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Fresh and Mechanical Properties of Metakaolin-Based High-Strength SCC

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ABSTRACT

Self-compacting concrete (SCC) is treated as a special concrete in modern applications due to its passing ability, filling ability and resistance against segregation. SCC has a significant role to play in the areas of mass concreting, like pier construction, foundation,… etc. In addition, it is also preferred for light-weight concrete structures; namely, precast members. In the present paper, a sincere attempt was made to study the effect of metakaolin (MK) on high-strength SCC. For this purpose, SCC with a characteristic compressive strength of 60 MPa was used with four different percentages of MK to replace cement, ranging from 5% to 20% with an increment of 5%. Fresh properties, such as slump flow, passing ability and filling ability, as well as mechanical properties, such as compressive and tensile strengths, were studied. Compressive strength was found to be higher for SCC with 20% MK. Split tensile strength was higher for MK with 10% replacement of cement. The correlation equation and root mean square value (R^2) were obtained for the relationship between cube compressive strength and cylinder axial compressive strength to determine the best fit, respectively.

KEYWORDS: Self-compacting concrete, Metakaolin, Fresh properties, Compressive strength, Tensile strength.

INTRODUCTION

Self-compacting concrete differs from conventionally vibrated concrete (CVC) in terms of mix composition; namely, quantity of aggregates and powder content in the mix. The interfacial transition zone was more effective in SCC than in CVC. Since smaller sizes of coarse aggregates are used in SCC, bond developed between aggregates and cement paste is better. There are three forms of SCC that could be developed; namely, powder type, viscosity modifying agent (VMA) type and combination type. In the present research work, the combination type SCC was developed by varying powder content in terms of metakaolin (MK), dosages of chemical admixtures in terms of super plasticizer and VMA in terms of stabilizer. Since MK is a highly reactive pozzolanic material, it helps in improving the mechanical properties of SCC. The works done by earlier researchers using MK as mineral admixture and on SCC are discussed in the following paragraphs.

Mechanical properties, such as compressive strength, elastic modulus, creep and shrinkage of SCC, were studied with eight different mix combinations. Specimens were sealed or cured with a w/b ratio ranging from 0.24 to 0.80. Among the total number of specimens cast, 50% of the mixes were SCC and the other 50% were CVC. Creep measurement was carried out at different ages ranging from 2 to 90 days. The results indicated that elastic modulus, creep and shrinkage of SCC did not differ much from those of CVC (Bertil, 2001). The mix design of SCC was formulated with different ingredients and super plasticizers. Rheological properties and compressive strength were tested to

