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Efficiency of calcined kaolin and silica fume as cement replacement material for strength performance

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ABSTRACT

The concept of efficiency can be used for comparing relative performance of various pozzolans when incorporated into concrete. In this paper, an alternative approach for evaluation of efficiency factor *k* of a pozzolanic material has been introduced. The method, developed following Abram's strength-W/C ratio rule, calculates efficiency in terms of relative strength and cementitious materials content. The advantage of this method is that only two mixtures are required to determine the *k* factor of a specific mixture. A laboratory investigation on silica fume (SF) and metakaolin (MK) concrete found that the computed efficiency factors varied with pozzolan type, replacement level and age. At 28 days, the *k* values ranged from 1.6 to 2.3 for MK and 2.1 to 3.1 for SF mixtures, while at 180 days the *k* values varied within 1.8 to 4.0 for MK and 2.4 to 3.3 for SF mixtures. Generally, the *k* factors increased with age but declined with higher pozzolanic content. It was also observed that change in W/CM ratio from 0.33 to 0.27 did not significantly affect the resultant efficiency factors.

Keywords: Efficiency factor; high-performance concrete (E); metakaolin (D); silica fume (D); compressive strength (C); water-to-cementitious materials ratio

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1. Introduction

The cementing efficiency factor *k* of a pozzolan is defined as the number of parts of cement in a concrete mixture that could be replaced by one part of pozzolan without changing the property being investigated, which is usually the compressive strength. This concept was proposed by Smith [1], and was initially applied in rational proportioning of fly ash concrete by using the "fly ash cementing efficiency *k*", defined such that a mass *f* of fly ash would be equivalent to a mass *kf* of cement in terms of strength development. Compressive strength is normally used as basis for the estimation of *k* value because it is a simple and a consistent industrial test and moreover can be used fairly well to assess the general quality, durability and performance of a particular concrete mixture. In essence, *k* is a factor that accounts for the difference between the contribution of Portland cement and fly ash to strength development.

Smith's model was in the form of $W/CM = W/(C + k\ FA)$ where *k* is assumed to be unique for each fly ash. The *k* factor is calculated by equating the W/C of Portland cement concrete to the W/CM of Portland cement-fly ash concrete, with the condition that the two concretes have the same workability and the same 28-day compressive strength. Results from Smith's experiment show that a constant *k* factor for a particular fly ash does not exist, however, a *k* value of 0.25 was suitable for use in preliminary mixture proportion of mixtures with up to 25% fly ash. Nevertheless, this method has been reported to be complicated for practical purposes [2].

The efficiency concept, which was initially developed for fly ash, can be easily applied to other supplementary cementitious materials as well, such as silica fume, slag and natural pozzolans. For example, previous studies [3, 4] found that the efficiency of silica fume for compressive strength varies between 2 to 5 for replacement in the range of 5 to 20% of cement by silica fume. The much higher *k* value for silica fume, in comparison to fly ash is attributed to its high amorphous silica content as well as its high surface area. Babu and

Kumar [5] attempted to quantify the 28-day cementitious efficiency for ground granulated blast furnace slag (GGBS) in concrete at various replacement levels. Their evaluations found that the overall strength efficiency factor varied from 1.29 to 0.70 for 10 to 80% GGBS contents.

2. Review of efficiency models

In 1993, Babu, Rao and Prakash [6] undertook an extensive investigation for different pozzolans and proposed methods for the estimation of efficiency and subsequently applied these factors in the mix design for concretes containing mineral admixtures. They proposed an "overall efficiency factor k" for a pozzolan that may be assessed via multiplication of two separate factors, the "general efficiency factor k_e", which is a constant for all percentages of replacement and the "percentage efficiency factor k_p", which varies with the replacement level. The authors subsequently used the model to assess the efficiency of concretes containing fly ash, silica fume and GGBS. It was found that the overall efficiency factor might change with age, cement type and content, curing conditions and temperature.

In 1995, Hassaballah and Wenzel [7] proposed a strength-based method to obtain k value for fly ash. This method is based on comparing the compressive strengths of two concrete mixtures having the same workability. The first mixture contains cement and fly ash while the second has the same cement content as the first, but no fly ash. If the two mixtures have similar workability, then it is expected that the 28-day compressive strength of the blended mixture (f_c') will be more than that of the second mixture (f_c). Therefore, the total contribution of fly ash to the compressive strength is the difference between f_c' and f_c. The authors then defined the ratio of this difference to the strength of control mixture (f_c), as the pozzolan efficiency factor ($k = (f_c' - f_c) / f_c$). Hence, according to this method, positive k values indicate strength improvement while negative values indicate strength loss.

