Workability and Mechanical Properties of High-Strength Self-Compacting Concrete Blended with Metakaolin

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Abstract

This study investigates the effects of metakaolin on the fresh state and compressive strength of high strength self-compacting concrete. The particle parking model (PPM) was adopted for the mix design of concrete constituents. The prime rational was to eliminate void in the self-compacting concrete (SCC). Metakaolin was used to replace cement at three incorporation ratios of 5%, 10% and 15% at varying water to cementitious ratios of 0.25, 0.30, 0.35 and 0.40. Mixes were designed to achieve both self-compatibility and high compressive strength. Several workability tests such as slump flow, L- box, V-funnel and J-ring were carried out. The compressive strength was measured at 7, 14 and 28 days of wet curing. The results showed that the mix design method was adequate to proportion SCC mixtures containing cement and metakaolin. All fresh state properties satisfied EFNARC criteria (EFNARC, 2005). The highest compressive strength of 69.6 MPa was obtained for concrete using metakaolin. For all mixtures, metakaolin increased compressive strength appreciably. A similar trend was observed in all the concrete mixes and there was progressive increase in compressive strength as metakaolin inclusion level increased.

Keywords—*Self-Compacting Concrete, Metakaolin, Compressive Strength, Particle Parking Model, Water/Cement Ratio.*

I. INTRODUCTION

Self- Compacting Concrete (SCC) refers to a highly fluid like type of concrete that flow without the need of mechanical vibration. It is non- segregating and employs its own weight in its flowing process. The major characteristic of self- compacting concrete is its ability to maintain its concrete durability, meeting performance requirements without the need for mechanical vibrations. Furthermore, economically, self-compacting concrete is viable, cheap and affordable and entails less expensive approaches to construction. Considering the economic and financial benefits of self- compacting concrete, this study investigates the effects of metakaolin on the fresh state and compressive strength of high strength self-compacting concrete using the particle parking model (PPM) for the mix design of concrete constituents. Due to the economic merits associated with the application of self-compacting concrete, copious experimental and analytical studies have been presented in a review of literature.

II. LITERATURE REVIEW

Ha Thanh, and Horst-Michael (2016) studied the effects of superplasticizer (SP) and mineral admixtures on self – compatibility and compressive strength of mortar and of Self-Compacting High-Performance Concrete (SCHPC). Experimental results of the combination of Rice Husk Ash (RHA) and Fly Ash (FA) shows that increase in superplasticizer dosage resulted in larger flowability but with lower plastic viscosity, and significantly improved self-compacting ability and compressive strength of the concrete. Compressive strength of SCHPC incorporating 20 wt% FA and 20wt% RHA reached about 130MPa after 56days. Erhan et al. (2015) in a similar research investigated the combined effects of Nano-Silica (NS) and Fly Ash (FA) on the fresh properties and rheology of the SCC’s. Employing the use of 16 SCC mixtures with FA contents of 0%, 25%, 50% and 75%, experimental results showed that the compressive strength of SCC mixtures decreased with a corresponding increase in FA content. In addition, the use of Nano Silica in SCC’s increased both slump flow and V-funnel flow times at all replacement levels of fly ash (FA).

To examine the relationship between Mechanical properties of SCC, Water/binder (W/B) ratio and powder content, two series of experimental programs were designed by Nikbin et al. (2014). One study consisted of sixteen concrete mixtures employed to examine the influence of W/B ratio on Mechanical properties of SCC at variable W/B ratios. The second study was designed to study the influence of limestone powder volume on mechanical properties of SCC. The results revealed that compressive strength decreased by 66% when the water/binder ratio was increased from 0.35 to 0.7 when limestone powder was used replacement in the ratio of 25%, 50%, 75% and 100%. Sina and Jiping (2017) investigated the Mechanical and microstructural properties of SCC mixtures blended with four Supplementary Cementitious Materials, (SCM’s), namely: metakaolin, ground granulated blast-furnace slag and fly ash at various incorporation ratios. The mechanical properties were examined against a control mixture (without SCM'S). Sina and Jiping (2017) observed that amongst other supplementary cementitious materials, metakaolin provided the most enhancing influence as replacement material for cement on mechanical micro structural properties of SCC at all curing stages. In a related research, Peiliang et al., (2017) studied the effects of metakaolin on hydration, microstructure and volume stability of steam cured High Strength Concrete (HSC) prepared at low water binder ratio of 0.25. From their study, Peiliang et al., (2017) opined that Metakaolin decreases the volume of expansion of steam cured HSC caused by heat treatment, as well as the drying shrinkage attribute of Steam cured HSC leading to a better volume of stability. They further attributed the increase in hydration of cement to the presence of metakaolin adding that the total porosity of Steam cured HSC decreased from 14.4% to 11.3% with the incorporation of metakaolin. Metakaolin was thus found to hinder the pore degradation caused by heat expansion during steam curing.