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assess the performance of SCC. It was understood from the results that the adopted method was simpler, less time-consuming, cost-saving and of high quality when compared to the method proposed by Japanese Ready-Mixed Concrete Association (JRMCA) (Nan Su et al., 2001). In another study, cement was replaced with low calcium F fly ash from 40% to 60% in SCC. The characteristic compressive strength varied between 26 MPa and 48 MPa. It was concluded that economical SCC mixes could be developed by incorporating high volumes of class F fly ash (Bouzoubaa and Lachemi, 2001). A new mix design method was proposed for SCC, based on cement paste and cube mortar studies with super plasticizer by trial mixes (Hajime and Masahiro, 2003). The fresh properties' test on SCC was found satisfactory with higher water/powder ratio of 1.180 to 1.215. No VMA was used. Characteristic compressive strength from 25 MPa to 33 MPa was obtained keeping cement content in the range from 350 kg/m^3 to 414 kg/m^3 (Paratibha et al., 2008). For developing SCC, combination of viscosity modifying agent with high range water reducing agent results in dynamic control of flow and increased segregation. Hence, a careful study was conducted on the rheological parameters and assessed the role of super plasticizer, particle packing and pseudo plastic VMA (Manu Santhanam and Subramanian, 2004). SCC was adopted for concreting walls and pump house structure in Tarapur Atomic Power Project (TAPP), 3rd stage and 4th stage; where a congested reinforcement took place. The mix proportions were made by limiting coarse aggregate to 23% instead of the recommended 28% of the total concrete volume and were found satisfactory (Amit et al., 2004). SCC technology was applied to nuclear power plant structures having congested reinforcement. Full scale mock up was carried out in nuclear power plant at Kaiga in Karnataka state, India. SCC mix was prepared by 50% of fly ash in total powder content and 70% of manufactured sand in total fine aggregate content. It was concluded that an economical mix could be developed with SCC by 50% of fly ash (Bapat et al., 2004). Analysis of cost comparison between SCC and CVC was carried out. It was observed that cost of SCC was 10% to 15% higher than that of CVC in terms of cost of concrete/m^3. When total cost includes labors involved and formwork includes vibration… etc, the cost difference between SCC and CVC was only marginal (Pai et al., 2014). Modification of microstructure in SCC was studied with the help of scanning electron microscopy (SEM) and it was noticed that the transition zone on SCC was free from micro-cracks when compared to CVC. The use of powder content in SCC caused a reduction in porosity and made concrete denser (Praveen and Kaushik, 2004). Ductile SCC, by replacing 20% of cement with 10% fly ash and 10% microwave incinerated rice husk ash, achieved the highest compressive strength without changing the self-compacting abilities (Muhd et al., 2014). A study to develop high-strength SCC with a characteristic compressive strength of 80 MPa was performed by using ultra fine fly ash and super plasticizer. It was found that the development of 80 MPa characteristic compressive strength was possible with ultra fine fly ash in SCC. In addition, concrete had excellent impermeability and resistance to freeze, thaw and drying shrinkage (Youjun et al., 2001). Self-compacting light-weight concrete using light-weight expanded clay aggregate was developed and its properties in fresh state and hardened state were studied. It was found that SCC with light-weight aggregate faced brittle mode of failure (Maghsoudi et al., 2014). SCC was developed by using lime stone quarry fines and fly ash as filler to understand its abrasion resistance effect. The obtained results inferred that the usage of above materials significantly improved the resistance to wear, as well as compressive, tensile and flexural strengths (Kumar et al., 2014). Rheology of SCC was studied by the influence of viscosity modifying agent with different mineral additions (limestone filler, natural pozzolana and slag). It was found that addition of dosage of viscosity modifying agent of 0.03% was sufficient to attain the fresh properties accompanied with a suitable super plasticizer dosage (Nécira et al., 2015). From the available literature, it was understood that very limited work was carried out on MK-based SCC and its effect on fresh and hardened properties. Hence, it is proposed to study the fresh and hardened properties of MK-based SCC for high-strength concrete. Correlation between compressive strengths of cube and cylinder was also developed based on linear and polynomial distribution.

EXPERIMENTAL INVESTIGATIONS

Materials

Cement used in the present work was Type I as per ASTM C150. In general, if the particle size was less than 125 µm (0.125 mm), it was termed as powder. Here, metakaolin (MK) was used as powder for replacing cement from 5% to 20%. Super plasticizer was used to obtain sufficient workability for the mixes. New generation super plasticizer [Tec mix 550] was used. The specific gravity was about 1.20. Viscosity modifying agent [Tec mix 640] was used as stabilizer to maintain cohesiveness of the mix. Chemical composition of materials used for the present work is given in Table 1.

Locally available river sand with a down size of 4.75 mm conforming to grading zone III was used as fine aggregate and crushed granite stones of 12.5 mm down size were used as coarse aggregate. The physical properties of fine and coarse aggregates were determined as per ASTM 127 and are listed in Table 2. Quantities of materials used for producing MK-based SCC are given in Table 3.

Table 1. Chemical composition of cement and GGBFS

Formula	**Concentration (%)**	
	Cement	**MK**
CaO	68.05	0.08
SiO_2	25.91	62.58
Al_2O_3	5.85	28.73
MgO	0.07	0.13
Fe_2O_3	0.12	1.10
SO_3	-	
TiO_2	-	0.55
Na_2O	-	1.89
K_2O	-	3.94

Table 2. Physical properties of materials used

Cement	Consistency: 34% Initial setting time: 38 min Specific gravity: 3.05
Fine Aggregate (FA)	Fineness modulus: 2.59 Water absorption: 1.25% Specific gravity: 2.65
Coarse Aggregate (CA)	Fineness modulus: 7.97 Water absorption: 1.1% Bulk density: 1395 kg/m^3 Specific gravity: 2.75 Max. size used: 12.5 mm
Metakaolin (MK)	Specific gravity: 2.50

Table 3. Quantity of Materials used for MK mix

No.	MK (%)	C (kg)	MK (kg)	FA (kg)	CA (kg)	w/p ratio	No. of Specimens		VMA (%)	SP (%)
							Cube	Cylinder		
1	5	9.5	0.5	13.5	11	0.40	3	6	0.10	1.4
2	10	9.0	1.0	13.5	11	0.40	3	6	0.10	1.4
3	15	8.5	1.5	13.5	11	0.40	3	6	0.10	1.4
4	20	8.0	2.0	13.5	11	0.40	3	6	0.10	1.4

