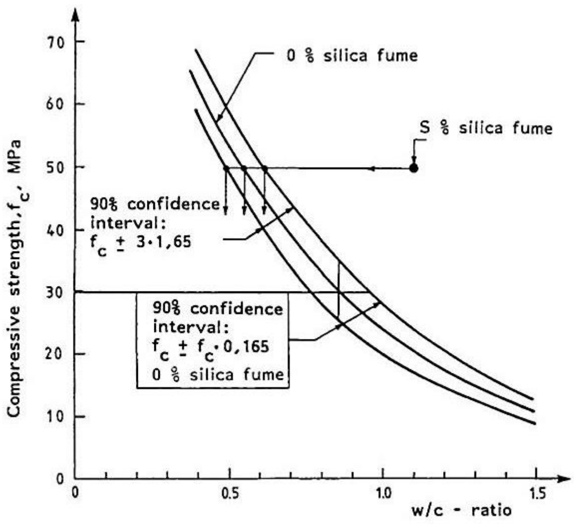

Figure 5. Principle sketch showing the calculation of the efficiency factor for SF in concrete when considering the compressive strength [37]

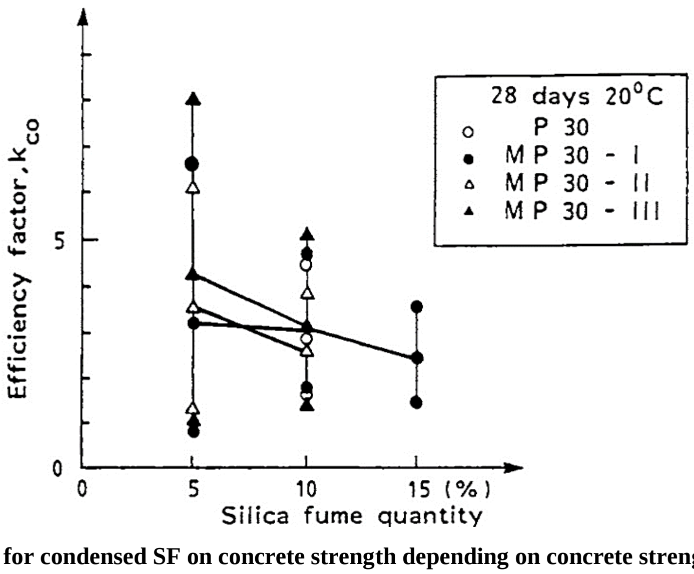

Figure 6. Efficiency factor for condensed SF on concrete strength depending on concrete strength and SF quantity when cured for 28 days in water at 20 C [37]

Modification on Bolomey's and Abram's equation to evaluate the contribution of SF to the strength of concrete was proposed by Slanicka [38] in 1991. The proposed modification showed that the strength of concrete is non-linearly influenced by Silica Fume. Using bolomey's equation the modified equation proposed is

$$f_c = 28.974\left[\frac{c}{w+A} + 2.654\left(\frac{SF}{W+A}\right)^{0.673} - 0.41\right] \quad (19)$$

Using Abram's equation the modified equation proposed is

$$f_c = \frac{164.51}{12.49^{exp}} \quad (20)$$

$$exp = \left[\frac{c}{w+A} + 2.99\left(\frac{SF}{W+A}\right)^{0.725}\right]^{-1} \quad (21)$$

The author proposed simple nomograms which enabled quick estimation of the influence of SF on the strength of concrete. The nomogram based on Equation 19 and 21 is shown in Figures 7 and 8 respectively.

