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Technical Report

Concrete mix design for high strength self-compacting concrete using metakaolin

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ABSTRACT

Metakaolin is a highly reactive pozzolanic admixture and has got significant potential for the development of concrete composites such as High Strength High Performance Concrete (HSHPC) and self compacting concrete (SCC), if appropriately designed. However, for obtaining the required performance in any of these concrete composites, metakaolin should be properly proportioned so that the resulting concrete would satisfy both the strength and performance criteria requirements of the structure. The present work is an effort towards obtaining a new mix methodology for the design of high strength self compacting metakaolin concretes based on the efficiency concept. The methodology has been successfully verified through a proper experimental investigation and the self compacting metakaolin concretes were evaluated for their self compactability and strength characteristics. The results indicate that the proposed method can be capable of producing high strength SCC of about 120 MPa.

1. Introduction

Self-compacting concrete (SCC) is one of the most important developments in the area of construction industry in recent years, due to many advantages it possess both in the fresh and the hardened state [1,2]. Because of the excellent filling ability, SCC fills all the spaces in the formwork avoiding the formation of honeycombing and finally resulting in high quality concrete structures [3]. The development of SCC generally involves the use of industrial wastes such as fly ash or slag [4–8]. However, metakaolin (MK) another highly reactive pozzolanic material was successfully used as a mineral admixture in the development of self-compacting concrete (SCC) in recent times, and this was considered to be a new development in the area of concrete technology [9].

Apart from the most commonly used mineral admixtures, such as fly ash, slag and silica fume, metakaolin is not a by-product. It is mostly manufactured by thermally activating purified kaolinite clay within a specific temperature range (650–800 °C) [10]. It has been reported that metakaolin, in general, is a poorly crystallized white powder with a specific surface of 12,000 m^2/kg and an average particle size between 1.5 and 2.5 μm [11]. The particle size of metakaolin lies between fly ash and silica fume [12]. It offers better workability and requires lesser amounts of high-range water-reducing admixture to obtain a comparable slump to silica fume concrete [11,13]. Besides this MK has a number of other advantages as well; it generates less bleed water, its texture is creamier so it does not darken the concrete as silica fume does and results in concrete colour that are similar to the conventional exposed concretes [11,14]. There are very few studies reported on the development of high strength SCC using metakaolin. The effect of MK on the rheological and strength properties of SCC was studied earlier. It was observed that as the metakaolin replacement increases, the corresponding 28 day compressive strength, the rheological parameters (plastic viscosity and yield stress) and the demand for HRWR also increases [15].

In another study it was found that the compressive strength of SCC with metakaolin grew very rapidly during the initial age and remained significantly higher, whereas the water absorption coefficient and water penetration depths remained very low [16]. The durability of SCC improves significantly as the replacement levels of metakaolin increased [17]. The effect of metakaolin and silica fume on the properties of Self Compacting Light-weight Concrete was also investigated [9]. Their results demonstrate that the use of metakaolin for improving the durability and mechanical properties of concrete is relatively a new approach in the area of concrete technology. This paper proposes a new design methodology for the development of high strength SCC using metakaolin by considering the efficiency factor of metakaolin. This newly developed mix design methodology has also been validated through a proper experimental investigation.

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2. Review of earlier mix design methods

A number of mix design methods for SCC had been proposed earlier and they differ considerably from the regular conventional concrete design. Okamura [18] and Ouchi et al. [19] were the first to propose a generalized method for SCC wherein concrete is considered to be a two phase material consisting of coarse aggregate and mortar. The coarse aggregate volume is at 50% of the solid volume of the concrete, and the fine aggregate volume is fixed at 40% of the volume of the mortar. The water/total powder ratio and the superplasticizer dosage are determined from the tests of fluidity on mortar. With these proportions, trails are performed on concrete to obtain the final mix composition. This methodology has been modified later by several researchers [20]. The CBI method proposed by Petersson et al. [21], determine the aggregate proportions and the minimum paste volume required, that assures the flow of concrete through the reinforcement, without any blocking. The total fines, water and superplasticizer contents are obtained based on the tests with coaxial rheometer.

Sedran et al. [22] proposed a numerical model for determining a compact aggregate skeleton with minimum voids, considering the wall effect and viscosity of the concrete. The total powder or the fines content is fixed by taking into account the strength required and the nature of the components used. The Marsh cone test was used to obtain the optimum superplasticizer for different combinations of fines. Subsequently the water and superplastizer dosages are finally adjusted to obtain the required fresh concrete behaviour using a rheometer and the slump flow test.