Concrete Mix Proportions

Mix design was developed by proper proportioning of fine and coarse aggregates in terms of volumetric batching (i.e., kg/m^3). Initially, fine aggregate was taken as 55% of total volume and left 45% was proportioned as coarse aggregate. There was a concept in SCC mix proportion that quantity of fines will be greater than coarse aggregate. Fines include cement plus metakaolin powder and fine aggregate, since it will generate flow, passing and filling ability of SCC. This was achieved by tentatively fixing up water to powder ratio on the mix and adding dosages of super plasticizer and stabilizer on the trial mixes by conducting fresh properties' tests; namely, slump flow, T500, V-funnel, L-box and U-box. Here, three trials were carried out by adjusting fine aggregate and coarse aggregate proportions with w/p ratio and dosages of super plasticizer and stabilizer. The concrete mix design was done as per ACI 211.1-91 method for concrete with a characteristic compressive strength of 60 MPa and the mix proportion was 1:1.35:1.1 with a w/p ratio of 0.40, satisfying all fresh properties of SCC as per EFNARC guidelines.

Fresh Properties of SCC

In terms of mix composition and workability tests, SCC differs from CVC. For CVC, slump test will be carried out to assess the degree of workability; whereas in SCC, different methods will be adopted to assess the fresh properties and fix the water to binder ratio. All the tests on fresh properties of concrete were done as per the guidelines laid by EFNARC for self-compacting concrete. Slump flow test was similar to conventional slump test, but the spread diameter of the flowable concrete was measured here and it should be greater than 650 mm. V-funnel test was used to assess the viscosity and filling ability of self-compacting concrete. A V-shaped funnel was filled with fresh concrete and the time taken for the concrete to flow out of the channel was measured and recorded as V-funnel flow time. L-box test was used to assess the passing ability of self-compacting concrete to flow through tight openings including spaces between reinforcing bars and other obstructions without segregation or blocking. Three-bar test was used in the present work. Three-bar test simulates more congested reinforcement. U-Box test was also used to assess the passing ability of fresh concrete. An opening with a slide gate was fitted between the two sections. Reinforcing bars with nominal diameter of 13 mm were installed at the gate with centre to centre spacing of 50 mm. This creates a clear spacing of 35 mm between the bars. The left hand section was filled with about 0.02 m^3 of concrete and then the gate was lifted to facilitate flow of concrete upwards into the other section. The height of concrete in both sections was measured. All the fresh properties were checked with specifications laid by EFNARC guidelines. Figures 1 and 2 show the photos related to fresh properties tested for SCC.

Specimen Details

After conducting fresh test on SCC mixes, concrete was immediately poured into the cube and cylinder moulds. Cubes of size 100 mm x 100 mm x 100 mm and cylinders of size 100 mm diameter and 200 mm height were used. After 24 hours of casting, the specimens were removed from the moulds. Then, the specimens were subjected to water curing in a water tank for the designated period.

Figure (1): Slump flow and T500 test

Figure (2): V-funnel and U-box test

Tests for Hardened Concrete

The concrete specimens were taken out of the curing tank at the corresponding age of testing and made surface dry. Specimens were tested in an automatic Compression Testing Machine (CTM) of 3000 kN capacity to determine cube compressive strength and split tensile strength. But, for axial compressive strength of cylinders, test was carried out using a Universal Testing Machine (UTM) of 1000 kN capacity.

RESULTS AND DISCUSSION

Fresh Properties of MK-Based SCC

Fresh properties of metakaolin-based SCC were studied as per EFNARC guidelines. Tests, such as T500, U-box, V-funnel, slump flow and L-box tests, were carried out and compared with permissible values given in EFNARC guidelines for SCC. The values obtained from various prescribed tests for SCC in fresh state are tabulated in Table 4. The use of MK as mineral admixture improved the fresh properties of SCC. Increase in percentage of MK as substitute to cement increases the workability of SCC. The reason could be due to its fineness. Good change in fresh properties was observed for lower percentage of MK. For higher percentage of MK, the change was insignificant. It was worthy to note that for all percentages of MK substitution, the values of fresh properties fell well within the permissible values of EFNARC guidelines. Good difference was observed in slump flow and L-Box test values due to change of MK.