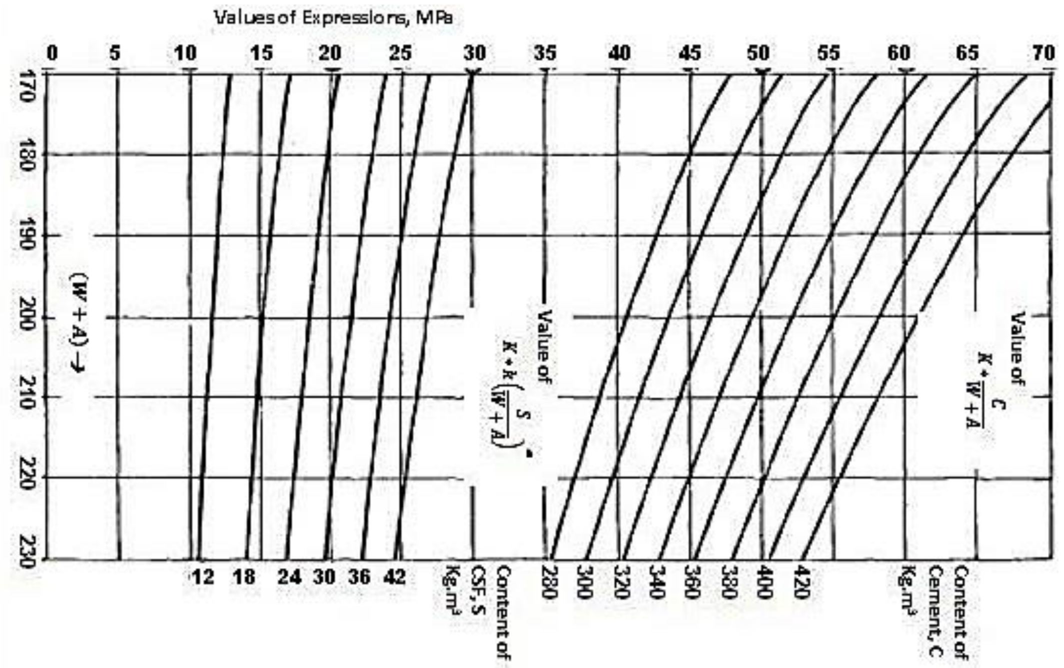

Figure 7. Nomogram of estimation of concrete strength after the Equation (19)

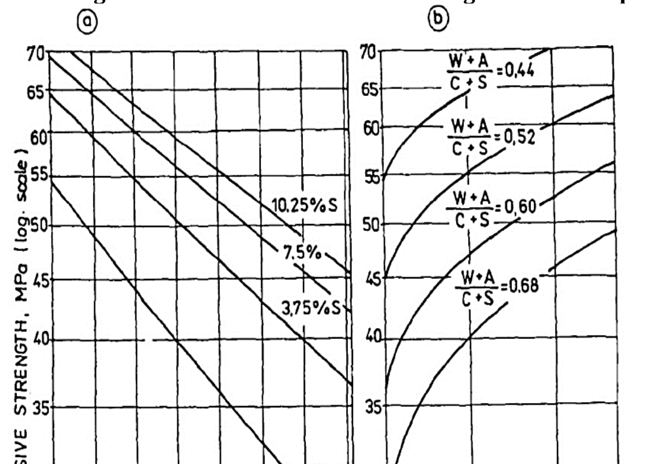

Figure 8. Nomogram of estimation of concrete strength after the Equation (21)

The derived nomograms (Figure 8), show the dependence of the strength of concrete (plotted in the logarithmic scale) on the ratio (W+A)/(C+S) in graded SF content in cementitious material and on the silica fumes content in cementitious material in graded ratios (W.A)/(C+S). Both the Figures clearly indicates that the dependence of strength is logarithmic with the factors. In 1995, Babu, Rao and Prakash [39]proposed a SF efficiency model in concrete. The model proposed for FA was effectively utilized by the authors to find the efficiency factor for SF. It was found that SF efficiency varies at all percentages of replacement. The "general efficiency factor" (k_e) for 28 days cube compressive strengths was assumed constant at 3.0 at all percentage replacement levels. The proposed equation for percentage efficiency factor is given as

$$k_p = 0.0015{p_r}^2 - 0.1223p_r + 2.8502 \tag{22}$$

The final equation incorporating the general efficiency factor is as

$$k = 0.0045{p_r}^2 - 0.3671p_r + 8.5552 \tag{23}$$

Where, $p_r = percentage\ replacement\ of\ SF.$

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%.With increasing SF content it showed a decreasing trend. An examination of the efficiencies acquired from the earlier data (Table 1) with studies on a "Lower Grade Silica Fume" in the research centredemonstrates that the proposed estimations of the effectiveness of SF are of lower bound and it is conceivable to accomplish significantly higher efficiencies with appropriate blend proportioning. The findings of the authors were represented through the graph and are shown through Figure 9 to 11.