The UPC method proposed a four step experimental methodology for the design of SCC [23,24]. In the first step, marsh cone test is used to determine the saturation dosage of superplasticizer, for the paste system having a water/cement ratio of 0.33–0.40. Next, the mini-slump test is used to choose the optimum filler dosage and, subsequently, the paste composition with the prescribed w/c ratio. In the third step, the minimum void content of the aggregate skeleton is determined by filling a container with dry mix of varying sand/gravel ratios in uncompacted state. With these relative aggregate proportions, concretes with various paste volumes are fabricated and the minimum paste volume that yields a self-compactable mix satisfying the strength required is chosen.

Dinakar [25] was the first to suggest a methodology for the design of self-compacting concrete with fly ash for specific strengths and for varying percentage replacements of fly ash, taking into account the efficiency factor of fly ash. From the methodology it was concluded that high volume as well as high-strength self-compacting fly-ash concretes can be produced. High volume replacements of fly ash up to 70% for 30 MPa and 30% for 90 MPa can be produced. Similarly a mix design methodology for the design of self-compacting concrete with slag was also proposed by Dinakar et al. [26] by considering the efficiency factor of slag, where replacements of the order 80% was used for 30 MPa and 40% for 90 MPa concretes. From the above discussion it is obvious that as such there is no specific mix design procedure available for designing high strength self-compacting concretes incorporating metakaolin based on the strength characteristics.

3. Efficiency factor of metakaolin

Generally concrete containing mineral admixtures are produced by simple addition, direct replacement or modified replacement. In recent times cementitious efficiency of the mineral admixture has been used in the modified replacement method for achieving specified strength grades. The efficiency factor (k-value) is defined as the portion of the pozzolanic material such as fly ash, slag, silica fume and metakaolin. that can be considered equivalent to Portland cement [27]. A value of $k = 1$ indicates that, the pozzolanic material used is equivalent to cement in terms of the compressive strength performance. A value of k less than one indicates that the performance of the pozzolanic material is inferior to cement. The quantity of the pozzolanic material is multiplied by the k value to estimate the equivalent cement content, which can be added to the Portland cement content to determine the resulting water to effective cementitious materials content ratio ($w/(c + k * m)$), required cement content, etc. However, the efficiency factor values for silica fume and metakaolin established earlier showed a much higher values than 1 for various replacement percentages. This clearly shows that these materials are superior to cement in terms of enhancing the strength of concrete and will be highly beneficial for the development of high strength concretes.

The efficiency factor (k) of metakaolin for various replacement levels was established earlier by the author by using the data available in the literature [28]. These same 'k' values were being used by the author in the present investigation to propose a new mix design methodology with metakaolin for developing high strength SCC based on the strength characteristics. Furthermore, earlier investigations have shown that metakaolin as a mineral admixture in concrete has the capability to produce concretes of more than 100 MPa and the same has been attempted here for self-compacting concrete by using a specific mix design methodology.

4. Proposed method for proportioning metakaolin in self-compacting concrete

The present investigation is an attempt to evaluate the efficiency of metakaolin in self-compacting concrete at various replacement percentages, through the efficiency concept proposed earlier for the design of high strength metakaolin concretes and suggest a methodology for incorporating metakaolin in self-compacting concrete. The procedure of the methodology is outlined in Fig. 1 and can be summarized in the following steps:

Step 1: Fix the total cementitious or powder content for SCC

For the development of SCC, the quantity of total fines (powder) is of utmost importance. Based on the experience of the author, for raw materials available in India, powder content of 550 kg/m^3 will be ideal for the development of SCC. The selected powder content should be in correspondence with the proposed 380–600 kg/m^3 range for SCC according to EFNARC guidelines [29].

Let the TCM = TP kg/m^3

Step 2: Fix the percentage of metakaolin and calculate the efficiency of metakaolin

Earlier Babu and Dinakar [28] had evaluated the efficiencies for the vibrated metakaolin concretes through the data available in the literature. It was seen that the efficiency factor (k) of metakaolin varied from 6.25 to 2.61 for the percentage replacements varying from 2.5 to 30% as shown in Fig. 2. The corresponding relationship for the efficiency factor (k_{28}) at 28 day for replacement levels varying from 2.5 to 30% proposed by Babu and Dinakar [28] are

$$k_{28} = 0.005813p^2 - 0.319017p + 7.01479 \quad (1)$$

where 'p' is the percentage replacement of metakaolin

The maximum compressive strength possible at the different percentage replacements of metakaolin, derived from the results of Wild et al. [30] was also evaluated by author and presented in Fig. 3. It can be seen from the figure that a maximum compressive strength of about 83 MPa at 28 days is possible at 20% replacement level and a maximum of 64 MPa at 5% replacement. The efficiency

