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EVALUATION OF CEMENTING EFFICIENCY IN QUATERNARY BLENDED SELF-COMPACTING CONCRETE

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ABSTRACT

The contribution of metakaolin (MK) to any property of hardened concrete may be expressed in terms of efficiency factor, k. For this new material to be generally accepted by the building industry, a good durability must be proven also in quantitative terms. Therefore a big challenge for researchers within this field is to determine the strength efficiency of metakaolin (MK) in binary, ternary and quaternary blended SCC mixes. For calculating the efficiency of Metakaolin, microsilica and fly ash combination in binary and ternary blended SCC, an equation has been proposed by author based on the principle of Bolomey's equation for predicting the strength of concrete containing mineral admixtures. The strength efficiency factor 'k' is evaluated for three cases in quaternary blended SCC mixes: (1) micro silica (MS) is singly blended in SCC, (2) micro silica (MS) is blended with fly ash (FA) in SCC and (3) Metakaolin (MK) is blended with micro silica (MS) and fly ash (FA) SCC mix. 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 SCC mixes.

Key words: metakaolin, strength efficiency factor, cementing efficiency factor, quaternary blended SCC, Self-compacting concrete.

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1. INTRODUCTION

The cementing efficiency factor, '*k'* of a pozzolanic material is defined as the number of parts of cement in a concrete mixture that could be replaced by one part of pozzolanic material without changing the property being investigated, which is usually the compressive strength. The efficiency factor for strength performance of a pozzolanic material is calculated on the basis of comparison between concrete strength and the w/c ratio for a non-blended mixture and a blended mixture. The efficiency factor is used for proportioning of blended concrete. A rational method of proportioning fly ash concrete was first proposed by Smith, in which the fly ash cementing efficiency factor, '*k'* was defined in such a way that the strength to water cement ratio relation for normal concrete is also valid for ternary and quaternary blended SCC mixes considering the effective water cement ratio, as given by [$W/(C + kP)$], where W is the weight of water in kg/m^3, C is the weight of cement in kg/m^3, P is the weight of blended pozzolanic material. For the optimally blended binary, ternary and quaternary Self Compacting Concrete (SCC) mixes, cementing efficiencies (k) are evaluated to highlight the synergic action of blended pozzolans in SCC mixes of all grades.

2. LITERATURE REVIEW

Bharat Kumar et al. (2001) proposed a method of mix proportioning for concrete containing mineral admixture (MA) by using Bolomey's equation for predicting strength. In their studies, a relative strength-based method to obtain efficiency values for strength performance is used. Malathy and Subramaniam (2007) used the above method to find the efficiency factor of silica fume and metakaolin in their binary mix by using following equation:

$$k = (1/P) \{-C + W (fc - A2) / A1\}$$

where fc is compressive strength of concrete in MPa, C is the cement content in kg/m^3,W is the water content in kg/m^3 and $A1$, $A2$ are constants influenced by ingredients, curing conditions and age of concrete. Efficiency factor increases with age which shows the activation of pozzolanic activity of mineral admixtures with time. K Ganesh Babu and V Sree Rama Kumar (2000) evaluated efficiency of various Supplementary Cementitious Materials (SCM) such as GGBS, silica fume, fly ash in concretes. As per their studies the overall strength efficiency was found to be a combination of general efficiency factor (depending on the age) and a percentage efficiency factor (depending upon the percentage of replacement), as was the case with a few other cementitious materials like fly ash and silica fume reported earlier. H S Wong, H Abdul Razak (2004), proposes an alternative approach for the evaluation of efficiency factor *k* of a pozzolanic material. The method, developed following Abram's strength–W/C ratio rule, calculates efficiency in terms of relative strength and cementitious materials content. Juma Sultan Al Rezaiqi (2011) reports the evaluation of the cementitious efficiency of Cement Kiln Dust (CKD), Sarooj clay (SA) and Copper Slag (CS) in concrete at different replacement percentages. Diego Aponte, Marilda Barra, Enric Vázquez (2012) presents the cementing efficiency of high lime fly ash with regards to mechanical and durability properties. The investigated variables were the rate of the incorporation of fly ash, the cement type, the water/cement ratio, and the curing age of the mix. Two cementing efficiency factors were determined; (i) in terms of the compressive strength, (ii) in terms of the chlorides diffusion coefficient. Both of them have been determined in relation to the water/cement ratio. The result shows that the cementing efficiency is strongly influenced by the water/cement ratio. Kanchan Mala, A K Mullick et al. (2013) proposed new method to find the efficiency factor of SF and FA individually in ternary blend cement system, based on principle of modified Bolomey's equation for predicting compressive strength of concrete using binary blend cement system. Efficiency factor for SF and FA were always higher in ternary blend cement system than their respective binary blend cement system.