Table 1. Ranges of Constituents in the SF Concretes Evaluated [16]

Sl no	Reference	Year	% Replacement Studied	SF Characteristic			Concrete Characteristic		
				SiO_2	LO.I	Cement Content (Kg/m^3)	w/(c+s)	Slump (mm)	f_{ck} (MPa)
1	Sellevold	1983	8, 16%	94-98	1.2-3.5	200-300	-	120-130	22-99
2	Sorensen	1983	10, 20, 40%	86-92	2.0-4.0	144-318	0.38-0.60	70-130	27-64
3	Jahren	1986	3, 6, 9%	88-98	NA	NA	0.34-0.59	10-90	35-81
4	Sandvik	1986	5, 10, 20%	92.1	0.8	240-300	0.70	60-150	30-44
5	Maage	1986	5, 10%	94.7	1.6	250-345	0.61-0.70	100-150	42-54
6	Skjolsvold	1986	5, 10, 13, 20%	NA	NA	180-494	0.37-1.06	100-190	23-79
7	Malhotra	1986	5, 10, 15, 30%	94.0	2.50	240-431	0.40-0.60	75-216	36-71
8	Yamoto	1986	5, 10, 15, 30%	88-91	2.50	238-500	0.25-0.55	15-110	28-83
9	Marusin	1986	5, 10, 15, 20%	94.0	2.50	283-395	0.29-0.38	70-130	38-56
10	Yogendran	1987	5, 10, 15, 20, 25%	NA	NA	354-502	0.28-0.47	0-55	40-68
11	Yamato	1989	10, 20, 30%	90-94	NA	224-320	0.55	69-92	20-47
12	Ganesh Babu	1990	10, 15, 20, 25%	72-75	7.0-10.0	230-353	0.33-0.61	0-55	61-112

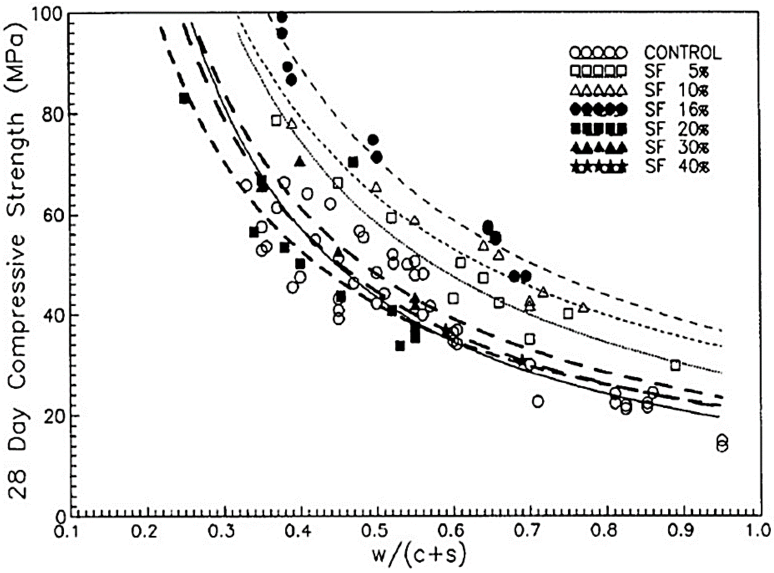

Figure 9. Compressive Strength vs. [w/(c + k .s)] [16]