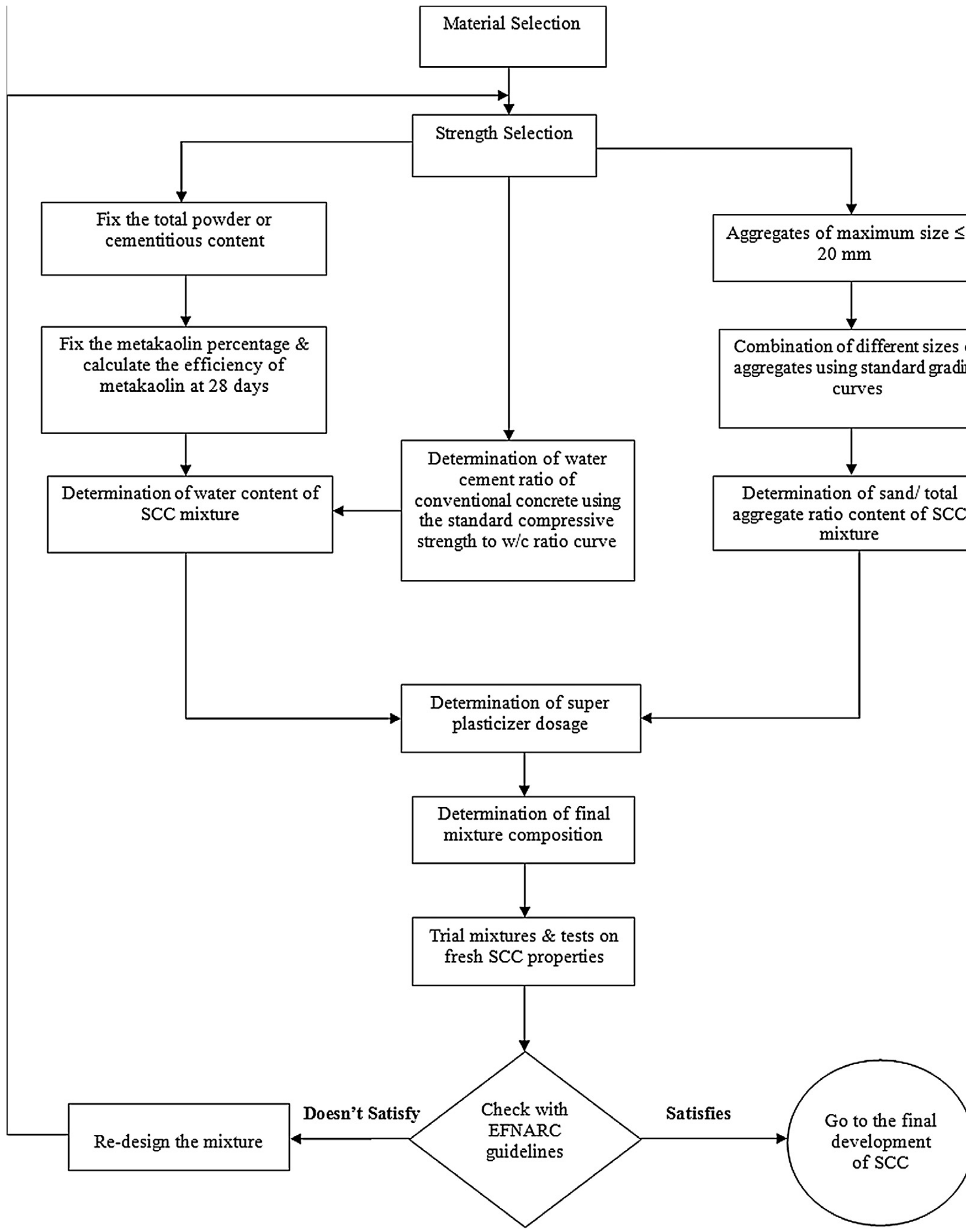

Fig. 1. Outline of the proposed mix design methodology.

curve (Fig. 2) and replacement percentages possible at particular strength (Fig. 3) were used in the present investigation to propose a mix design methodology for the design of self-compacting metakaolin concretes. In this procedure the 28 day efficiency curve shown in Fig. 2 is used for calculating the efficiency of metakaolin for any replacements varying between 2.5% and 30%. The percentage replacement of metakaolin is chosen as per the strength requirement using Fig. 3. The efficiency of metakaolin for this percentage is calculated using Eq. (1). However, with the use of present day metakaolin, the experimental results have shown that it is possible to replace even lower percentages if one can modulate the aggregate gradings and the filler proportions to minimize the water content needed.