3. MIX PROPORTION

Quantities required for 1 cu.m are evaluated for ordinary grade (M20) , standard grade (M40) and high strength grade (M80 and M100) of binary, ternary and quaternary blended Self-Compacting Concrete (SCC) made with optimum proportions of Fly Ash (FA), Microsilica (MS) and Metakaolin (MK) combination based on calculations from Nan Su mix design method. Final quantities, for all SCC mixes considered, are assumed after several trial mixes on quantities computed using Nan Su mix design method subjected to satisfaction of EFNARC flow properties and are tabulated in Table 1

Table 1 Final optimized mix proportions of blended SCC mixes for various grades

Grade of SCC Mix	Mix No	Mix Designation (Values indicate percentage by weight of 'P'	% of FA Added bwp*	Quantities in kg / cu.m									
				OPC (i)	FA (ii)	MS (iii)	MK (iv)	Total Powder Content 'P' kg (i)+(ii)+(iii)+(iv)	Fine Aggregate	Coarse Aggregate	Water	S.P.	W/P ratio
M20	C1	C100	-	486	-	-	-	486	904	812	221	9.5	0.45
	B2	C50+FA50	-	243	243	-	-	486	904	812	221	9.5	0.45
	B7	C80+MS20	-	389	-	97	-	486	904	812	221	9.5	0.45
	B13	C75+MK25	-	365	-	-	121	486	904	812	221	9.5	0.45
	T3	C35+FA50+MS15	-	170	243	73	-	486	904	812	221	9.5	0.45
	T15	C25+FA60+MK15	-	123	290	-	73	486	904	812	221	9.5	0.45
M40	C1	C100	-	531	-	-	-	531	891	786	185	9.5	0.35
	B1	C60+FA40	-	319	212	-	-	531	891	786	185	9.5	0.35
	B5	C85+MS15	-	452	-	79	-	531	891	786	185	9.5	0.35
	B10	C80+MK20	-	425	-	-	106	531	891	786	185	9.5	0.35
	T5	C50+FA40+MS10	-	265	212	54	-	531	891	786	185	9.5	0.35
	T9	C35+FA50+MK15	-	186	265	-	80	531	891	786	185	9.5	0.35
M80	B2	C95+MS5	-	665	-	35	-	700	714	658	167	12.5	0.25
	T3	C65+FA20+MS15	-	455	140	105	-	700	714	658	167	12.5	0.25
	Q11	C50+FA28+MS11+MK11	30	455	259	98	98	910	714	658	167	12.5	0.25
M100	B2	C90+MS10	-	630	-	70	-	700	689	636	154	16.0	0.22
	T2	C71+FA19+MS10	-	500	130	70	-	700	689	636	154	16.0	0.22
	Q11	C55+FA23+MS11+MK11	30	500	214	98	98	910	689	636	154	16.0	0.22

4. COMPRESSIVE STRENGTH

The compressive strength of binary, ternary and quaternary blended SCC mixes of ordinary grade (M20), standard grade (M40) and high strength grade (M80 and M100) made with Fly Ash (FA), Microsilica (MS) and Metakaolin (MK) at 3,7,14,28, 60 and 90 days is recorded and presented in Table 2.