Table 4. Test on fresh properties of SCC using MK

No.	MK (%)	T500 (s)	U-Box test (h_2-h_1) (mm)	V-Funnel Test (s)	Slump flow test (mm)	L-Box test (h_2/h_1)
1	5	5	26	12	670	0.85
2	10	4	24	10	695	0.88
3	15	4	23	9	725	0.95
4	20	3	21	8	740	0.97
Range as per EFNARC		2 -5	0-30	8-12	650-800	0.8-1.0

Hardened Properties of MK-Based SCC

Figure 3 depicts the results of compressive strength of MK-based SCC at the ages of 7 days and 28 days to understand the effect of MK and age of concrete. It was observed from the results that increase of MK increases the compressive strength irrespective of age of concrete and percentage of MK as substitute to cement. The rate of gain in compressive strength of MK-based SCC at the age of 7 days was found to be 37, 41, 45 and 53% of characteristic compressive strength for MK substitution of 5, 10, 5 and 20%, respectively. At the age of 28 days, none of the MK-based SCC attained a characteristic compressive strength of 60 MPa. The values gained in MK-based SCC were found to be 78.5, 82.5, 87.5 and 97.5% for MK substitution of 5, 10, 15 and 20%, respectively. It was surprising to note that compressive strengths of cylinders for MK-based SCC at the ages of 7 days and 28 days were slightly higher than cube strength values. In general, for CVC, cube strength will be 1.25 times the cylinder strength or cylinder strength will be 0.8 times the cube compressive strength, due to dimensional effect. But, in case of MK-based SCC, cylinders gave better results due to the reason that SCC performed better in axial compression. Flowable nature of concrete could also be a reason for such performance.

Tensile strength of concrete was tested through split tension test and the results are depicted in Figure 4. The tensile strength trend differed from the trend of compressive strength results in MK-based SCC. Increase in MK substitution from 5% to 10% increased tensile strength and further increase of MK to 15% or 20% showed a reduction in strength. Because of more fineness of MK and better flowability of MK-based SCC, it was more brittle in nature and gained good compressive strength. This could be the reason why MK-based SCC was found to be poor in tensile strength. Tensile strength gained was also much less compared to that of CVC, in which around 10% of compressive strength will be tensile strength. In MK-based SCC, this value was in the range from 60% to 70% only. Also, for higher percentage of MK substitution, the tensile strength showed a reverse trend to good amount of fine particles. From the compressive strength point of view, MK can be substituted till 20%, since compressive strength was comparable with characteristic compressive strength, whereas 10% MK substitution was found to be optimum from tensile strength point of view.

From the experimental investigations conducted on MK-based SCC, 20% MK was found to be optimum replacement to cement and could be used for the members subjected to compression predominantly, like columns, foundations,… etc. Since 10% MK gave an optimum result in terms of tensile strength, this could be tried with tension members, like beams, slabs,… etc. Hence, it was suggested that when a characteristic compressive strength of 50 MPa was required in the field, mix design is to be done for a characteristic compressive strength of 60 MPa if 20% MK was used as mineral admixture in SCC. MK is not a waste product from any industry and plenty of clay was available for use. With the help of calcination process, good amount and good quality of metakaolin could be made available.