Let the metakaolin percentage be p%.

$$\text{Cement content } (c_s) = \text{TP}(1 - p) \text{ kg/m}^3 \quad (2)$$

$$\text{Metakaolin content } (m) = \text{TP}(p) \text{ kg/m}^3 \quad (3)$$

Step 3: Calculation of water content in SCC

The water to effective cementitious materials content ratio of self-compacting concrete with metakaolin is calculated using $w_s/(c_s + k_{28} * m)$, where 'w_s' is the water content of self-compacting metakaolin concrete which needs to be determined. With respect to any of the National mix design procedures, the water cement ratio of normal or conventional concretes (w_n/c_n) is chosen based on the compressive strength required using the standard water cement ratio curves shown in Fig. 4 [31]. This water cement ratio obtained for normal concrete shall be used to determine the water content of self-compacting concrete using the following relation

$$w_n/c_n = w_s/(c_s + k_{28} * m) \quad (4)$$

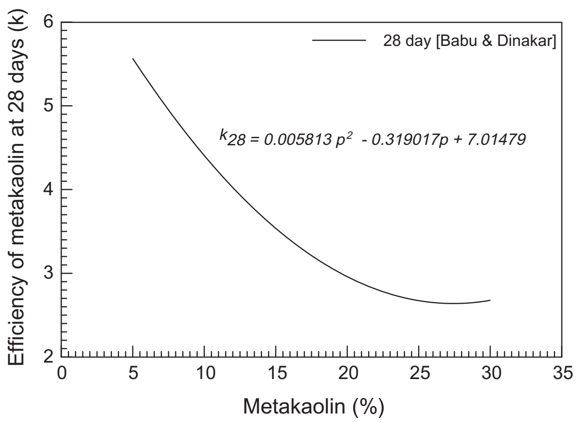

Fig. 2. Variation of efficiency factor (k) with percentage replacement of metakaolin.

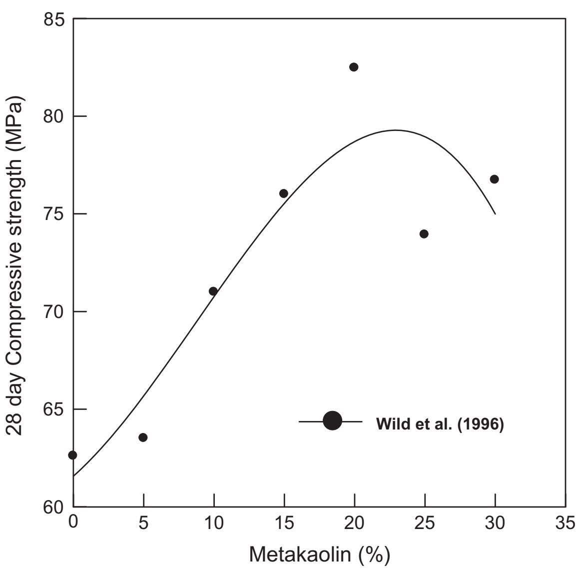

Fig. 3. Maximum possible percentage replacement Vs compressive strength [30].

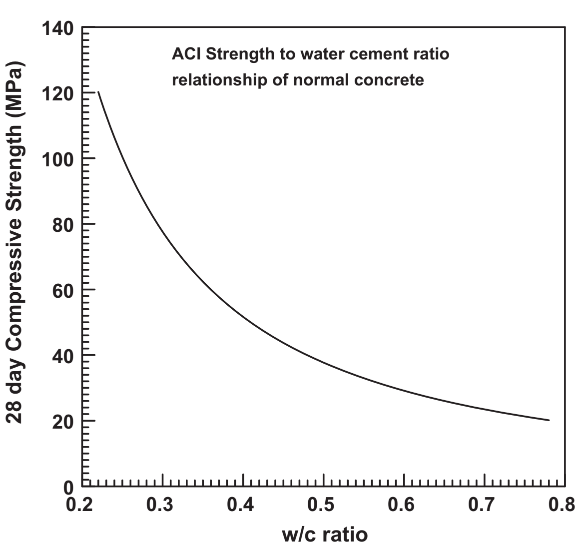

Fig. 4. Strength to water-cement ratio relationship of conventional concrete [31].

Therefore, $w_s = (w_n/c_n)\ (c_s + k_{28} * m$ kg/m^3

Step 4: Determination of coarse and fine aggregate contents

Now the total aggregate content can be determined according to the absolute volume method. For the development of high strength concrete the aggregate grading has assumed a greater significance [32]. An appropriately graded aggregate enhances the consistency resulting in a dense concrete. This increase in consistency is the prerequisite for the development of SCC. To achieve this, combined aggregate grading as recommended by the DIN 1045 [33] standards was utilized. Alternatively one can always follow the continuous grading curves, if required. Three types of coarse aggregates were used for these investigations.