From the literature reviewed, it can be inferred that sufficient research has been carried out on additives to normal strength concrete and the effect on its mechanical and structural properties. However, there is limited research on the impact of additives on self-compacting concrete. This research thus examines the workability and mechanical properties of self-compacting concrete, using metakaolin as a partial replacement for cement.

III. MATERIALS AND METHODS

The following materials were used in the experimental design;

- Crushed granite (coarse aggregate) with a maximum grade size of 10mm (conforming to EN 12620).
- Fine aggregate (river sand) and conforming to EN 12620
- Metakaolin conforming to (EN 934-2) obtained from Kaolin. Metakaolin is one of the most natural abundant mineral found in Kogi, Edo state, and other Northern parts of Nigeria.
- Portland cement manufactured by Dangote cement conforming to EN197-1.
- Water conforming to EN1008 was used in this study
- Superplasticizer dosage (SP): For developing a flowable self-compacting concrete, poly carboxylate ether (PCE) based superplasticizer was used. Based on the manufacturer's prescription, the dosage level should be between 1% and 1.3% of the total cementitious or powder content of superplasticizer conforming to EN 934-2 was used in this study.

The sample preparation and tests were carried out in the structural laboratory of Rivers State University, Port Harcourt Nigeria, and a comprehensive report on this study is obtainable in Obunwo et al., (2018).

IV. MIX DESIGN PROCEDURE

For self-compacting concrete, coarse aggregate maximum size of 10 mm was selected to ensure adequate flowability. Three combinations of coarse and fine aggregate were selected with the following ratios: 60:40, 55:45 and 52:48 respectively followed by the determination of compacted bulk density and specific gravity of aggregates. The aggregates' combination that provided the least void was selected.

For the selected mixture of 52 and 48, the bulk density of the blended mixture was measured experimentally and packing density (PD) and void content (VC) were computed. The mix designs used in this research work is parking density method for self-compacting concrete. Table 1 shows a summary of the mix ratio employed in this research.

The mechanical properties examined the flowability, identified using the Slump flow test, the Viscosity, identified using the T_{50} slump flow test or V-funnel test, the Passing ability, identified using the L-Box test and the segregation, identified using the V-funnel at $T_{5minutes}$ or segregation resistance (sieve) test (EFNARC, 2005). Table 1 shows a summary of the mix ratio employed in this research for all the various concrete mixes.

TABLE I
Summary of the Mix Ratio for this Research

Mix	Percentage replacement	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Course aggregate (kg/m^3)	Metakaolin (kg/m^3)	w/b ratio	Superplasticizer (%)
Mix 1	0%	478.91	904.1	979.34	0	0.4	1.3
	5%	453.96	904.1	979.34	23.95	0.4	1.3
	10%	431.01	904.1	979.34	47.89	0.4	1.3
	15%	407.07	904.1	979.34	71.84	0.4	1.3
Mix 2	0%	524.66	893.84	968.32	0	0.35	1.3
	5%	498.43	893.84	968.32	26.23	0.35	1.3
	10%	436.63	893.84	968.32	52.47	0.35	1.3
	15%	416.37	893.84	968.32	78.7	0.35	1.3
Mix 3	0%	596.93	863.33	935.28	0	0.30	1.3
	5%	567.08	863.33	935.28	29.85	0.30	1.3
	10%	537.24	863.33	935.28	59.69	0.30	1.3
	15%	507.39	863.33	935.28	89.54	0.30	1.3
Mix 4	0%	622.87	883.67	957.31	0	0.25	1.3
	5%	591.73	883.67	957.31	31.14	0.25	1.3
	10%	560.58	883.67	957.31	62.29	0.25	1.3
	15%	529.44	883.67	957.31	93.43	0.25	1.3

V. RESULTS AND DISCUSSION

A. Fresh state

The highest rate of slump flow reduction was observed for mix 4 (i.e. Mixture with 15% metakaolin replacement). While the lowest slump flow reduction was measured for mix 1 especially for the control, an indication that Metakaolin (MK) inclusion in SCC resulted to an increase in slump flow losses.