More recently (2002), Papadakis, Antiohos and Tsimas [8, 9] proposed a method to evaluate efficiency factor for various natural and artificial pozzolans by using the concept of pozzolanic activity index. Pozzolanic activity was determined as the ratio of strengths, of a pozzolanic mortar to that a control mortar. The authors correlated the *k* value with active silica content of the supplementary cementitious materials and an analytical relationship was obtained. By experimental comparison, it was concluded that these expressions are only valid for artificial pozzolans, while for the case of natural pozzolans the *k* value is overestimated.

3. Proposed model to evaluate pozzolan efficiency

Conventionally, the efficiency factor for strength performance of a pozzolan is calculated on the basis of comparison between concrete strength and the W/C ratio for a non-blended mixture and between concrete strength and W/CM ratio for a blended mixture. However, this method can be rather complicated for practical application, since it requires an extensive set of data in order to establish beforehand, a relationship between strength and W/CM ratio for different amounts of a particular pozzolan.

In this paper, a relative strength-based method to obtain efficiency values for strength performance is used. The first mixture is the OPC control mixture, while the second is a blended mixture containing a pozzolanic material as a partial replacement for cement. The total cementitious materials content and other mixture characteristics such as water and aggregate contents are the same for both mixtures. Also, both mixtures are subjected to similar curing history. Therefore, strength development for the control is principally dependent on the rate of cement hydration while for the blended mixture, is dependent on the combination of cement hydration and pozzolanic reaction. By observing the relative strength, which is defined as ratio of strengths of the blended mixture to the control, an understanding of the rates of reaction in a blended pozzolanic system relative to the control system can be achieved. If the pozzolan contributes positively to strength development at a certain age, then the resulting relative strength value will be greater than unity.

The method follows the fundamental principle of Abram's rule, which states that the strength of a fully compacted concrete, for a particular concrete mixture, is inversely proportional to the water-to-cement ratio. The basic assumption of the proposed method is that the strength of a blended mixture is inversely proportional to the water-to-effective cement content ratio (W/C_{eff}), where the effective cement content is $C' + kP$.

For control mixture:

$$S_C \propto \frac{1}{W/C}$$

$$S_C = K_1 \frac{1}{W/C} \tag{1}$$

For pozzolanic mixture:

$$S_P \propto \frac{1}{W/C_{eff}} \propto \frac{1}{W/C'+kP}$$

$$S_P = K_2 \frac{1}{W/C'+kP} \tag{2}$$

Where S_C = strength of control mixture

S_P = strength of pozzolanic mixture

W = water content (kg/m^3)

K_1, K_2 = proportionality constant

k = strength efficiency factor

C = cement content (control mixture) (kg/m^3)

C_{eff} = effective cement content ($C'+kP$)

C' = cement content (pozzolanic mixture) (kg/m^3)

P = pozzolanic material content (kg/m^3)

Since the materials proportion, W/CM ratio, curing history and testing conditions for both control and blended mixture are similar, it is assumed that the proportionality constants K_1

and K_2 are equal. Thus, any effects of the pozzolan on strength is taken directly into account by the efficiency factor k. Dividing Eq. (2) by Eq. (1) gives relative strength, R_S

$$R_S = \frac{S_P}{S_C} = \frac{C' + kP}{C}$$

Therefore,

$$k = \frac{R_S C - C'}{P} \qquad (3)$$

The above analysis yields an equation for k, in terms of relative strength, cement content of control and blended mixture, and pozzolan content. If the strengths of the control and pozzolanic mixture are equivalent (relative strength $R_S = 1$), then the equation gives $k = 1$, since $C – C' = P$. This indicates that the pozzolan has the same cementing efficiency as ordinary cement and that one part of the pozzolan replaces one part of cement without any changes in strength. If $R_S > 1$, then the equation gives $k > 1$, indicating that the pozzolan in question has a higher cementing efficiency than cement. Conversely, if $R_S < 1$, then the equation gives $k < 1$, which shows that the pozzolan is less efficient than cement in terms of strength contribution.

4. Research objectives and scope

This research aims to evaluate the suitability of the proposed method as an alternative way of determining pozzolan efficiency. An obvious advantage of the proposed method is in its rapidity and simplicity, since only two mixtures are required to determine the k values of a particular pozzolan. The scope of this study is limited to mixtures incorporating silica fume (SF) and metakaolin (MK). The study intends to investigate the effects of variables such as age, percentage of replacement and W/CM ratios on the obtained k values. Silica fume was chosen because it is well recognised as a highly effective pozzolanic microfiller, while metakaolin is a relatively new material that has generated much research interests in recent years. Furthermore, the raw material for metakaolin that is kaolin is abundantly available in

Malaysia. This study is part of an extensive research programme on the feasibility of Malaysian kaolin as a pozzolan for concrete.