Total volume = 1000 *litres*.
Assuming air content = 2%, Air = 20 *litres*.
Net concrete volume = 980 *litres*.
Let the cement, metakaolin and water content be c_s, m and w_s kg/m^3 respectively.
Volume of cement $(V_c) = c_s/G_c$ *litres*, where G_c is the specific gravity of cement.
Volume of metakaolin $(V_{metakaolin}) = m/G_m$ *litres*, where G_m is the specific gravity of metakaolin.
Volume of water $(V_w) = w_s/G_w$ *litres*, where G_w is the specific gravity of water.
Volume of paste $(V_{paste}) = (c_s/G_c + m/G_m + w_s/G_w)$ *litres*.
Volume of Total Aggregate $(V_{agg}) = (980 - V_{paste})$ *litres*.

In the combined aggregate grading for SCC let the percentage of fine aggregate in the total aggregate content be x% and that of the coarse aggregate (CA) content be y% (CA_1, mm = y_1%, CA_2, mm = y_2% and CA_3, mm = y_3%). This percentage of fine aggregate should be in correspondence with the proposed 48–55% range for fine aggregate in SCC according to EFNARC standards [29].

Step 5: Calculation of superplasticizer (SP) dosage

Since for developing self-compacting concretes polycarboxylate ether (PCE) based admixtures are generally used and based on the experience gained in our laboratory, it was found that the dosage levels should be between 0.9% and 1.5% of the total cementitious or powder content. Similarly, to attain stability or robustness to the mix viscosity modifying agents (VMAs) are also used; the dosage levels of VMAs should be between 0.1% and 0.3% of the total cementitious or powder content.

Step 6: Trial mixtures and fresh tests on SCC

Trials mixtures can be carried out using the proportions calculated as above. Fresh property tests such as slump flow, *L*-Box, *V*-Funnel tests should be carried out on SCC and they should comply with the specifications of EFNARC.

Step 7: Adjustment of mixture proportion

If the results of the fresh tests mentioned above fail to meet the performance required, adjustments should be made until all the properties of SCC satisfy the requirements according to EFNARC guidelines given in Table 1.

5. Development of high strength SCC with metakaolin – Sample design calculation

The validity of the mix methodology was carried out on three different concretes of strengths 80, 100 and 120 MPa which have

Table 1
Regulations for Self-compacting Concrete given by EFNARC (2005).

Parameters	EFNARC guidelines
Volume of paste (litres/m^3)	300–380
Powder content (kg/m^3)	380–600
Water content (kg/m^3)	150–210
Fine aggregate in total aggregate (%)	48–55
Size of coarse aggregate (mm)	⩽20
Slump flow (SF) class (mm)	
SF1	550 – 650
SF2	660–750
SF3	760–850
Viscosity class (V-Funnel time in s)	
VF1	⩽8
VF2	9–25
VS1 (T_{500})	⩽2
VS2 (T_{500})	>2
Passing Ability classes (L-Box)	
PA1	⩾0.8 with 2 rebars
PA2	⩾0.8 with 3 rebars

been designed with the mix design methodology explained above for metakaolin replacements varying between 7.5 and 22.5%. The mix details are presented in Table 2. The applied Ordinary Portland cement (similar to ASTM Type I) and the metakaolin meet the requirements mentioned in IS: 12269 (53 grade) [34] and ASTM: C618 respectively. The chemical and physical characteristics of cement and metakaolin are given in Table 3. Crushed granite with nominal size of 20 mm and good quality well-graded river sand of maximum size 4.75 mm were used as coarse and fine aggregates, respectively. The different size fractions of coarse aggregates (20 mm downgraded, 12 mm downgraded and 6 mm downgraded) were taken in order to get a dense concrete. The specific gravities of aggregates were determined experimentally. The coarse aggregates with 20, 12 and 6 mm fractions had specific gravities of 2.89, 2.87 and 2.88, whereas the fine aggregate had specific gravity of 2.65, respectively. The high range water reducer (HRWR) used in this study was a commercially available polycarboxylate ether (PCE). Commercially available viscosity modifying agent (VMA) was also used. As an example, the design procedure is explained for an SCC with design strength of 80 MPa and a cement replacement level of 7.5%.

Step 1: Fix the Total Cementitious or Powder Content for SCC
Let the TCM = 550 kg/m^3
Step 2: Determination of Efficiency of metakaolin and metakaolin content

For concrete of compressive strength 80 MPa according to Fig. 3 the percentage replacement of metakaolin should be around 20%, but in the present investigation lower percentage (7.5%) was chosen for designing 80 MPa SCC. Similarly for 100 and 120 MPa SCCs percentages such as 15 and 22.5 were chosen instead of those given in Fig. 3. With the present day high grade cements and high quality metakaolin it is possible to appreciate lower percentages of metakaolin. Refer to concrete mixtures given in Table 2.

Table 3
Characteristics of cement and metakaolin.