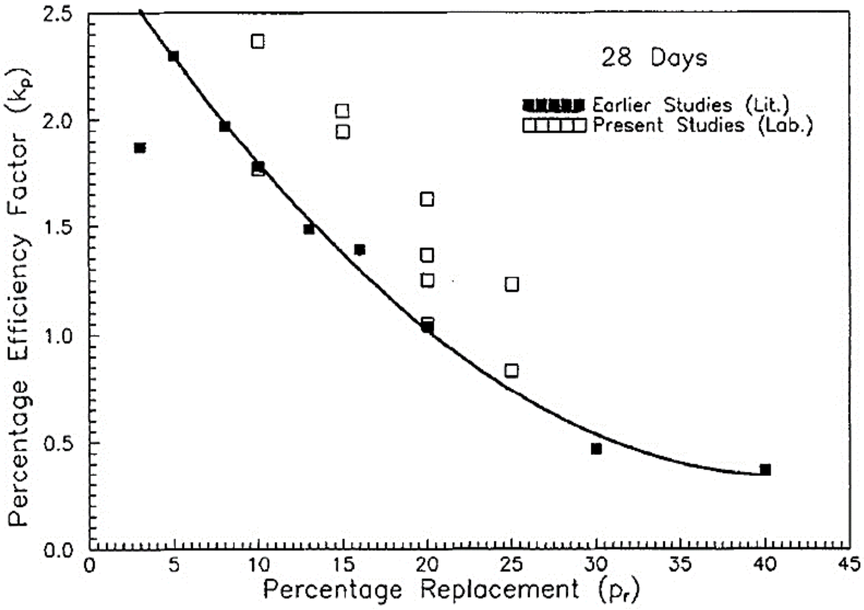

Figure 10. Percentage Efficiency vs. SF Replacement [16]

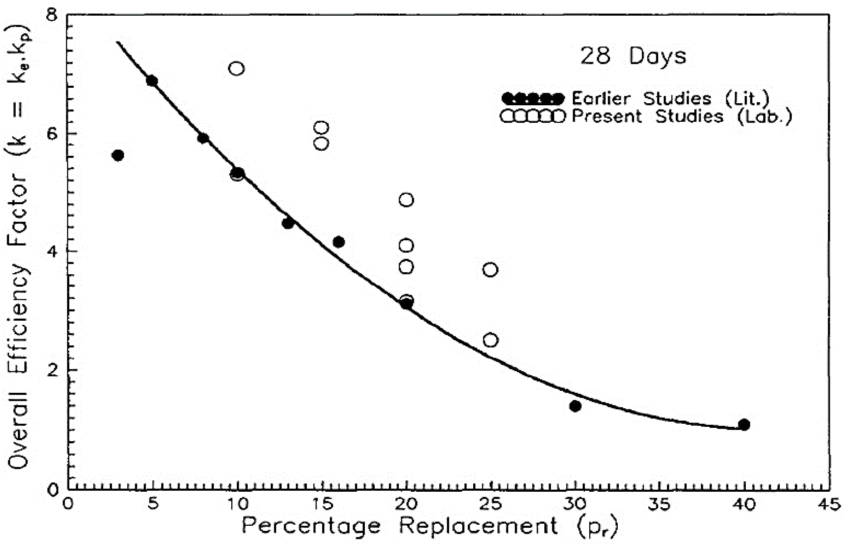

Figure 11. Overall Efficiency vs. SF Replacement [16]

Guttierrez and Canovas 1996 [40] developed a model on the compressive strength of SF concrete based on a constant efficiency factor of SF as 4.75. Duval and Kadri, 1998 [41] have proposed a function α(SF/c) which represents the contribution of SF in "equivalent " cement to compressive strength.

$$f_c(t) = \beta R_{c28} \frac{C}{(y+1)\cdot W}\{A(t) + 1.36 - [2.1(SF/c)^2 - 0.6]^2\} \quad (24)$$

Later he related the function to "percentage efficiency factor" proposed by Babu et al,1995[39].

$$f_c(t) = \beta R_{C28} \frac{C}{(y+1)W}\left[A(t) + 1 + (0.0015{p_r}^2 - 0.1223p_r + 2.8502)\frac{sf}{c}\right] \quad (25)$$

Bhanja 2002 [42] proposed a logarithmic model using the efficiency factor for SF concrete. He based his model on the concept that in the present scenario almost all concretes contains SCM along with cement and hence he proposed a modification in Abram's formulation of the water-cement ratio law. The proposed logarithmic model was based on water to cementitious material (w / c_m) instead of w/c ratio and predicted the compressive strength. The efficiency factor generally varied up to 7 in a descending order with increasing SF content. The model was validated with the test results of previous authors and is presented as:

$$\log f_c = 2.2258 - 1.299\left(\frac{w}{c_m}\right) + 0.1325\left(\frac{kSF}{c}\right) \quad (26)$$

$$f_c = \frac{168.19}{19.91^{\beta}} \quad (27)$$

$$\beta = \left(\frac{w}{c_m}\right) - 0.102\left(\frac{kSF}{c}\right) \quad (28)$$

Wong and Abdul Razak 2005 [17] conducted anexperimental investigation to achieve the efficiency of silica fume-induced high-performance concrete. The authors proposed an efficiency model by modifying Abram's law for water-cement ratio by keeping the fundamental principle of the law intact.

