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Effect of Mix Design on the Fresh Properties of SCC Containing Metakaolin

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Abstract: The fresh properties of self-consolidating concrete (SCC) containing different percentages of metakaolin (MK) is studied and evaluated by varying the mixture components and mixture proportions. A total of 28 mixtures with varied percentage of MK and varied mix design were investigated for the effects on viscosity, flow ability, passing ability and segregation resistance. The coarse to fine (C/F) aggregate ratio, binder content, high range water reducer admixture (HRWRA) and air content were varied to determine the optimum fresh properties of SCC containing MK. The results indicated that increasing the percentage of MK in SCC enhanced the viscosity and reduced the flow ability while demanded a higher percentage of HRWRA. Also, increasing the percentage of MK improved the passing ability and segregation factor compared to the control mixture. By increasing the C/F ratio, the flow ability, passing ability and segregation factor were reduced while the viscosity increased up to a C/F ratio of 0.9 and then decreases with a higher C/F ratio. The results also indicated that increasing the air content decreased the viscosity and the segregation factor while improving the passing ability and flow ability of the mixture.

1 Introduction

Mineral admixtures have been used in SCC to improve the quality of both the fresh and mechanical properties such as compressive strength, slump flow, passing ability, etc (Ding and Li, 2003 and Balaguru, 2001). These same admixtures have been used as partial replacements with cement to reduce the overall cost while maintaining (with either a small or no change at all) essential fresh and mechanical properties of SCC (Uysal et al. 2011.).

In recent years a new type of supplementary cementitious material (SCM) known as MK has been used in the production of NC and with little applications with SCC. MK is a kaolin clay that is burned at temperatures ranging from 600 to 900 degrees Celsius. The process turns the kaolinite into calcinate which can then be used as a cement replacement. Unlike other SCMs (especially SF), MK is carefully produced in a controlled manner to remove impurities and obtain particular particle sizes and therefore has a much higher degree of pozzolanic reactivity (Brooks, 2001; Ding, 2002).

When using SCM as a partial replacement of cement in SCC, it is desirable to obtain successful fresh properties (and also mechanical properties) results to help the flow ability, passing ability and segregation resistance of the mixture. SCMs can be used to improve the fresh properties of SCC containing no SCMs or the integrity of the SCC mixture can be maintained with the addition of SCMs. Gesoglu et al., 2007 studied the effect of various SCM types and various combinations and amounts of SCMs on the fresh properties of SCC. They showed that ordinary plain SCC obtained a higher viscosity compared to all other mixtures using SCMs according to the slump flow time. In addition all mixtures using SCMs had an L-box H2/H1 ratio greater than the control mixture and obtained ratios that were greater than specified by EFNARC (Gesoglu et al., 2007). When using MK it has been shown to decrease the flow ability of the mixture (without using HRWR) but increases the viscosity of the mixtures (Justice et al., 2007; Salman et al., 2008). The increase in the viscosity can help the suspension of the aggregates and reduce the segregation of the mixtures and keep the mixture homogenous (Cyr et al., 2003).

In addition to using SCMs in SCC the mixture design also affects the desired fresh properties of SCC. For SCC the volume of coarse aggregate, the amount of fine materials (binder), amount of HRWR and the air content of the mixture all affect the flow ability, viscosity and passing ability of fresh SCC. A study by Marar et al. (2011), showed that increasing the total cement content (or binder content) increased the slump of the mixtures. According to a concrete manual published in 2003, using air entrainment is known to increase the workability while decreasing undesirable properties such as segregation (Properties and Mix Designations, 2003).

There is limited information about the fresh properties of SCC containing MK available in the literature. The extent of this paper is to investigate the effect MK will have on the fresh properties of SCC by varying the replacement percentage of cement with MK and then study the effect of mixture design of SCC containing the optimum percentage of MK. The slump flow, viscosity and passing ability will be studied and compared to determine any effects that MK will have on these properties. Replacement of cement with SF and SG with their respective optimal levels determined from previous research by others will be carried out to compare with the results obtained from using MK. The effect of the mixture design of SCC containing an optimum replacement percentage of MK will also be studied by varying the C/F ratio, binder content, the HRWR amount as well as the air content of SCC mixtures.