Table 2 Compressive Strengths of various grades of optimally blended SCC mixes

Grade of SCC Mix	Mix No	Mix Designation (Values indicate percentage by weight of Total Powder)	Compressive Strength (MPa)					
			3 days	7 days	14 days	28 days	60 days	90 days
M20	C1	C100	10.07	16.36	20.15	25.18	25.34	27.68
	B2	C50+FA50	5.78	11.60	17.39	20.29	28.98	32.24
	B7	C80+MS20	11.61	18.87	26.13	29.03	32.13	33.24
	B13	C75+MK25	18.54	20.16	27.70	33.77	34.35	35.12
	T3	C35+FA50+MS15	9.10	16.22	20.19	22.13	29.37	32.81
	T15	C25+FA60+MK15	15.67	19.88	23.12	27.11	33.29	36.87
M40	C1	C100	20.36	33.32	39.73	48.18	50.19	53.10
	B1	C60+FA40	12.83	21.75	28.61	43.35	53.60	56.78
	B5	C85+MS15	25.77	31.89	42.01	51.99	54.23	57.96
	B10	C80+MK20	41.16	44.76	51.49	53.73	55.41	58.19
	T5	C50+FA40+MS10	20.20	26.01	34.82	44.56	52.13	59.87
	T9	C35+FA50+MK15	34.79	40.13	47.33	49.22	52.37	59.92
M80	B2	C95+MS5	35.43	57.56	78.71	88.56	91.22	93.19
	T3	C65+FA20+MS15	26.18	50.12	65.98	83.17	90.54	94.51
	Q11	C50+FA28+MS11+MK11	50.02	64.19	81.10	85.26	90.71	97.16
M100	B2	C90+MS10	42.11	65.80	92.13	106.04	107.81	109.11
	T2	C71+FA19+MS10	40.51	65.32	81.04	95.31	104.20	111.83
	Q11	C55+FA23+MS11+MK11	66.12	78.32	87.18	93.14	110.71	113.28

bwp* – By weight of Total Powder Content ; W/P ratio – Water/Powder Ratio

5. CEMENTING EFFICIENCY FACTORS

The effect of synergic action of metakaolin (MK), microsilica (MS) and fly ash (FA) combination on the strengths of binary, ternary and quaternary blended SCC may be modelled by using a Cementing Efficiency Factor (k). The Cementing Efficiency Factor is defined as the ratio of the cementing efficiency of blended SCC to the cementing efficiency of the reference SCC. It was observed that this overall strength efficiency of blended SCC was found to be a combination of efficiency factor ‘k_a’ depending on the age and efficiency factor ‘k_p’ depending upon the percentage of SCM replacement .This evaluation makes it possible to design blended SCC for a desired strength at any given percentage of replacement.

$k=k_a+k_p$

k= overall strength efficiency factor

k_a= efficiency factor depending on age

$k_{p=}$ efficiency factor depending on percentage of replacement

So it is felt that cementing efficiency concept can be used to understand the behavior of blended SCC to reference SCC.

A number of empirical expressions are frequently used to describe or predict the strength of normal hardened cement paste. The more well-known expression of Bolomey’s relates strength and water/cement ratio. This Bolomey’s empirical expression frequently used to predict the strength of concrete is theoretically well justifies when applied to hardened SCC. Strength data from experiments on normal hardened cement paste are frequently reported in the literature to be well fitted by Bolomey’s empirical expression. The concept of efficiency can be used for comparing the relative performance of SCMs when incorporated into SCC. Efficiency factors found from Bolomey’s strength equation are used to describe the effect of the SCMs combination replacement in SCC in the enhancement of strength and durability characteristics. This factor will give only an indication of the added materials’ effect on concrete strength, since it does no distinguish between filler effect and chemical reactions. The well-known Bolomey's equation often used to relate strength and water/cement ratio is:

$$S = A [(C/W)] + B \quad (1)$$

S is the compressive strength in MPa,

C is the cement content in kg /m^3,

W is the water content in kg/m^3

A and B are Bolomey's coefficients /or constants

Equation (1) has been shown to practically reduce to following two equations

$$S = A [(C/W) – 0.5]...... \quad (2)$$

$$S = A [(C/W) + 0.5]...... \quad (3)$$

From these above two normalized equations which represent two ranges of concrete strengths based on the change in slope when P/W (powder-water ratio) is plotted against strength. However, it is found that the equation (2) is useful for most of the present day concretes when an analysis was done on test results available and also the extensive data published by Larrard also mentions this equation in his famous book, on 'Concrete Mix Proportioning – A scientific approach'. Therefore, equation (2) can be generally used for re-proportioning MK+MS+FA SCC. The value of constant 'A' can be found out for the given concrete ingredients, by considering a concrete mix of any w/c ratio.