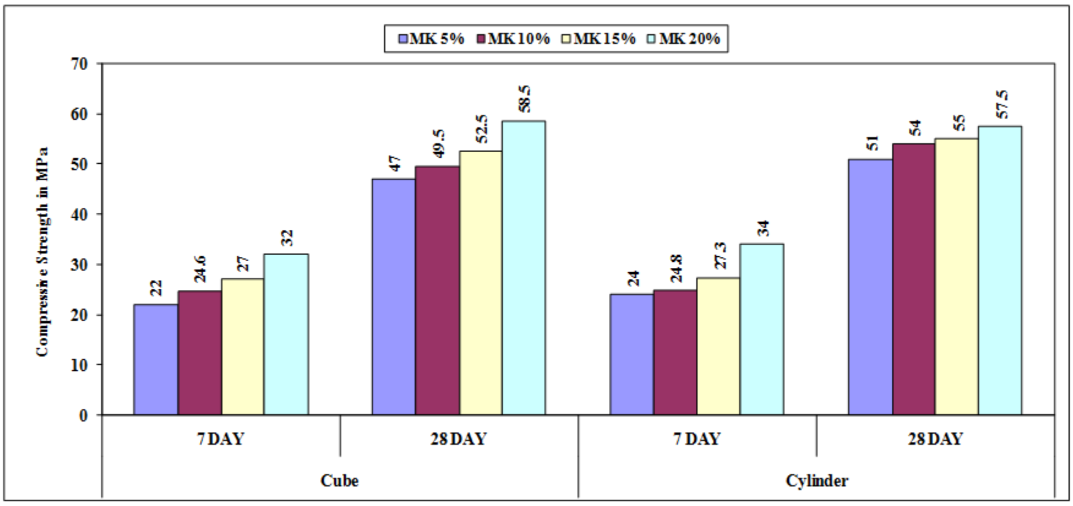

Figure (3): Effect of age of concrete on compressive strength of MK-based SCC

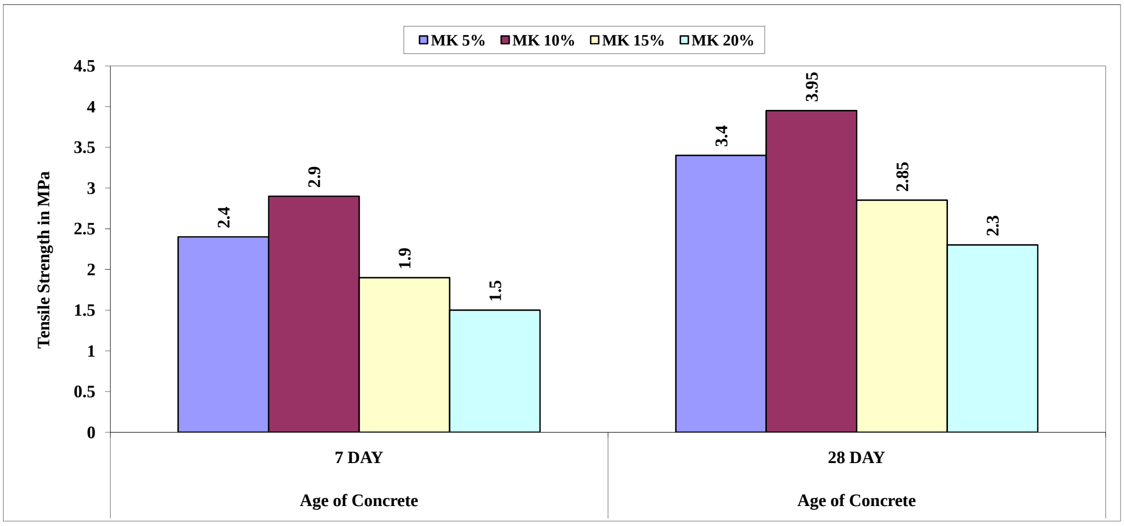

Figure (4): Effect of age of concrete on tensile strength of MK-based SCC

Correlation between Compressive Strengths of Cubes and Cylinders

For the same mix proportions and percentages of MK SCC mixes, compressive strengths of cubes and cylinders were compared. A linear equation was obtained by correlating the results of cube and cylinder compressive strength. From the equations obtained, it was understood that the coefficient of correlation (R^2) between cube and cylinder compressive strength was found to be 0.95 ($y = 3.75x + 42.5$). Since SCC was a flowable concrete, once it is poured on the formwork; namely, cube/ cylinder mould, it will have a capillary rise like a fluid flow. Thus, it would create a pressure that was similar to fluid pressure equal to density multiplied by height of pouring of formwork. Based on the concepts above, the correlation between cube compression and cylinder axial compression in terms of second order polynomial equation was developed. The final equation was $y = 0.875x^2 - 0.625x + 46.875$ and corresponding R^2 value was 0.99. Hence, the relationship between cube and cylinder compressive strength was more highly correlated by second order polynomial equation than by linear equation, since SCC has a fluidity nature from its rheology.

CONCLUSIONS

From the experimental investigations conducted on fresh and hardened properties of MK-based high-strength SCC, the following conclusions were drawn:

- W/P ratio of 0.4, the dosage of super plasticizer of 1.4% and 0.1% VMA were found to be the optimum values to produce high-strength SCC and the same was concluded from tests on fresh properties. These values fell well within EFNARC guidelines. Hence, it was possible to produce high-strength SCC with MK as substitute to cement.
- Fresh properties of SCC made with MK irrespective of its percentage as substitute to cement satisfy the guidelines framed by EFNARC in terms of slump flow, filling ability and passing ability.
- Correlation was made between cube and cylinder compression test values by linear equation and second order polynomial equation. It was found that higher values of correlation coefficient were obtained and hence, both results were matching with each other.
- Higher percentage of MK as substitute to cement (say 20%) gave better results in terms of compressive strength and the magnitude was less than the characteristic compressive strength of concrete for which it was designed.
- Maximum compressive strength of 58.5 MPa was achieved for 20% MK. Hence, it was suggested that for the field requirement of characteristic compressive strength of 50 MPa, mix design has to be made for 60 MPa if 20% MK is used in SCC.
- In a similar way, 10% MK was found to be the optimum percentage of replacement of cement in terms of tensile strength.

It was suggested that SCC with 20% MK could be used for members like foundations and columns, where compression predominates, whereas SCC with 10% MK could be used for members like slabs and beams, where tension or flexure predominates.

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