2 Experimental Program

2.1 Materials

The MK used was delivered from the Eastern United States by Advanced Cement Technologies, conforming to ASTM C-618 Class N. The chemical and physical properties of cement, MK, SG and SF are shown in Table 1.

SG, SF and type GU cement used in this investigation were similar to ASTM Type I. Natural crushed stone with a 10mm maximum size and natural sand were used for the coarse and fine aggregates respectively. Each aggregate type had a specific gravity of 2.6 and the absorption of 1%. HRWR similar to Type F (ASTM C494) was used to adjust the flow ability of the mixture. The specific gravity, volatile weight and pH of the HRWR were 1.2, 62% and 9.5 respectively.

Table 1: Chemical and Physical Properties of all SCM used

Chemical Properties (%)	Cement	MK	SG	SF
SiO_2	19.64	51-53	40.3	>85
Al_2O_3	5.48	42-44	8.4	-
Fe_2O_3	2.38	<2.2	0.5	-
FeO	-	-	-	<5
TiO_2	-	<3.0	-	-
C	-	-	-	<10
P_2O_5	-	<0.2	-	-
SO_4	-	<0.5	-	-
CaO	62.44	<0.2	38.71	<5.0
MgO	2.48	<0.1	11.06	<5.0

Na_2O	-	<0.05	-	-
C_3S	52.34	-	-	-
C_2S	16.83	-	-	-
C_3A	10.50	-	-	-
C_4AF	7.24	-	-	-
K_2O	-	<0.40	0.37	-
L.O.I	2.05	<0.50	0.65	-
Physical Properties				
Specific gravity	3.15	2.56	2.89	2.2
Grain Size	45 um	45	-	-
Blaine Fineness (m^2/kg)	410	410	-	-
Color	Grey	Pink	Grayish white	Black

2.2 Mixture Proportions and Mixture Details

2.2.1 Stage 1 – Optimization of SCC Using Metakaolin

The mixture proportions of SCC containing different percentages of MK and other SCMs are shown in Table 2.

The mixtures are designated according to the type of SCM replacement (SF, SG and MK) and percentage of cement replacement (0, 5, 10, etc.). For example a mixture with a 10% MK replacement would be designated as MK10.

Table 2 - Mixture Proportions for Varying MK percentages for SCC

Concrete Type	Cement (kg/m^3)	SCM Type	SCM (kg/m^3)	CA* (kg/m^3)	FA* (kg/m^3)	Water (L/m^3)	HRWR (L/m^3)
MK0	450	-	0	833.9	926.6	180	2.17
MK5	427.5	MK	22.5	831.9	924.4	180	2.39
MK10	405	MK	45.0	829.9	922.1	180	4.46
MK15	382.5	MK	67.5	827.9	919.9	180	5.29
MK20	360	MK	90.0	825.9	917.6	180	4.92
MK25	337.5	MK	112.5	823.8	915.4	180	5.38
SG30	315	SG	135.0	821.8	913.1	180	1.69
SF8	414	SF	36.0	830.7	923.0	180	2.92

*Coarse (CA) and Fine (FA) aggregate respectively

A total of 8 SCC mixtures were tested in this stage. Six mixtures varied the MK replacement level from 0% to 25% while the remaining two mixtures contained selected replacement levels for SF and SG. 8% and 30% cement replacement levels were chosen for SF and SG respectively. Choosing 8% SF and 30% SG was based on optimal values obtained from previous work carried out with these SCMs (Hassan et al. 2010; Hassan et al. 2008). All mixtures had the same C/F ratio of 0.9 and constant w/c of 0.4. The amount of HRWR was varied so as to obtain a slump flow diameter of 650 ± 50mm. The slump flow diameter and the J-Ring slump flow diameter were used to evaluate the deformability and flow ability of fresh SCC. The time to reach 500mm slump flow diameter and time to reach 500mm J-Ring slump diameter (T_{50} and T_{50J}) the initial v-funnel times was accurately determined for all tested SCC mixtures using video tape recording. Slump flow - J-Ring flow diameter and L-Box heights was measured for all tested mixtures to evaluate the passing ability of SCC. The initial v-funnel time and the v-funnel time after 5 minutes were used to determine the segregation factor for all SCC mixtures tested. The segregation factor is calculated using equation 1, where t_0 is the initial v-funnel time and t_5 is the v-funnel after 5 minutes.