5. Experimental investigation

5.1 Materials and mixture proportions

ASTM Type I ordinary Portland cement was used. Silica fume was a commercial densified type while metakaolin was obtained by calcination of refined Malaysian kaolin at 700^{o}C for 7 hours, using a rotary electrical furnace. Specific gravities of the cement, silica fume and metakaolin are 3.11, 2.22 and 2.52. Chemical composition of the cementitious materials is given in Table 1. Aggregates were single-sized 10-mm crushed granite stone and medium graded silica sand, both in accordance to the grading requirements of BS 882: 1992.. Specific gravities for the coarse and fine aggregate were 2.57 and 2.65 respectively. A liquid polycarboxylic ether based superplasticizer was used to improve workability of the concrete mixture. The admixture has a specific gravity of 1.05 and contains 20% solids dosage. Mixing and curing water was taken directly from tap supply at temperature of approximately 28^{o}C.

Sherbrooke method [10] was used for the design of twenty-one concrete mixtures with water-to-cementitious material ratio (W/CM) of 0.27, 0.30 and 0.33 (Series A, B, and C respectively). At each W/CM ratio, mixtures with 0, 5, 10 and 15% replacement by weight of cement with silica fume and metakaolin were prepared. Total cementitious materials content used for all mixtures was 500 kg/m^3, while coarse aggregate content was 1050 kg/m^3. Since superplasticizer content is known to have an effect on concrete strength even at constant W/CM ratio [11], the superplasticizer dosage for Series A, B and C were fixed at 1.8%, 0.8% and 0.5% by weight of cementitious material content respectively. Hence, any change in concrete properties at a specific W/CM ratio is primary due to the presence of pozzolans. Mixture proportions are summarised in Table 2.

5.2 Specimen preparation

Concrete mixtures were batched using a pan mixer. Cube specimens for compressive strength testing were moulded using 100-mm steel moulds and compacted in three uniform layers by means of vibrating tables. The amount of vibration required to ensure good compaction was adjusted based on the Vebe time of the fresh concrete. Forty cube specimens were prepared for each mixture. The moulds were stripped after 24 hours, and the specimens were cured in a water tank at 28^{o}C until the day of testing.

5.3 Concrete testing

Fresh concrete were tested for slump (BS 1881: Pt. 102: 1983) and Vebe (BS 1881: Pt. 104: 1983). Compressive strength test (BS 1881: Pt. 103: 1983) was performed on 100-mm cube specimens at ages 1, 3, 7, 28, 56, 90 and 180 days, using a digital compression-testing machine with maximum load capacity of 2000-kN. At least three specimens were tested at each age to compute the average strength. Additional specimens were tested when the deviation of any individual cube strength exceeded 3% from the mean and the new average was computed based on three closest strength results. All specimens were tested in wet condition.

6. Analysis of results

6.1 Workability

Workability characteristics of fresh concrete were assessed with respect to slump and Vebe time. These are shown in Table 3. The mixtures had slump values ranging from 30 to 260 mm while Vebe time was in the range of 1 to 15 seconds. The large variation of workability across mixtures was due to the constant superplasticizer dosage used for mixtures with the same W/CM ratio. The superplasticizer content was fixed with the intention of maintaining a standard material proportion and avoiding any effects of variation in superplasticizer content onto strength properties. Consequently, the slump reduced systematically as the amount of mineral admixture in the mixture increased. It is noted that silica fume caused a more severe loss of workability compared to metakaolin. This is attributed to its extremely high surface area of 21 m^2/g, measured via nitrogen adsorption, which is double that of metakaolin (9.5 m^2/g). To minimise the effect of variation in workability on air content and hence strength, the compaction energy was varied by giving longer vibration time to mixtures with low workability. The measured Vebe time was used as a reference for the amount of vibration required for each mixture to ensure sufficient compaction for all specimens.

6.2 Efficiency factor

Compressive strength results are given in Table 4. The average coefficient of variation for all measurements is approximately 1%. It is observed that the pozzolans did not produce an immediate strength enhancement; instead the blended mixtures only achieved higher strengths than the control from 7 days onwards. Strength loss in the early ages, which was proportional to the cement replacement level, was probably due to dilution effect of the pozzolan and as well as the slow nature of the pozzolanic reaction. Generally, strength was found to be inversely proportional to the W/CM ratio, indicating that the Abram's rule is observed. This is shown in Fig. 1. However, reducing the W/CM ratio from 0.30 to 0.27 did not trigger a significant strength enhancement as anticipated. After 90 days of curing, the average strength enhancement achieved by the 10% MK mixtures was 13.5%, while mixtures with 10% SF achieved 17% increment.