Chemical composition	Cement (%)	Metakaolin (%)
Silica (SiO_2)	34	54.3
Alumina (Al_2O_3)	5.5	38.3
Ferric oxide (Fe_2O_3)	4.4	4.28
Calcium oxide (CaO)	63	0.39
Magnesium oxide (MgO)	1.26	0.08
Sodium oxide (Na_2O)	0.1	0.12
Potassium oxide (K_2O)	0.48	0.50
Sulphuric anhydride (SO_3)	1.92	0.22
Loss on ignition (LOI)	1.3	0.68
Blaine (m^2/kg)	360	15,000[a]
Specific gravity	3.15	2.5

[a] B.E.T. surface area.

Cement content (c_s) = 508.75 kg/m^3.
Metakaolin content (m) = 41.25 kg/m^3.

The efficiency of metakaolin at 28 days (k_{28}) for replacement of 7.5% calculated using Eq. (2) is 4.95 (k_{28} = 4.95).

Step 3: Determination of water content of SCC

From Fig. 4 for conventional 80 MPa concrete, the water cement ratio (w_n/c_n) is 0.31. This water cement ratio is used to determine the water content of self-compacting concrete using Eq. (4)

$$0.31 = w_s/(508.75 + 4.95 \times 41.25)$$

Therefore, w_s = 221 kg/m^3

Step 4: Calculation of coarse and fine aggregate contents

For SCC the aggregates were combined in such a way, so that it meets nearly the combined grading specification of DIN 'B' curve. The actual and the standard DIN 'B', combined aggregate curves are presented in Fig. 5. For normal vibrated concretes DIN 'A' curve was utilized and the combined aggregate grading adopted was presented in Fig. 6. The percentage fractions of aggregates used are also presented in the same figures.

Total volume = 1000 *litres*.
Assuming air content = 2%.
From above cement content (c_s) = 508.75 kg/m^3.
Metakaolin content (m) = 41.25 kg/m^3.
Water (w_s) = 221 kg/m^3.
Volume of paste *(V_{paste})* = 161.50 + 16.50 + 221 = 399 *l*.
Volume of Total Aggregate *(V_{agg})* = 980−399 = 581 *l*.

Table 2
Mix details of the concretes developed.

Name	TCM (kg/m^3)	MK (%)	Cement (c) kg/m^3	(k_{28})	Total Aggregate (kg/m^3)				Water (kg/m^3)	w/(c + k_{28} * m)	SP (%)	VMA (%)
					20 mm	12 mm	6 mm	Sand				
NC80	516	0	516	0	683	490	340	348	160	0.31	0.40	0
SCC80	550	7.5	508.75	4.95	336	450	84	739	221	0.31	0.90	0.10
NC100	596	0	596	0	661	474	330	337	155	0.26	0.60	0
SCC100	550	15	467.5	3.54	348	466	87	765	197	0.26	1.25	0.05
NC120	681	0	681	0	639	458	318	325	150	0.22	0.90	0
SCC120	550	22.5	426.2	2.78	361	484	90	795	170	0.22	1.45	0.05

TCM – Total Cementitious Materials Content (Powder Content), MK – Metakolin.
k - Efficiency of metakaolin, SP – Super plasticizer, VMA – Viscosity Modifying Agent.
NC – Normal or Conventional Concrete, SCC – Self-compacting Concrete.

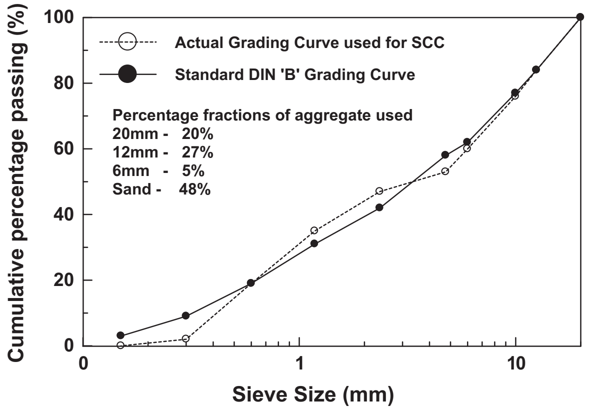

Fig. 5. Comparison between the actual and the standard combined aggregate grading used for SCC.

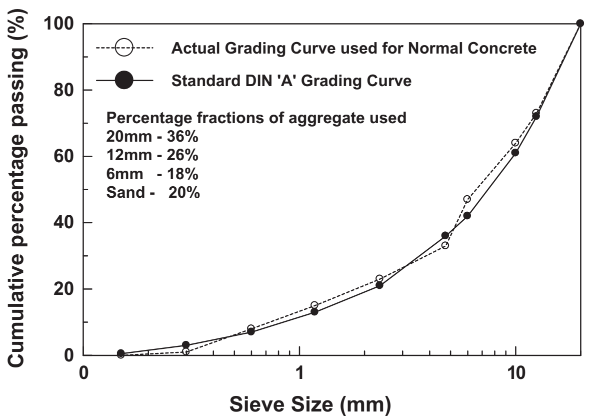

Fig. 6. Comparison between the actual and the standard combined aggregate grading used for Normal Concrete.