Fig. 1 shows a plot of the slump flow (mm) against W/(B+MK) ratio. It shows the change in slump flow as the water/binder ratio is increased. It can be observed from Fig.1 that the slump flow value decreases as the metakaolin content increases. It can also be observed that the slump flow values are well within the acceptable slump flow classes range of SF1 (550 to 650) and SF2 (660 – 750mm) of the EFNARC (2005) criteria for acceptability of self-compacting concrete.

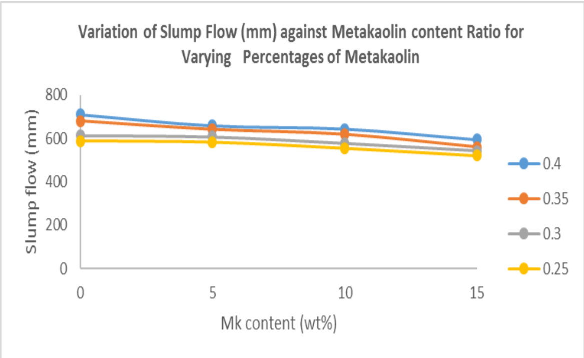

Figure 1 Slump flow T_{50cm} (sec)

The T_{50} flow times was measured in the range of 5.2 -12.5 for mix 1, the control mix exhibits the lowest flow time. Whereas, mixture with partial replacement of Portland cement by 15% MK exhibit the highest flow of test of 12.5.

Similar trend was observed for other mixtures (mix 2, 3 and 4). Therefore, it can be inferred that the incorporation of metakaolin increased T_{50} flow time of the SCC. This agrees with the previous findings of Mandandoust and Mousavi (2012) who reported the highest flow time 4.08 seconds with partial replacement of Portland cement by 20% MK. Guneyiyi et al., (2009) also reported an increase in flow time due to higher content of metakaolin. Thus, it can be confirmed that the inclusion of metakaolin enhances cohesion of mix which is principally responsible for the delayed in flow time.

B. J-Ring Flow Test

The J-ring flow test and the J-ring tests were carried out in other to determine the passing ability of the various mixes. Fig.3 shows the plot of J-ring flow (mm) against MK content ratio. It was observed that the J-ring flow reduced at lower water/binder ratios. This is an indication that J-ring is significantly influenced by W/B ratios. Figure 2 shows the relationship between the passing ability of the experimental mixes and the metakaolin content ratio.

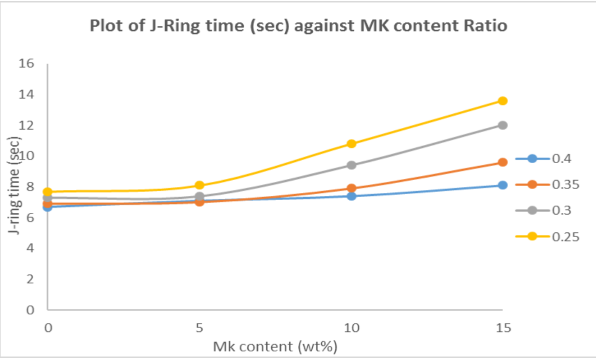

Figure 2 Plot of J-Ring time (Sec) against MK content ratio

It was further observed that there was an increase in the J-ring time as the water/binder ratio was increased and all the trial mix were in the acceptable range for self-compacting concrete.