The *k* values for all mixtures at ages greater than 7 days are presented in Fig. 2. Generally, it is observed that the efficiency factors for mixtures in Series A and Series B increased with age due to increase in relative strength brought by the pozzolanic reaction. Results from Series C however, did not produce a consistent trend. At 28 days, the *k* values ranged from 1.6 to 2.3 for MK and 2.1 to 3.1 for SF mixtures, while at 180 days the *k* values varied within 1.8 to 4.0 for MK and 2.4 to 3.3 for SF mixtures. In general, mixtures with 5 percent MK or SF achieved the highest k values. The efficiency factors declined for higher pozzolanic contents, despite the observed overall strength enhancement. This drop in efficiency is due to a non-proportional gain in relative strength when the pozzolanic replacement was increased from 5% to 15%. Hence, it can be concluded that at high SF or MK contents, the relative contribution of the pozzolan to concrete strength decreased. It should also be noted that when W/CM ratio was reduced from 0.33 to 0.27, no significant change in *k* was observed.

The computed efficiency values for silica fume compares well with the values obtained in previous research. According to Jaren [12], the efficiency factor for silica fume ranges from 2 to 5 and the value varies with SF and cement content, age, curing conditions, type and dosage of superplasticizer and type of cement. Other studies have also quoted similar efficiency values for silica fume at 5% to 20% replacement levels [3, 4]. Babu, Rao and Prakash [6] proposed an “overall efficiency factor *k*” for a pozzolan, which is a multiplication of two separate factors, the “general efficiency factor k_e” and the “percentage efficiency factor k_p”. Babu and Prakash [13] subsequently studied some 160 concretes with 28 day strengths of 20 MPa to 100 MPa, and found that the value for k_e to be 3.0, while k_p ranges from 0.37 to 2.28 for replacement of up to 40% SF; thus giving an overall efficiency factor *k* of 1.11 to 6.85 for the SF concretes studied. Unfortunately, previous study on the efficiency of metakaolin concrete is unknown and thus comparison cannot be made.

6.3 Discussion and future consideration

Based on the obtained results, it is highly evident that a single *k* value for a silica fume or metakaolin does not exist, even for a specific cement-pozzolan content. The efficiency of a pozzolan is dependant on the mixture proportion and age of testing. However, variation in W/CM ratio did not seem to have much effect on the resulted efficiency factors. This could be due to the small range of W/CM ratios investigated in the present study.

The computed efficiency factors may be incorporated in the design of a blended concrete mixture, a method known as rational proportioning. The *k* value can be used to transform a certain amount of pozzolan to an equivalent amount of cement in terms of strength contribution; hence it can be used as a basis for a more efficient proportioning of blended concrete. In situation when it is required that a certain targeted strength be achieved, the design of mixtures incorporating specific pozzolans at various quantities can be performed with greater confidence, when compared to the ordinary weight-to-weight replacement or addition method. The strength-based efficiency factor may be employed in conjunction with other factors such as those related to cost for the optimisation and effective utilisation of a pozzolan in concrete at various levels of replacement.

However, the validity of the efficiency factor approach in the proportioning of blended concrete mixtures has been under considerable criticisms over the years. The main concern is that the *k* value for a particular pozzolan depend not only on their mineralogical composition but also on the curing condition, age, type of cement, strength grade and quantity of pozzolan in relation to cement in the mixture, apart from the parameter for which the efficiency is under study [14, 15]. Unfortunately, due to limited available data, further refinement of the proposed Eq. (3) to take into account for all these factors is not possible. Researchers have also derived *k* from various properties, such as based on cost, permeability, maturity, lime combustion, and workability; and all these factors differ from one another [11]. Thus, in this aspect, the rational proportioning method is considered complex and may have a limited practical importance for normal applications.