In the combined aggregate grading for SCC it was observed that the percentage of fine aggregate in the total aggregate content is 48% and the coarse aggregate is 52% (20 mm = 20%, 12 mm = 27% and 6 mm = 5%). This percentage of fine aggregate is in correspondence with the proposed 48–55% range for fine aggregate in SCC.

Volume of fine aggregate (V_{fa}) = 0.48 × 581 = 278.88 *l*.
Volume of coarse aggregate (V_{ca}) = 0.52 × 581 = 302.12 *l*.
Total mass of concrete = coarse aggregate + water + sand + cement + metakaolin = 335.81 + 450.22 + 83.66 + 221 + 739.03 + 508.75 + 41.25 = 2379.72 kg.

Step 5: Calculation of superplasticizer (SP) dosage

According to previous engineering experience in our laboratory, it was found that the dosage of SP is 0.9% and that of VMA used is 0.1% of the total cementitious content for meeting the SCC regulations of EFNARC SCC guidelines.

$$W_{sp} = 0.009 \times (508.75 + 41.25) = 4.95 \text{kg/m}^3$$

$$W_{vma} = 0.001 \times (508.75 + 41.25) = 0.55 \text{kg/m}^3$$

Step 6: Trial mixtures and fresh tests on SCC

Trails batches are made using the contents of materials determined as above. The methods and test results are discussed in Section 6.

6. Experimental program

A 120 kg batch has been prepared for each mixture. For determining the self-compactibility properties–slump flow, *V*-flow time and *L*-box blocking ratio tests were performed. The order of testing was: (a) Spread flow test; (b) *V*-flow test; (c) *L*-box test. The tests were performed in accordance with EFNARC (2005) standards. The compressive strength was obtained on 100 mm cube specimens. Generally demoulding was done between 12 and 24 h of casting. In general, potable water was used for curing all the concretes until testing was carried out at 3, 7, 28 and 90 days. Three specimens of each mixture were tested and the mean values were reported. All the concretes were put under moist environment immediately after initial set and before demoulding.

The fresh properties of self-compacting concrete mixtures are presented in Table 4. All the metakaolin SCCs were designed to obtain a slump flow diameter of 680 ± 25 mm, which was achieved by varying the HRWR and VMA dosages. However, the HRWR demand increased from 4.95 to 7.98 kg/m^3 as the metakaolin content and the grade of concrete increased from 7.5% to 22.5% and 80 to 120 MPa. This may be attributed to the higher specific surface area of the binder containing metakaolin and also because of its higher reactivity compared to cement alone.

6.1. Fresh SCC properties

According to the results obtained in Table 4, meakaolin content with 22.5% exhibited the highest T_{500} slump flow time. Even though slump flow diameter of all the SCC mixtures were kept constant between 680 and 650 mm, T_{500} slump flow time and *V*-funnel flow time of the SCC mixtures were influenced significantly by the metakaolin replacements. The fresh property results also indicate that there exists a direct correlation between the metakaolin content, T_{500} slump flow and *V*-funnel flow times. An increase of the metakaolin replacements levels in the SCC mixtures also augmented both T_{500} and *V*-funnel flow times correspondingly. For the case of 80 MPa with 7.5% metakaolin replacement, T_{500} slump flow and *V*-funnel flow times were found to be around 3.5 and 21 s, respectively. Whereas these values were increased to around 5.2, 6.8 and 25, 28 s for 15% and 22.5% metakaolin content, respectively. It can be seen from Table 4, the L-Box height ratio was also slightly affected for 22.5% metakaolin replacement. According to the EFNARC SCC guidelines [29], viscosity of SCC can be assessed either by using the T_{500} time during the slump flow test or by the *V*-funnel flow time. However, the obtained T_{500} and *V*-funnel flow times did not measure the viscosity of SCC directly but it is mainly related to the rate of flow. Based on the results of the fresh properties of SCCs developed, these can be classified as SF2/SF1, VS2/VF2 and PA2 according to EFNARC consistency regulations presented in Table 1. This type of SCC is suitable for tall and slender structures. Even though the SCC mixture with 22.5% metakaolin replacement did not satisfy the minimum passing ability criteria (0.80), but still it had shown the capability to consolidate under its own weight.