Equation 1: $Segregation\ Factor, S_f = \frac{t_5 - t_0}{t_5}$

The air content of the fresh SCC mixtures was measured by following a procedure given in ASTM C231-97e1. It should be noted that no air entraining admixtures were used in any mixture and the entrapped air was measured in each case to ensure it did not have any effect on the concrete mixtures. The fresh properties of all tested mixtures are shown in Table 3.

Table 3: Fresh propoty results for the tested mixtures

Concrete Type	Slump Flow		V-Funnel Times		S_f*	L-Box H2/H1	J-Ring T_{50J}, s	Slump Flow - J-ring Flow	% Air
	Diameter, mm	T_{50}, s	Initial, s	After 5 minutes, s					
Control	630	2.18	16.76	42.91	1.560	0.18	2.99	85	2.00
MK5	630	3.17	25.33	56.00	1.211	0.23	3.35	65	1.20
MK10	680	3.41	28.83	49.21	0.707	0.30	3.78	48	1.45
MK15	655	3.31	29.67	45.60	0.537	0.34	4.10	35	1.55
MK20	665	4.46	31.44	42.72	0.359	0.43	4.74	32	0.95
MK25	665	5.20	33.16	71.69	1.162	0.39	5.48	42	0.70
SF8	665	3.03	13.72	34.23	1.495	0.38	3.98	48	0.80
SG30	635	3.31	14.74	32.70	1.218	0.42	2.50	48	1.75

*Segregation Factor

2.2.2 Stage 2 - Varying Mixture Design of SCC Containing Metakaolin

The mixture proportions of SCC containing MK and other SCMs with varying mixture parameters are shown in Table 4.

Table 4 - Mixture Design for Varying Mixture Proportions

Concrete Type	Binder Amount (kg/m^3)	Cement (kg/m^3)	SCM Type	SCM (kg/m^3)	C/F Ratio	CA* (kg/m^3)	FA* (kg/m^3)	Water (L/m^3)	HRWR (L/m^3)	AEA (L/m^3)
0.7C	450	450	-	-	0.7	724.9	1035.6	180	2.88	0
0.7MK	450	360	MK	90.0	0.7	717.9	1025.6	180	5.72	0
0.7SF	450	414	SF	36.0	0.7	719.7	1028.1	180	3.31	0
0.7SG	450	315	SG	135.0	0.7	720.8	1029.7	180	1.85	0
0.9C	450	450	-	-	0.9	834.0	926.6	180	2.17	0
0.9MK	450	360	MK	90.0	0.9	825.9	917.6	180	4.92	0
0.9SF	450	414	SF	36.0	0.9	831.6	924.0	180	3.08	0
0.9SG	450	315	SG	135.0	0.9	831.0	923.4	180	1.69	0
1.2C	450	450	-	-	1.2	960.3	800.3	180	2.27	0

1.2MK	450	360	MK	90.0	1.2	951.0	792.5	180	4.62	0
1.2SF	450	414	SF	36.0	1.2	953.3	794.4	180	3.02	0
1.2SG	450	315	SG	135.0	1.2	954.8	795.7	180	1.24	0
500C	500	500	-	-	0.9	789.8	877.5	200	1.97	0
500MK	500	400	MK	100	0.9	780.8	867.5	200	4.92	0
500SF	500	460	SF	40	0.9	783.0	870.0	200	2.92	0
500SG	500	350	SG	150	0.9	784.5	871.7	200	1.39	0
5%C	450	450	-	-	0.9	834.0	926.6	180	2.31	26.15
5%MK	450	360	MK	90.0	0.9	825.9	917.6	180	4.60	35.38
5%SF	450	414	SF	36.0	0.9	827.9	919.9	180	3.08	21.54
5%SG	450	315	SG	135.0	0.9	829.2	921.3	180	1.31	15.38
7%C	450	450	-	-	0.9	834.0	926.6	180	2.15	40.00
7%MK	450	360	MK	90.0	0.9	825.9	917.6	180	4.62	53.85
7%SF	450	414	SF	36.0	0.9	827.9	919.9	180	3.09	40.00
7%SG	450	315	SG	135.0	0.9	829.2	921.3	180	1.33	23.08