7. Conclusion

This study proposed an alternative approach to evaluate the contribution of a pozzolanic mineral admixture in enhancing strength properties of concrete. The proposed method is based on a formulation to calculate efficiency factor in terms of relative strength, cement content of control and blended mixture, and pozzolan content, which was developed following the fundamental principle of Abram's rule. The advantage of the proposed method is that it only requires two mixtures to determine the *k* factor of a particular pozzolan. An experimental investigation was conducted to demonstrate the use of the model in determining the efficiency of silica fume and metakaolin when incorporated into high-performance concrete mixtures. It was found that the computed efficiency factors varied with pozzolan type, replacement level and age. At 28 days, the *k* values ranged from 1.6 to 2.3 for MK and 2.1 to 3.1 for SF mixtures, while at 180 days the *k* values varied within 1.8 to 4.0 for MK and 2.4 to 3.3 for SF mixtures. Generally, the *k* factors increased with age but declined at high pozzolanic contents. It was also observed that change in W/CM ratio from 0.33 to 0.27 did not significantly affect the resultant efficiency factors. Based on the obtained results, it was concluded that a single *k* value for a pozzolan does not exist, even for a specific cement-pozzolan content. Although the calculated *k* factors were found to be similar with values obtained by previous research, further laboratory investigation is necessary to establish the reliability of the proposed method, particularly with respect to its incorporation into the design of blended concrete.

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REFERENCES

[1] I.A. Smith, The Design of fly ash concrete, Proceedings of the Institute of Civil Engineers, London, 36 (1967) 769-790.

[2] E.E. Berry, V.M. Malhotra, Fly ash in concrete, CANMET SP85-3, 1996, Ottawa Canada.

[3] FIP, State of the art report: Condensed Silica Fume in Concrete, London, Thomas Telford Ltd (1988).

[4] E.J. Sellevold, T. Nilsen, Condensed silica fume in concrete: A world review, In: V.M. Malhotra (Ed.), Supplementary Cementing Materials for Concrete, Canadian Government Publishing Centre, Ottawa, Canada, (1987) 167-243.

[5] K.G. Babu, V. S. Rama Kumar, Efficiency of GGBS in concrete, Cem Concr Res 30 (2000) 1031-1036.

[6] K.G. Babu, G.S.N. Rao, P.V.S. Prakash, Efficiency of pozzolans in cement composites, In: R.K. Dhir & M.R. Jones (Eds.), Proceedings, Concrete 2000 Economic & Durable Construction through Excellence, Vol. 1: Design, Materials & Construction, University of Dundee, Scotland, E & FN Spoon, (1993) 497-509.

[7] A. Hassaballah, T.H. Wenzel, A strength definition for the water to cementitious materials ratio, In: V.M. Malhotra (Ed), Proceedings, ACI Fifth International Conference, Fly Ash, Silica Fume and Natural Pozzolans in Concrete, Milwaukee, Wisconsin USA (1995) 417-437.

[8] V.G. Papadakis, S. Tsimas, Supplementary cementing materials in concrete Part I: Efficiency and design, Cem Concr Res 32 (2002) 1525-1532.

[9] V.G. Papadakis, S. Antiohos, S. Tsimas, Supplementary cementing materials in concrete Part II: A fundamental estimation of the efficiency factor, Cem Concr Res 32 (2002) 1533-1538.

[10] P.C. Aïtcin, Sherbrooke mix design method, Proceedings: The one-day short course on Concrete Technology and High-Performance Concrete: Properties and Durability, University of Malaya, Kuala Lumpur, 1997.

[11] A.M. Neville, Properties of Concrete, Fourth edition, Addison Wesley Longman Ltd., Essex England, 1996.

[12] P. Jaren, Use of silica fume concrete, In: ACI Special Publication SP-79, V.M. Malhotra (Ed.) American Concrete Institute, Detroit (1983) 625.

[13] K. Ganesh Babu, P.V. Surya Prakash, Efficiency of silica fume in concrete, Cem Concr Res 25 (6) (1995) 1273-1283.

[14] J.G.L. Munday, L.T. Ong, R.K. Dhir, Mix proportioning of concrete with PFA, a critical review, In: V.M. Malhotra (Ed.), Proceedings, First International Conference on the use of Fly Ash, Silica Fume and other Mineral by-products in Concrete, ACI, Detroit, SP-79, (1983) 267-288.

[15] M. Maage, Efficiency factor for condensed silica fume in concrete, In: V.M. Malhotra (Ed.), Proceedings, Fly ash, silica fume and natural pozzolans in concrete, Vol. II, SP-114, ACI, Detroit, (1989) 783-798.