For structural concrete, Equation (1) can be simplified as

$$S = A [(C/W) – 0.5] \quad (4)$$

A strength efficiency factor, k, can then be computed using modified Bolomey's equation

$$S = A [(C+ kP)/W) – 0.5] \quad (5)$$

Where S is the compressive strength in MPa,

C is the OPC content in kg / m^3,

P is the amount of SCMs replaced bwc.

W is the water content in kg/m^3 and k denotes efficiency factor of SCMs combination

By knowing the amounts of 'C', 'P', 'W' and the strength 'S' achieved for each SCMs dosage replacement , efficiency factor "k" has been computed for each of the replacement dosages. Thus, W/(C+ kP) is the water/effective powder ratio and kP is the equivalent cement content of SCMs combination. 'SCMs /OPC ratio' is an important factor for determining the efficiency of SCMs in SCC. So SCMs proportioning is arrived at based on the strength data experiments on SCMs blended SCC Mixes. Efficiency factors found from this strength equation are used to describe the effect of the SCMs replacement. This factor describes the mineral admixture's ability to act as cementing material recognizing that mineral admixture's contribution to concrete strength which comes mainly from its ability to react with free calcium hydroxide produced during cement hydration (Pozzolanic Reaction (PR)).

6. EVALUATION OF CEMENTING EFFICIENCY FACTORS

The present work is an effort to quantify the cementitious efficiency of optimum proportions of Fly Ash (FA), Microsilica (MS) and Metakaolin (MK) combination in binary, ternary and quaternary blended Self-Compacting Concrete (SCC) systems of ordinary grade (M20) , standard grade (M40) and high strength grade (M80 and M100) in terms of efficiency factor 'k'. Table 3 shows bolomey's coefficients (A) for various grades of SCC mixes calculated using bolomey's equation. Then Efficiency factors for optimally blended binary, ternary and quaternary SCC mixes of ordinary grade (M20), standard grade (M40) and high strength grade (M80 and M100) were then determined using same bolomey's equation. Bolomey's coefficients are calculated from the reference mixes.

Table 3 Bolomey's Coefficients (A) for various grades of SCC mixes

Grade of SCC Mix	Bolomey's Coefficients (A)					
	3 days	7 days	14 days	28 days	60 days	90 days
M20	5.93	9.63	11.86	14.82	14.91	16.29
M40	8.59	14.06	16.76	20.33	21.17	22.40
M80	9.60	15.59	21.32	23.99	24.71	25.24
M100	10.41	16.27	22.77	26.21	26.65	26.97

Table 4 Efficiency factors for various grades of blended SCC mixes at different ages of curing

Grade of SCC Mix	Mix No	Mix Designation (Values indicate percentage by weight of Total Powder)	Efficiency Factors					
			3 days	7 days	14 days	28 days	60 days	90 days
M20	C1	C100	-	-	-	-	-	-
	B2	C50+FA50	0.34	0.55	0.79	0.70	1.22	1.25
	B7	C80+MS20	1.59	1.59	2.15	1.59	1.64	1.68
	B13	C75+MK25	3.61	1.72	2.16	1.69	1.70	1.73
	T3	C35+FA50+MS15	0.88	0.99	1.00	0.86	1.19	1.22
	T15	C25+FA60+MK15	1.57	1.22	1.15	1.08	1.32	1.34
M40	C1	C100	-	-	-	-	-	-
	B1	C60+FA40	0.23	0.28	0.42	0.79	1.14	1.17
	B5	C85+MS15	2.47	0.76	1.32	1.44	1.45	1.51
	B10	C80+MK20	5.23	2.42	2.23	1.48	1.49	1.51
	T5	C50+FA40+MS10	0.99	0.64	0.80	0.88	1.06	1.21
	T9	C35+FA50+MK15	1.94	1.29	1.27	1.05	1.08	1.19
M80	B2	C95+MS5	1.00	1.00	1.00	1.00	1.00	1.00
	T3	C65+FA20+MS15	0.34	0.68	0.59	0.85	0.98	1.04
	Q11	C50+FA28+MS11+MK11	1.74	1.21	1.06	0.94	1.00	1.08
M100	B2	C90+MS10	1.00	1.00	1.00	1.00	1.00	1.00
	T2	C71+FA19+MS10	0.88	0.98	1.00	0.69	0.99	1.08
	Q11	C55+FA23+MS11+MK11	2.12	1.37	0.76	0.76	1.05	1.12