C. V-Funnel Test

From the V-funnel for the various mixtures presented, the V-funnel time for all mixes were in the range of 6.17-16.32 seconds respectively. The results revealed that V-funnel times increased when Portland cement is progressively replaced with metakaolin at all water/binder ratios investigated. For instance, mix 1 at 15% metakaolin content, V-funnel time is 16.32 seconds, whereas for the control mix a value of 8.02 seconds was recorded. Therefore, it can be concluded that the viscosity of concrete increases when Portland cement is partially replaced with metakaolin, a trend similar in findings to Guneyisi and Gesiglu (2008). Figure 3 shows the variation of V-Funnel time (sec)

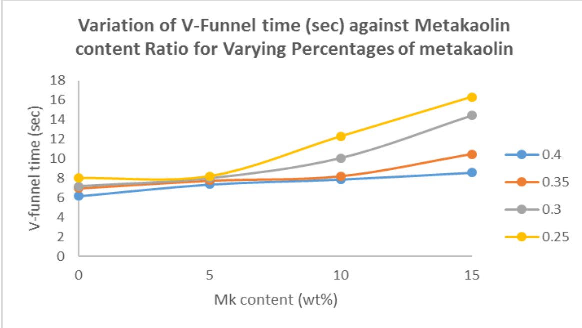

Figure 3 Variation of V- funnel time (Sec) against Metakaolin content ratio for varying percentages of MK.

against W/(B+MK) ratio for varying percentages of metakaolin. It can be observed that as the percentage of metakaolin increases the V-Funnel time (sec) of the concrete increases this is as a result of the reduction in workability of the fresh concrete.

D. Blocking ratio (L-Box Test)

The measured values for L-box test is presented in table 4.2. The result revealed that all SCC mixtures containing MK provide an acceptable blocking ratio, mixtures containing 15% MK content exhibit a tendency to blocking. This observation agrees with the recommendation of Mandandoust and Mousavi (2012) for fresh state properties of SCC. Figure 4 shows the variation of L Box (h_2/h_1) against metakaolin content ratio for varying percentages of metakaolin.

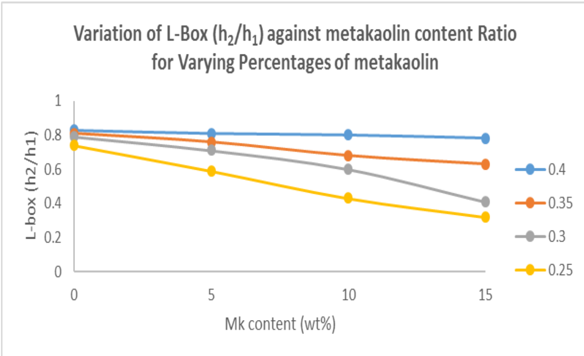

Figure 4 variation of L Box (h_2/h_1) against metakaolin content ratio for varying percentages of MK

It can be inferred that as the percentage of metakaolin increases, the L-Box (h_2/h_1) ratio of the concrete reduces. This is because of the reduction in workability of the fresh concrete.

E. Compressive strength

The mean values for the concrete mixes were computed using SPSS V20 and the compressive strengths of all SCC mixtures at 7, 14 and 28 days for all water/binder ratios were documented in Obunwo, 2018. The compressive strength for 0.40 water/binder ratio, SCC group ranged from 24 MPa to 56 MPa. For Mix 1, the 7-day early age compressive strength was

24.0 MPa for the control mixture. At 5% cement replacement level with metakaolin, 25% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 30.42% increase in compressive strength was measured. An increase of 37.5% was observed at 15% MK content.

For 0.35 water/binder ratio, the compressive strength for the SCC group ranged from 29 MPa to 64.3 MPa. The 7-day early age compressive strength was 29.0 MPa for the control mixture. At 5% cement replacement level with metakaolin, 10.35% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 19.31% increase in compressive strength was measured. An increase of 22.76% was observed at 15% MK content.

Considering the 0.30 water/binder ratio, compressive strength for the SCC group ranged from 32.3 MPa to 67.6 MPa. The 7-day early age compressive strength was 32.3 MPa for the control mixture. At 5% cement replacement level with metakaolin, 8.36% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 20.74% increase in compressive strength was measured. An increase of 26.39% was observed at 15% MK content. Furthermore, the compressive strength for 0.25 water/binder ratio for the SCC group ranged from 35 MPa to 69.6 MPa. The 7-day early age compressive strength was 35 MPa for the control mixture. Details of the variation in compressive strength are presented in Figure 5.