Table 1
Chemical composition of cement, metakaolin and silica fume

%	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	P_2O_5	TiO_2	MnO	LOI
Cement	20.99	6.19	65.96	3.86	0.20	0.17	0.60	0.05	0.40	0.06	1.53
MK	57.40	35.26	0.02	0.94	0.18	<0.01	3.17	0.09	0.43	<0.01	2.52
SF	92.06	0.48	0.40	2.11	0.63	0.28	1.24	0.02	<0.01	0.23	2.54

Table 2
Mixture proportions

Mixture	Cement (kg/m^3)	MK (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	W/CM	Granite stone (kg/m^3)	Silica sand (kg/m^3)	SP * (l/m^3)
	Series A (W/CM = 0.27)							
C – 0.27	500	-	-	135	0.27	1050	720	43
MK 5 – 0.27	475	25	-	135	0.27	1050	720	43
MK 10 – 0.27	450	50	-	135	0.27	1050	715	43
MK 15 – 0.27	425	75	-	135	0.27	1050	710	43
SF 5 – 0.27	475	-	25	135	0.27	1050	725	43
SF 10 – 0.27	450	-	50	135	0.27	1050	715	43
SF 15 – 0.27	425	-	75	135	0.27	1050	715	43
	Series B (W/CM = 0.30)							
C – 0.30	500	-	-	150	0.30	1050	695	19
MK 5 – 0.30	475	25	-	150	0.30	1050	690	19
MK 10 – 0.30	450	50	-	150	0.30	1050	685	19
MK 15 – 0.30	425	75	-	150	0.30	1050	680	19
SF 5 – 0.30	475	-	25	150	0.30	1050	685	19
SF 10 – 0.30	450	-	50	150	0.30	1050	680	19
SF 15 – 0.30	425	-	75	150	0.30	1050	680	19
	Series C (W / CM = 0.33)							
C – 0.33	500	-	-	165	0.33	1050	700	12
MK 5 – 0.33	475	25	-	165	0.33	1050	695	12
MK 10 – 0.33	450	50	-	165	0.33	1050	690	12
MK 15 – 0.33	425	75	-	165	0.33	1050	685	12
SF 5 – 0.33	475	-	25	165	0.33	1050	690	12
SF 10 – 0.33	450	-	50	165	0.33	1050	685	12
SF 15 – 0.33	425	-	75	165	0.33	1050	680	12

* SP = Superplasticizer

Table 3
Workability characteristics

Mixture	W/CM	Slump (mm)	Vebe (s)	W/CM	Slump (mm)	Vebe (s)	W/CM	Slump (mm)	Vebe (s)
C	0.27	165	8	0.30	225	3	0.33	240	1
MK 5		155	8		220	3		225	1
MK 10		150	10		210	3		195	3
MK 15		115	10		205	4		155	4
SF 5		100	8		215	3		180	3
SF 10		50	12		117	5		100	6
SF 15		35	15		30	16		35	16