A total of 24 SCC mixtures were tested in this stage. From stage 1, the optimum MK replacement percentage was 20%. This was chosen based on the results for the fresh and mechanical properties tested during stage 1. The second part of this investigation was to optimize the mixture design of SCC containing the optimum percentage of MK, to study the impact that varying the C/F ratio, binder content, HRWR dosage and air content would have on the fresh properties. For this twelve mixtures varied the C/F ratio from 0.7 to 1.2 (to represent SCC designed for improved passing ability and flow ability and a more economical mixture design respectively), another 4 mixtures were mixed using a larger binder content of 500 kg/m^3 and the last eight mixtures used air contents of 5 and 7%. The mixtures using a total binder content of 500 kg/m^3 and air contents of 5 and 7% had a constant C/F ratio of 0.9 while all mixtures used a constant w/b ratio of 0.4. The amount of HRWR was varied so as to obtain a slump flow diameter of 650 ± 50mm. The air content of the fresh SCC mixtures was measured by following a procedure given in ASTM C231-97e1.

All fresh properties tests for stage 2 were carried out as per the stage 1 tests. The mixtures are designated according to the type of SCM replacement (SF, SG and MK) and the varying mixture parameter (C/F ratio, binder content and air content). For example a mixture with a 7% air content and using a MK replacement would be designated as 7%MK while a mixture using 500 binder and a SF replacement would be labeled as 500SF.

Table 5: Fresh proporty results for the tested mixtures

Concrete Type	Slump Flow		V-Funnel Times		S_f*	L-Box H2/H1	J-Ring T_{50J}, s	Slump Flow - J-ring Flow	% Air
	Diameter, mm	T_{500}, s	Initial, s	After 5 minutes, s					
0.7C	640	1.86	7.44	10.23	0.375	0.40	2.56	63	1.60
0.7MK	670	3.19	2.11	24.83	0.175	0.25	4.6	7	1.70
0.7SF	640	1.97	7.03	9.99	0.421	0.26	3.86	28	1.50
0.7SG	625	1.45	4.41	6.57	0.483	0.34	2.36	15	1.40
0.9C	630	2.18	16.76	42.91	1.560	0.18	2.99	85	2.00
0.9MK	665	4.46	31.44	42.72	0.359	0.43	4.74	32	0.95
0.9SF	665	3.03	13.72	34.23	1.495	0.38	3.98	48	0.80

0.9SG	635	3.31	14.74	32.70	1.218	0.42	2.50	48	1.75
1.2C	615	2.03	11.06	28.94	1.617	0.30	3.17	55	1.80
1.2MK	635	3.66	33.13	60.26	0.819	0.12	-	195	1.30
1.2SF	615	2.29	11.63	22.89	0.968	0.16	4.0	40	1.60
1.2SG	655	1.9	10.30	20.08	0.950	0.36	1.96	8	2.00
500C	615	1.32	5.61	5.65	0.00713	0.53	2.17	48	1.40
500MK	675	2.13	6.85	8.59	0.254	0.77	3.81	3	1.20
500SF	680	1.36	6.58	7.73	0.175	0.73	2.0	35	2.00
500SG	615	0.93	4.80	4.91	0.0229	0.68	1.67	5	0.85
5%C	643	2.21	14.92	18.67	0.251	0.42	2.64	56	4.90
5%MK	653	3.10	12.16	14.22	0.169	0.84	4.64	3	4.90
5%SF	668	1.47	7.21	12.82	0.778	0.50	2.64	29	4.50
5%SG	675	0.97	6.60	6.63	0.00454	0.80	3.01	48	4.70
7%C	643	1.62	4.83	4.93	0.0207	0.76	2.54	38	6.70
7%MK	648	2.83	9.48	16.32	0.200	0.67	4.55	24	6.00
7%SF	668	1.39	6.09	6.86	0.126	0.74	2.5	31	7.50
7%SG	630	1.22	5.14	5.51	0.072	0.76	2.1	35	7.40