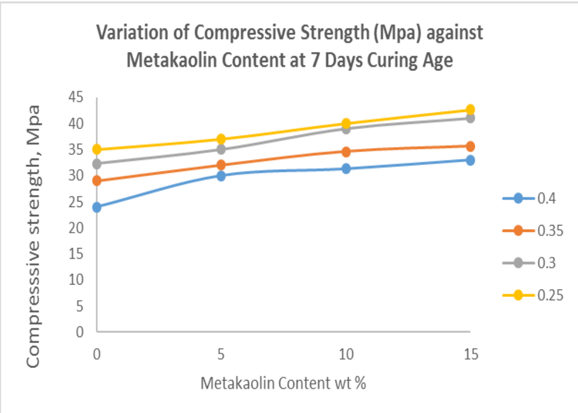

Figure 5 Variation of Compressive Strength (MPa) against MK content at 7 days curing age.

At 5% cement replacement level with metakaolin, 5.71% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 7.5% increase in compressive strength was measured. An increase of 21.71% was observed at 15% MK content and 0.4 water/cement ratio, the 28-day compressive strength was 44.3 MPa for the control specimen. At 5% cement replacement level with metakaolin, 13.52% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 9.3% increase in compressive strength was measured. An increase of 19.07% was measured at 15% metakaolin content. The compressive strengths of the control specimens were used as basis for the comparison.

At 0.35 water/binder ratio, the 28-day compressive strength was 54 MPa for the control specimen. At 5% cement replacement level with metakaolin, 13.52% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 9.3% increase in compressive strength was measured. An increase of 19.07% was measured at 15% metakaolin content. The compressive strength of the control specimens was used as a basis for the comparison.

At 0.30 water/binder ratio, the 28-day compressive strength was 58 MPa for the control specimen. At 5% cement replacement level with metakaolin, 10.35% increase in compressive strength was compressive strength was measured. An increase of 16.6% was measured at 15% metakaolin content.

At 0.25 water/binder ratio, the 28-day compressive strength was 61 MPa for the control specimen. At 5% cement replacement level with metakaolin, 10.82% increase in compressive strength was measured. At 10% cement replacement level with metakaolin content, 12.13% increase in compressive strength was measured. An increase of 14.1% was measured at 15% metakaolin content. The compressive strength of the control specimens was used as a basis for the comparison.

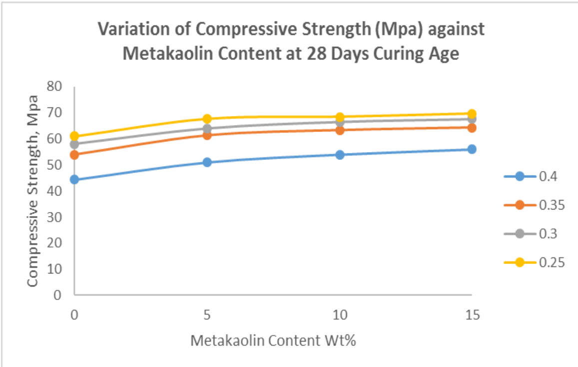

Figure 6 Variation of Compressive Strength (MPa) against MK content at 28 days curing age.

VI. FINDINGS AND CONCLUSION

The aim of this study was to examine the effects of metakaolin inclusion on the fresh state and compressive strength development of self-compacting concrete. To achieve higher strength, the Particle Parking Model (PPM) was used. Compressive strength was measured at 7, 14 and 28 days of water curing. The following salient conclusion were drawn:

- Within the range of water/binder ratios of 0, 25, 0.30, 0.35 and 0.4, replacement level beyond 15%

is not appropriate due the tendency of blocking revealed by the L-box test.

- ❖ At all curing ages, there was progressive increase in compressive strength as the replacement levels of cement with metakaolin increases from 0 to 15 %.
- ❖ Although, similar trends were observed in the evolution of compressive strength, the highest in compressive strength compared to the control mix at early age strength of 7 days was highlighted. This is traceable to increase hydration due the presence of metakaolin.
- ❖ In all mixes, metakaolin increased strength significantly, therefore, metakaolin should be adopted in the production of High strength self-compacting concrete.

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