7. DISCUSSIONS

Table 4 presents efficiency factors for various grades of optimally blended binary, ternary and quaternary SCC mixes of ordinary grade (M20), standard grade (M40) and high strength grade (M80 and M100) at different ages of curing. The efficiency factor (or k-factor) is defined as the part of the SCM in a pozzolanic concrete which can be considered as equivalent to Portland cement, having the same properties as the concrete without SCM (k= 1 for Portland cement) which means that 1 kg of cement can be replaced with k-factor of SCM or SCMs combination (optimal). Compressive strengths are achieved early in metakaolin based binary and ternary blended SCC of all grades than in microsilica based binary and ternary blended SCC. Due to synergy effect, the interaction of two or more admixtures is so that their combined effect is greater than the sum of their individual effects. In the other words, for reflecting synergic effect, the efficiency factor of Metakaolin, microsilica and fly ash combination should be higher in ternary blended SCC than in binary blended SCC system. For calculating the efficiency of Metakaolin, microsilica and fly ash combination in binary and ternary blended SCC, an equation has been proposed by author based on the principle of Bolomey's equation for predicting the strength of concrete containing mineral admixtures. The efficiency factors evaluated can be used for proportioning of blended SCC. For compressive strength of metakaolin (MK based SCC mixes , k is in the range of 1.08 to 1.69, which means that in a given SCC mix, 1 kg of MK based pozzolanic material may replace 1.08 to 1.69 kg of cement without impairing the compressive strength. This may be valid, provided that the water content is kept constant. Bolomey's coefficients 'A' are calculated from the control mixes. Using computed 'A' value, calculate strength efficiency factors k at all ages for all percentage replacement levels of metakaolin (MK) and fly ash (FA) combination in SCC.

It is observed from efficiency factor is 1.69 for C75+MK25 and1.32 for C25+FA60+MK15 ordinary grade M20 SCC mixes. For Standard grade M40 SCC mixes, k is 1.48 for C80+MK20 and 1.08 for C35+FA50+MK15 combinations. Metakaolin (MK) and fly ash (FA) blended SCC mix is found to be more efficient because of high usage of waste by-product FA and high reduction of cement content. This study is carried out to understand the cementing efficiency of Metakaolin (MK) in binary, ternary and quaternary blended SCC mixes at 3,7, 14,28, 60 and 90 days. This evaluation makes it possible to design binary, ternary and quaternary blended SCC for a desired strength at any given percentage of replacement. The strength efficiency factor 'k' is evaluated for three cases in quaternary blended SCC mixes: (1) micro silica (MS) is singly blended in SCC, (2) micro silica (MS) is blended with fly ash (FA) in SCC and (3) Metakaolin (MK) is blended with micro silica (MS) and fly ash (FA) SCC mix.

It can be observed that efficiency factors for binary (Mix B2), ternary (Mix T3) and quaternary (Mix Q11) blended high strength (M80) SCC mixes are 1.00, 1.04 and 1.08 respectively. All the three M80 grade SCC mixes give similar strength and satisfy EFNARC specifications. The efficiency factor for quaternary (C50+FA28+MS11+MK11) blended high strength SCC mixes is 1.08 which means that 1 kg of cement can be replaced with 1.08 kg of FA+MS+MK pozzolanic mixture. Efficiency factor for quaternary blended SCC mix reveals that for similar strength, 50% of cement can be replaced with FA28%+MS11%+MK11% combination of pozzolanic mixture. Similar observations are made in blended high strength (M100) SCC mixes.

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 SCC mixes.

8. CONCLUSIONS

Based on the above discussions the following conclusions are drawn:

The contribution of metakaolin (MK) to any property of hardened concrete may be expressed in terms of efficiency factor, k. For compressive strength of metakaolin blended SCC mixes , k is in the range of 1.08 to 1.69, which means that in a given SCC mix, 1 kg of metakaolin (MK) based pozzolanic material may replace 1.08 to 1.69 kg of cement without impairing the compressive strength. This evaluation makes it possible to design metakaolin blended binary, ternary and quaternary SCC mixes for a desired strength at any given percentage of replacement.

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