*Segregation Factor

3 Discussion of Test Results

3.1 Effect of Metakaolin

3.1.1 Viscosity and Flow Ability

The T_{50} of the slump flow test was used to evaluate the mixture viscosity; by comparing the time it takes the mixture to flow a diameter of 500mm. An increase in the T_{50} time indicates a decrease in flow time to reach a 500mm diameter and represents a increase in the viscosity. Table 3 shows that increasing the MK level from 0 to 25% increases the T_{50} time from 2.34 to 5.20 seconds, respectively. As well the initial v-funnel times increased from 16.76 to 33.16 seconds as the MK percentage increases from 0 to 25%. This result is what is expected from the replacement of cement with MK which shows that by increasing the percentage of MK the viscosity of the SCC mixtures also increase (Cyr et al. 2003; Hassan et al. 2010). The high v-funnel times for the MK mixtures do not satisfy the requirements for appropriate SCC mixtures. The results also indicate that, 5% to 10% MK showed comparable results to that of the other SCMs tested. From Table 3 SG and SF have T_{50} times of 3.31 and 3.03 respectively while the 5 and 10% levels of MK have times of 3.17 and 3.41 seconds respectively. The flow ability of the mixtures was determined using the T_{50J} times. These results are also shown in Table3 and it can be seen that as the MK level was increased from 0 to 25% the T_{50J} time rose from 2.99 to 5.48 seconds, respectively. This indicates a decrease in the flow ability and is excepted as the percentage of MK is increased in SCC (Cyr et al. 2003; Hassan et al. 2010).

3.1.2 Passing Ability and Segregation

In Table 3, it is observed that as the percentage of MK increased from 0 to 20% the difference between the slump flow and J Ring decreased, which indicates improved passing ability. As well, the L-Box H2/H1 ratio increased with increasing percentage of MK up to 20%, showing an improvement in the passing ability. In general, all SCC mixtures showed an improvement in the passing ability compared to the control mixture. Further increasing the MK percentage from 20 to 25% results in an increase in the difference between the slump flow and J-Ring diameter and results in a reduction in the L-Box H2/H1 ratio but still shows an improved passing ability compared to SCC containing no SCMs. These results are similar to what other researchers have found that adding SCM to SCC increases the passing ability of the mixture (Khayat et al., 2002). The results in Table 3 also indicate that SF and SG showed similar results to that of 10% MK replacement.

The segregation factor results can be seen in Table 3. From this table it can be seen that the segregation factor decreases with increasing MK percentage from 0 to 20%. Further increasing the MK replacement percentage from 20 to 25% results in an increase in the segregation factor, however all MK replacement percentages exhibit a segregation factor lower compared to SCC using no SCMs. The results in Table 3 also show that SF had a higher segregation factor compared to all MK replacement percentages while SG showed a similar segregation factor to that of MK5.

Increasing the segregation factor, slump flow – J-Ring diameter and the reduction of the H2/H1 with increasing the MK replacement from 20 to 25% could be attributed to the high thickening of the mixture containing 25% MK as a partial replacement which resulted from the high dosage of MK or the excessive amount of HRWR added. A thickening of the paste obstructs the whole paste from being able to flow through the bars of the J-Ring and L-Box.

3.1.3 HRWR Demand

The HRWR demand results are presented in Table 2. The HRWR demand was seen to increase as the percentage of MK partial replacement was increased from 0 to 25%. As the partial percentage of MK was increased to 25%, the HRWR demand increased by 148% compared to the control mixture. This increase in HRWR was also observed by Hassan et al who showed a 30% increase in the HRWR demand when using 25% MK (Hassan et al., 2012). Using a partial replacement of 8% SF showed a higher HRWR demand similar to using a 5% partial MK replacement, while using a partial replacement level higher than 5% MK resulted in a HRWR demand compared 8% SF replacement. 8% partial SF replacement required 35% more HRWR to produce a similar slump flow to that of the control mixture. 30% partial SG replacement had the lowest HRWR demand compared to any other mixtures and required 22% less HRWR compared to the control mixture.