6.2. Compressive strength

The compressive strengths were evaluated at 3, 7, 28 and 90 days for self-compacting metakaolin as well as normal concretes. As already stated the normal concretes were designed for target strengths of 80, 100 and 120 MPa, based on the modified ACI water cement ratio to strength relation [31]. The results of the normal concretes were presented in Table 5. From the results it can be seen that strengths of more than 100 MPa at 28 days can be developed with the aid of high grade cement and super

Table 4
Fresh properties of the concretes investigated.

S. No.	Concrete grade (MPa)	Name	Slump (mm)	T_{500} (sec)	Slump flow (mm)	V – Funnel flow time (sec)	L – Box ratio For Gap of 40 mm
1	80	NC80	110	–	–	–	–
2		SCC80	–	3.5	680	21	0.87
3	100	NC100	100	–	–	–	–
4		SCC100	–	5.2	660	25	0.81
5	120	NC120	100	–	–	–	–
6		SCC120	–	6.8	650	28	0.78

Table 5
Compressive strengths of the concretes investigated.

S. no.	Concrete grade (MPa)	Name	Compressive strength (MPa)			
			3 day	7 day	28 day	90 day
1	80	NC80	54.6	75.70	88.9	97.7
2		SCC80	54.9	75.76	94.1	101.2
3	100	NC100	60.9	84.48	103.2	109.5
4		SCC100	53.3	87.07	105.8	112.2
5	120	NC120	62.0	86.05	101.5	111.6
6		SCC120	57.7	94.25	107.5	121.2

plasticizer designed at lower water cement ratios. The target strengths were easily attained in the case of the normal concretes designed for 80 and 100 MPa at 28 days and strengths even higher than target strengths were obtained. Also 120 MPa concrete had not attained the designed target strength at 28 days but at 90 days it showed strength of 111 MPa. Moreover it was also observed that significant strength gain was observed even after 28 days in lower strengths (80 MPa concrete), but in higher strength (100 and 120 MPa) the strength gain was marginal.

The self-compacting metakaolin concretes were also designed for equivalent 28 day strengths (as that of normal concretes). The results of the compressive strengths achieved by these concretes at various replacement levels are presented in Table 5. The SCCs that were designed for 80 and 100 MPa had achieved their target strengths at 28 days and exhibited higher strengths than normal concrete at 90 days, whereas SCC 120 MPa reached the designed value at 90 days. The results of 80 MPa concrete shows that, strength gain rate of self-compacting metakaolin concrete at 7.5% replacement was higher than that of normal concrete at 28 and 90 days studied. Though all the SCCs containing metakaolin attained a low 3 day strength compared to normal concrete, the strength gain was higher than that of normal concretes from 28 day onwards. In general, the strength gain of self-compacting metakaolin concretes after 28 days were higher compared with the normal concretes. The results of self-compacting metakaolin 100 MPa concrete shows that with 15% metakaolin replacement, attained strengths of 105 and 112 MPa at 28 and 90 days.

For SCC120 the strength gain rate is higher than that of normal concrete from 7 day onwards. Also the SCC120 had achieved its design strength at 90 day. As stated earlier, the normal concrete NC120 has not attained the target strength at 28 days by adopting low water cement ratio along with the use of superplasticizer. The 120 MPa SCC with 22.5% metakaolin replacement has achieved slightly higher strength than the corresponding normal concrete at 28 days but achieved strength of 121 MPa at 90 days. From the results of the above investigation it is obvious that with the available materials, particularly the cement and metakaolin; apart from the grading of aggregates, high-strength SCC mixtures with metakaolin could be developed at different replacements. Replacement of up to 22.5% for 120 MPa concrete was possible. Hence, the proposed mix design methodology can be recommended for the design of high strength self-compacting concretes using metakaolin.

7. Conclusions

In this paper a mix proportioning procedure for developing high strength SCC with metakaolin has been presented considering the efficiency factor of metakaolin. The salient conclusions of the study can be presented as follows:

(1) Using the earlier established efficiency values for metakaolin, it was found that self-compacting metakaolin concretes designed with the proposed methodology could achieve the expected strengths (80, 100 and 120 MPa) in general, at all the metakaolin percentages (7.5%, 15%, 22.5%) for a fixed power content of 550 kg/m^3.
(2) The proposed methodology is based on simple calculations that lead to five steps. In the first step the total powder content is fixed. Next based on the strength requirements the percentage of metakaolin is fixed, and the efficiency factor (k) is determined for the same percentage with the equation proposed earlier. In the third step the water content required for SCC is obtained and in the fourth step the coarse and fine aggregate contents are determined using the combined aggregate grading curves of DIN standards. Lastly the fresh self-compacting properties are evaluated through the slump flow and V-funnel tests for flowability, the L-Box test for the passing ability.
(3) As far as the mechanical properties are concerned, the compressive strength of the concretes obtained with the proposed mix methodology surpass very high strengths of 100 MPa at 28 days and 120 MPa at 90 days.

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