Table 4
Cube compressive strength

Mixture	Compressive strength (MPa) *						
	1d	3d	7d	28d	56d	90d	180d
C – 0.27	39.0 *(0.6)*	68.0 *(1.3)*	72.5 *(1.3)*	84.0 *(1.2)*	86.5 *(1.2)*	87.5 *(0.9)*	90.0 *(0.9)*
MK 5 – 0.27	35.0 *(2.3)*	67.0 *(0.6)*	76.5 *(1.4)*	89.0 *(0.8)*	95.0 *(0.7)*	98.0 *(0.4)*	99.0 *(0.8)*
MK 10 – 0.27	26.5 *(2.8)*	63.0 *(0.3)*	80.0 *(1.0)*	94.0 *(0.5)*	97.0 *(1.0)*	100.5 *(0.8)*	102.0 *(0.5)*
MK 15 – 0.27	26.0 *(0.5)*	60.5 *(0.6)*	79.5 *(0.6)*	94.5 *(0.2)*	98.0 *(0.6)*	100.0 *(0.8)*	100.5 *(0.6)*
SF 5 – 0.27	35.0 *(1.0)*	63.0 *(0.5)*	75.5 *(1.0)*	88.5 *(1.2)*	93.0 *(0.8)*	96.5 *(0.9)*	97.5 *(0.9)*
SF 10 – 0.27	25.0 *(1.8)*	61.0 *(1.5)*	79.0 *(0.4)*	95.5 *(1.0)*	100.0 *(0.6)*	104.0 *(0.9)*	107.0 *(0.2)*
SF 15 – 0.27	24.5 *(0.6)*	59.5 *(1.5)*	76.5 *(1.3)*	101.0 *(1.1)*	103.5 *(0.9)*	106.0 *(0.7)*	109.0 *(0.6)*
C – 0.3	48.0 *(0.6)*	63.5 *(1.1)*	72.0 *(0.5)*	83.5 *(0.2)*	84.5 *(0.8)*	85.5 *(0.9)*	87.5 *(0.8)*
MK 5 – 0.3	45.5 *(1.1)*	62.5 *(0.6)*	76.5 *(0.8)*	88.5 *(1.6)*	94.0 *(0.7)*	96.0 *(0.4)*	100.5 *(0.6)*
MK 10 – 0.3	41.5 *(1.6)*	68.0 *(1.5)*	81.0 *(1.3)*	93.5 *(0.7)*	95.0 *(1.0)*	96.5 *(0.9)*	100.5 *(0.6)*
MK 15 – 0.3	38.0 *(3.2)*	60.5 *(1.2)*	80.0 *(1.6)*	94.5 *(0.3)*	96.5 *(1.4)*	97.5 *(0.7)*	99.5 *(0.3)*
SF 5 – 0.3	46.0 *(2.6)*	62.0 *(1.6)*	81.0 *(1.1)*	91.0 *(1.1)*	95.5 *(0.3)*	95.5 *(0.9)*	97.5 *(1.1)*
SF 10 – 0.3	42.0 *(1.2)*	61.5 *(2.8)*	78.5 *(0.4)*	95.0 *(0.5)*	97.0 *(0.9)*	99.0 *(0.8)*	103.0 *(0.7)*
SF 15 – 0.3	38.0 *(2.2)*	57.5 *(0.8)*	74.5 *(2.5)*	98.5 *(0.3)*	101.5 *(0.4)*	104.0 *(1.0)*	106.5 *(1.0)*
C – 0.33	41.0 *(1.1)*	58.0 *(1.3)*	62.5 *(0.6)*	75.0 *(1.1)*	78.0 *(1.2)*	79.0 *(0.2)*	81.5 *(1.0)*
MK 5 – 0.33	35.5 *(0.6)*	56.0 *(3.1)*	70.0 *(1.2)*	78.5 *(0.7)*	80.5 *(0.1)*	84.0 *(1.0)*	86.0 *(0.8)*
MK 10 – 0.33	34.0 *(0.9)*	59.0 *(1.3)*	74.0 *(1.1)*	84.5 *(0.8)*	87.0 *(1.1)*	89.0 *(0.5)*	92.5 *(0.2)*
MK 15 – 0.33	32.0 *(1.3)*	48.0 *(3.3)*	70.0 *(1.7)*	82.0 *(0.3)*	87.5 *(1.0)*	87.5 *(0.2)*	90.5 *(0.2)*
SF 5 – 0.33	35.0 *(3.8)*	55.0 *(2.3)*	69.5 *(1.8)*	83.0 *(0.3)*	85.0 *(0.9)*	90.0 *(0.6)*	90.0 *(0.8)*
SF 10 – 0.33	32.0 *(1.9)*	53.0 *(2.0)*	70.5 *(2.0)*	89.5 *(0.9)*	90.5 *(1.1)*	92.0 *(0.9)*	93.5 *(0.5)*
SF 15 – 0.33	31.0 *(3.1)*	47.5 *(1.3)*	70.5 *(1.7)*	88.5 *(0.2)*	93.0 *(0.4)*	95.5 *(0.6)*	100.5 *(0.3)*

* Coefficient of variation (%) is indicated in parentheses.