3.2 Effect of C/F Ratio

3.2.1 Viscosity and Flow Ability

The results for the T_{50} and the initial v-funnel times used to judge the viscosity while the T_{50J} time was used to measure the flow ability of SCC are shown in Table 5. From this table it can be seen SCC using 20% MK shows a reduction in the flow ability as the C/F ratio is increased from 0.7 to 1.2 as indicated by the increase in the T_{50J} time. The viscosity, indicated by T_{50} and initial v-funnel times, of this mixture increases as the ratio is increased from 0.7 to 0.9 and further increasing the C/F ratio to 1.2 reduces the viscosity of the mixture. SCC using SF or SG replacements showed a similar trend as that of MK. As the C/F ratio increased from 0.7 to 0.9 the viscosity of SCC containing SF or SG increased and then the viscosity decreased as the ratio is further increased to 1.2. The flow ability for SF replacement also decreased as the C/F ratio was varied from 0.7 to 1.2 as indicated by the T_{50J} times while using a SG replacement results in no difference in the flow ability with an increasing C/F ratio. SCC containing no SCMs showed a similar trend to mixtures using MK and SF replacements with an increasing C/F ratio.

Although the T_{50}, T_{50J} and v-funnel tests can all indicate to the mixture viscosity, the v-funnel and T_{50} tests did not show the same trend as the T_{50J} results. The v-funnel and T_{50} times for all mixtures (except those containing MK) increased as the c/f ratio was increase to 0.9 and then decreases as the c/f ratio was further increased to 1.2. Contrary to this, the T_{50J} times continuously increased as the c/f ratio was increased from 0.7 to 1.2. The reason for this could be related to the collision of the coarse aggregate at the J-Ring bars during the flow compared to the v-funnel and slump flow tests which have more free flow of the SCC mixture. As the c/f ratio is increased in the mixture, there is more coarse aggregate that can collide with the J-Ring bars and delay the flow time. This was unclear in the mixtures using MK as partial replacements because of the high viscosity of the paste, compared to the other tested mixtures. The high viscosity of the MK paste may have helped to improve the suspension of the coarse aggregate during the flow.

3.2.2 Passing Ability and Segregation

The results for the fresh properties for varying the C/F ratio can be seen in Table 5. From this table it can be seen that increasing the C/F ratio affects the passing ability and segregation factor depending on the type of SCM used. SCC using MK replacement shows a decreasing trend as the C/F ratio was increased from 0.7 to 1.2 as indicated by the slump flow – J-Ring diameter and L-Box H2/H1 ratio. SCC using no SCMs and SCC using SF and SG shows a reduction in the passing ability as the C/F ratio was increased from 0.7 to 0.9. Further increasing the C/F ratio from 0.9 to 1.2 shows an enhancement in the passing ability as indicated by the slump flow – J-Ring diameter. This could be due to the increase in the flow ability, indicated by the T_{50J} times and reduction in the viscosity, indicated by both the T_{50} and v-funnel times, as previously discussed.

It should be noted that the results of the L-Box test are commonly used to judge the passing ability as that of the slump flow - J-Ring results. In this investigation, the results of the J-Ring test for all mixtures, except for MK, showed a reduction in the passing ability as the C/F ratio was increased from 0.7 to 0.9 and further increasing the C/F ratio to 1.2 resulted in an enhancement in the passing ability. The L-Box results however, show a continuous reduction in the passing ability with an increasing C/F ratio. This results matches the results by Su et al. in which a filling box test was performed (similar idea to that of the L-Box) and it was observed that using a lower C/F ratio provided a better filling ability, or passing ability (Su et al., 2002). The L-Box has a large volume of concrete retained at a higher elevation behind the L-Box gate compared to the slump cone used in the J-Ring test. As well the L-Box tests has a smaller opening in which this concrete has to pass compared to the ring used for the J-Ring test. This high elevation of the concrete and reduced opening in the L-Box caused a higher discharge of concrete to pass through a relatively smaller space, which gave a better chance for the coarse aggregate to collide and accumulate behind the L-Box gate reducing the H2/H1 ratio. Therefore the L-Box test shows a continuous reduction in the passing ability as the C/F ratio is increased. This situation was not as clear in the MK mixtures. The reason for this could be related to the high viscosity of the MK paste which provided a better suspension of the coarse aggregate and allow a better flow ability.

However the segregation factor for SCC containing no SCMs and using MK replacement shows to continuously decrease as the C/F ratio is increased from 0.7 to 1.2. Using SF and SG replacements in SCC results in a segregation factor that increases as the C/F ratio was increased from 0.7 to 0.9 and then decreases as the C/F ratio is further increased to 1.2.

The v-funnel time after 5 minutes is affected by the viscosity and segregation of the mixture. A less viscous mixture result in a matrix which cannot hold the coarse aggregate in suspension and thus it settles and blocks the gate. Increasing the volume of coarse aggregate can also compound with this issue and increasing the segregation factor.