$$R_S = \frac{f_P}{f_c} = \frac{c' - kP}{c} \quad (29)$$

$$k = \frac{R_S c - c'}{P} \quad (30)$$

Where f_P and f_c are the compressive strength of pozzolanic mixture and control mixtures, respectively. P represents the pozzolan in kg/m^3 while c and c' represents the cement content of control and pozzolanic mixture respectively in kg/m^3.It has been reported by the author that the age of concrete, replacement levels and pozzolan type are the several factors influencing the effectiveness of silica fume. The k factor ranged from 2 to 3.5 at 180 days while it ranged from 2.1 to 3.1 at 28 days. It has been further reported that the effectiveness of the pozzolanic material decreases with an increase in the pozzolanic content. In contrast, change in water-cement ratio has no or little significance on the "resultant efficiency factors". The authors further recommended reliability analysis of the proposed model before incorporation into the design of SF concrete.

Malathy and Subramanian 2007 [43] found the efficiency factor for different mineral admixtures like SF with different replacement levels so that according to the target strength, the corresponding mineral admixture can be replaced to get high-performance concrete using Bolomey equation. The author evaluated the value of efficiency factor using the Equation 31.

$$k = \frac{1}{f}\left\{-c + \frac{w[f_c - A_2]}{A_1}\right\} \quad (31)$$

They proposed an efficiency factor for SF at 7 days and 28 days at different replacement levels. The efficiency factor for SF replaced concrete mixes show an increasing trend as the replacement level is increased up to 10 %, whereas, FA mixes show a decreasing trend. They concluded that the efficiency factor for SF concrete with all replacement levels is greater than 1 at 7 days.

Recently Thorstensen and Fidjestol,(2015) studied the inconsistencies in the pozzolanic Strength Activity Index (SAI) for SF according to EN and ASTM [44].

3. Efficiency Models for Supplementary Cementitious Material

In the recent times, the interest of the researchers is towards the evaluation of the efficiency factor of supplementary cementitious material (SCM). Atcin, 1998 [45] was the first to propose the efficiency model for SCM. Babu et al., 2000 [16,39,46], Bharat et al., 2001 [47], Papakadis et al., 2002 [48]has proposed efficiency model for SCM (FA, SF, GGBS, metakaolin) in terms of durability properties, which include carbonation depth, freezing and thawing etc. For GGBS, Babu et al. [46] attained the value of k within the range of 0.80 and 1.29 after 28 days of curing.

Uyan et al. [49] proposed a logarithmic function to determine the efficiency coefficient of slag which is dependent on the age and replacement rate. The efficiency coefficient was based on the principle that mortars having the same w/b ratio will have the same compressive strength. The main results of the study are that the efficiency factor increases with age and decreases with decrease in replacement rate. The water to effective binder ratio was identified by modifying the Smith Model.

Pekmezci and Akyuz [50] proposed a parabolic equation between the equivalent cementitious material and natural pozzolan in concrete to determine the equivalent cementing material. The correlation has the form

$$C' = aT^2 + bT \quad (33)$$

Where C′ is the cementitious material and T is the natural pozzolan while 'a' and 'b' is the regression coefficient. To obtain the cementing efficiency factor for natural pozzolan the authors used the modified Bolomey and Ferret equation into the form presented in Equations 10 and 11.Through their study, they reported that the optimum pozzolan/cement ratio to obtain the maximum strength is approximately 0.28. Further, they commented that Efficiency decreases with the increase of the pozzolan/ cement ratio.

Abdelkader et al., 2010 [51] proposed a logarithmic function to determine the efficiency co-efficient of GGBS. The author through his investigation and survey observed that the k value is proportional to the logarithmic of the time for a given mix design. The water to effective binder ratio was identified by modifying the Feret Model. The proposed model was similar to that proposed by Uyan et al.[49]. The model equation had the following expression

$$k = A + B\ln(t) \tag{34}$$

The coefficient A is the above expression is dependent on the starting point of the hydraulic reaction acquired in the age of 1 day. While the coefficient B represents the kinematic increase of the coefficient of efficiency with time. The authors with an acceptable coefficient of regression expressed the following expression for both the coefficient.

$$A = -11.34p^2 + 8.94p - 1.81 \qquad (r^2 = 0.68) \tag{35}$$

$$B = 1.14p^2 - 1.56 + 0.74 \qquad (r^2 = 0.7) \tag{36}$$

The authors further confirmed that the form given to these coefficients has similarity with the previous works on the efficiency of mineral admixtures[41, 49, 50].