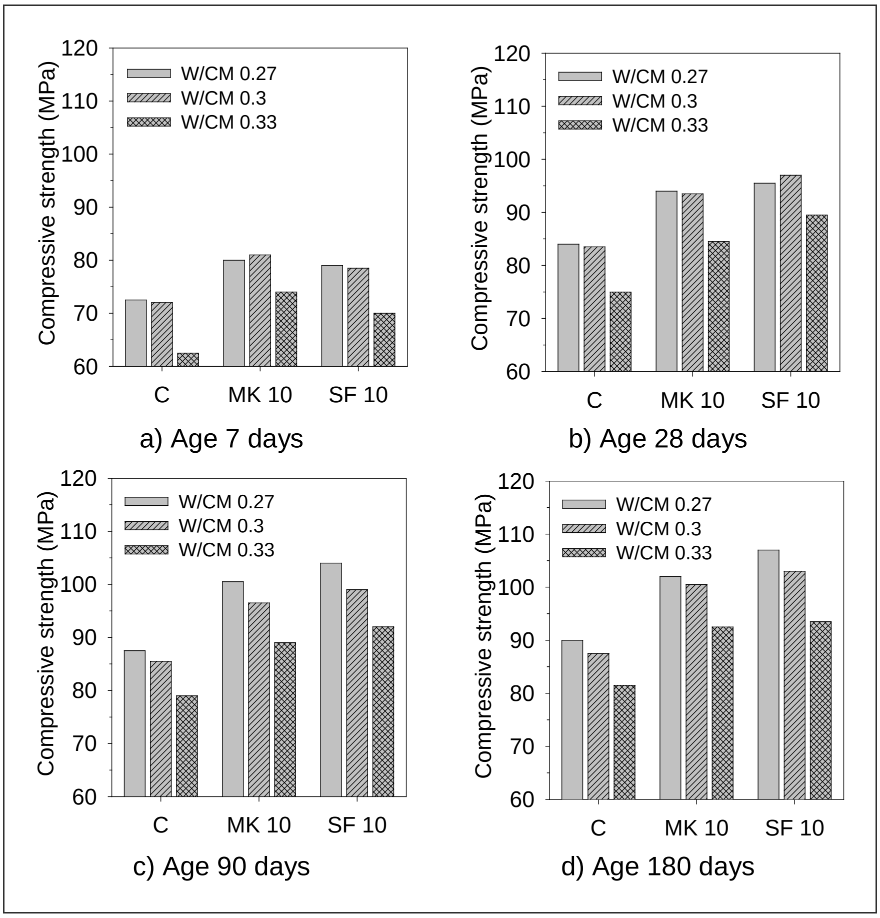

Fig. 1 Variation of compressive strength with W/CM ratio

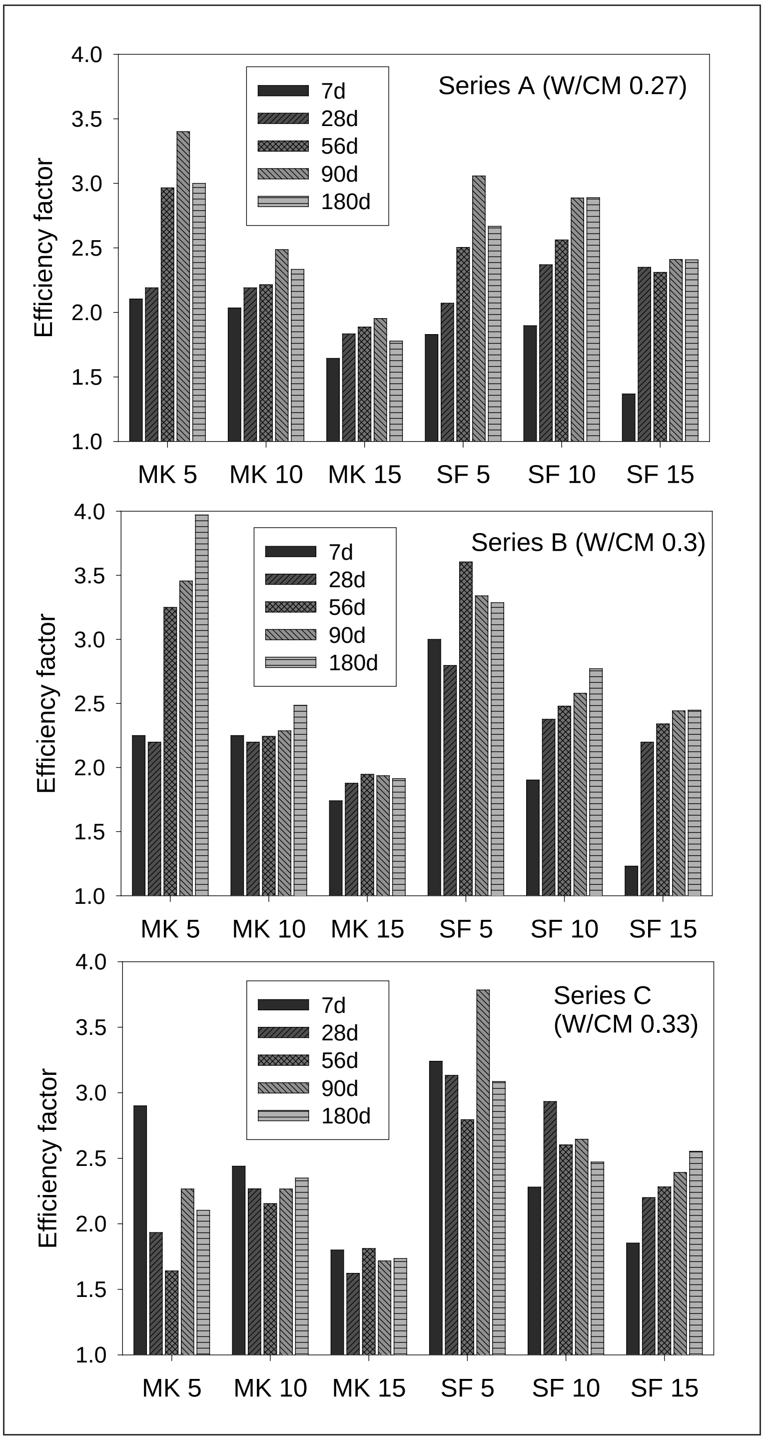

Fig. 2 Efficiency factors