Pornkasem et al, 2018 [52] adopted the modified Ferrets equation proposed by Papakadis and Tsimas [53] to evaluate the efficiency factor for Rice Husk Ash (RHA). The modified Ferret equation for compressive strength is presented in the form of Equation 37:

$$q_u = k\left[\frac{C+KP}{W} - a\right] \tag{37}$$

Where k represents efficiency factor, C is cement, W denotes water and P is pozzolanic content, K and a are constants which can be determined by the nominal mix. They observed that for the mixtures with 10% cement content, the RHA shows the same efficiency as cement upto adding content of 15% while further increase in RHA content, the efficiency factor decreases.

In one study Topcu et al. (2018), investigated the efficiency factor of andesite waste powder as a mineral additive and compared with F type fly ashes. The efficiency factors of mineral additives were likewise investigated according to the curing ages of concrete specimens. Concrete specimens were prepared at various cement dosages to determine the efficiency factors of mineral additives at various substitution levels. The efficiency factors were determined by determining the variable Feret coefficient for each specimen series [54].

Lollini et al. in 2016 [55] evaluated the efficiency factor of SCM with respect to compressive strength. The author utilized the Smiths model to assess the k value valid for strength. The author further used the Abrams Law to determine the w/c ratio. The Abrams coefficient A and B was determined by interpolating (Least square method) the cube compressive strength (f_c) data of OPC concrete. Finally after replacing the cement content in Equation 4, c, with the equivalent cement content, c_{eq}, according to:

$$C_{eq} = C + k \times P \tag{38}$$

Where, k denotes the efficiency value and A is the content of SCMs in the binder. The authors in their study reported that the 'k' value of different SCM was usually found to be lower than 1 and was also valid for resistance to penetration of carbonation. For FA and GGBS, the 'k' value was obtained higher than 1 while for ground limestone and natural pozzolana the 'k' value was lower than 1. The authors further reported that for the case of resistance to chloride penetration the 'k' value of different SCM needs to be evaluated as large uncertainty was observed.

Boukhatem et al., 2011 [56] developed an ANN model which provided a more accurate tool to calculate *k- value* and to capture the effects of five main parameters, such as age, amount of substitution, and concrete composition (w/b, replacement level and cement dosage) and for predicting the efficiency factor of GGBS in terms of percentage replacement and concrete testing age, the author also developed a mathematical model using ANN model.

Chore et al. 2018 [57] stated that a quantitative understanding of the efficiency of SCMs as a mineral admixture in concrete is essential for its effective utilization. The performance and effective utilization of various SCMs can be possible to analyze, using the concept of the efficiency factor (k-value). The authors further presented an overview of the artificial neural network (ANN) for the prediction of the efficiency factor of SCMs in concrete. It is found that the model generated through ANN provided a tool to calculate efficiency factor (k) and capture the effects of different parameters such as, water-binder ratio; cement dosage; percentage replacement of SCMs and curing age.

4. Conclusion

The pozzolanic activity of various SCMs has been customarily decided with respect to the compressive strength of concrete; however, the k-value idea has been likewise stretched out to different properties e.g. the durability properties. The assessment of the k-value, with respect to the compressive strength, is generally produced using the correlation between strength and the water/ cement ratio, i.e. Abram's law, for the reference Portland cement concrete, however additionally different methodologies have been connected, e.g. the correlation of the quality of two blends having a similar workability. The method for calculating efficiency factors results in relatively high uncertainties. In other cases, the efficiency factors have also been calculating considering compressive strength, water permeability, carbonation and chloride diffusion. From the review of the literatureIt can be seen that there was no homogeneous relationship used to estimate the K value. Today, SCMs are widely used in concrete either in blended cement or added separately in the concrete mixer. The significance of this review is to determine the efficiency factor of SCMs (k-factor) which describes the efficiency of SCMs to act as a cementing material. Currently, there is no specific mixture proportioning method available to design SCM concrete for a desired strength and workability. In this review, the efficiency of SCMs with regard to physical characteristics such as compressive strength and workability in concrete may be investigated using a soft computing technique approach.

8. Conflicts of Interest

The authors declare no conflict of interest.

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