3.2.3 HRWR Demand

Looking at Table 4, it can be seen that as the C/F ratio is increased from 0.7 to 0.9 the amount of HRWR required for the control mixture to achieve the desired slump flow decreased by 27%. Further increasing the C/F ratio to 1.2 for the control mixture resulted in no additional HRWR. All other mixtures showed a decrease in the HRWR demand as the C/F ratio was increased. MK replacement required 19% less HRWR as the C/F ratio was changed from 0.7 to 1.2. As well both SF and SG replacements required 9% and 33% less HRWR respectively.

3.3 Effect of Binder Content

3.3.1 Viscosity and Flow Ability

The T_{50}, initial v-funnel and T_{50J} times are shown in Table 5. These tests were used to show the effect of binder content on the viscosity and flow ability of the SCC mixtures. From these results it can be seen that as the binder content was increased from 450 to 500 kg/m^3 there was a large improvement in the viscosity, as indicated by the T_{50} and initial v-funnel times, and flow ability of the mixtures as indicated by the T_{50J} times. All SCC mixtures regardless of the use of SCM or the type of SCM show the same decreasing for the viscosity while the flow ability greatly improves with the increase binder content.

3.3.2 Passing Ability and Segregation

Table 5 shows the results for the fresh properties for varying mixture designs. From this table it can be seen that increasing the binder content from 450 to 500 kg/m^3 improves the segregation factor and the passing ability of all mixtures. Using SCC containing MK replacement shows a reduction in the slump flow – J-Ring diameter of 90% and the L-Box ratio increased 79% when the binder content was increased to 500 kg/m^3. The segregation factor also decreased for SCC mixtures using MK replacement by 29% when a 500 kg/m^3 binder content was used. All other SCC mixtures using SF, SG and no SCMs observed a similar decreasing trend as the binder content was increased from 450 to 500 kg/m^3.

3.3.3 HRWR Demand

Table 4 shows the results for the HRWR demand for varying binder content. Table 4 shows the HRWR demand for the control, SG and SF replacement mixtures was slightly lower when the binder content was increased from 450 to 500 kg/m^3. The mixture using 20% MK replacement required no additional HRWR to achieve the desire slump flow diameter. The HRWR demand for the control mixture decreased by 9% while for both SF and SG replacements requires 5% and 18% less HRWR when using an increased binder amount.

3.4 Effect of Air Content

3.4.1 Viscosity and Flow Ability

As mentioned above the T_{50}, initial v-funnel and T_{50J} times were used to measure the viscosity and flow ability of the mixtures. The results of which can be seen in Table 5. From these results it can be seen that increasing the air content from 0 to 7% shows to decrease the viscosity (shown by the T_{50} and initial v-funnel times) of the mixture while improving the flow ability (indicated by the T_{50J} times) of the SCC mixture. SCC containing no SCMs showed a constant decreasing trend in the T_{50} time and initial v-funnel time with increasing air content to 7%. SCC containing SCMs shows a large decrease in the T_{50} and initial v-funnel times as the content was increased from 0 to 5%. Further increasing the air content from 5 to 7% resulted in a slight improvement in the viscosity and flow ability of the mixtures. These results match those found by Struble et al. (2004) where the viscosity of the mixtures increased with increasing air content.

3.4.2 Passing Ability and Segregation

From Table 5 it can be seem as the percentage of air is increased from 0 to 7% the segregation factor appears to decrease while the passing ability, indicated by the slump flow – J-Ring diameter, shows an increasing trend. Mixtures using 20% MK replacement shows an improvement in the passing ability as the air content is increased to 5%. The slump flow – J-Ring diameter decreased by 91% as the air content was increased to 5%. The L-Box ratio also increased by 95% to 0.84 as the air content rose to 5%. Increasing the air content further to 7% yielded no additional benefits for the passing ability as indicated by the slump flow – J-Ring diameter flow. The L-Box ratio for the control mixture and SCC containing SF increased with further rise in the air content to 7%. However SCC containing MK and SG resulted in no additional benefit with increasing the air content from 5 to 7%. The segregation factor was observed to follow the same trend as it decreased from 0 to 5% air contents and results in no further reduction as the air content was increased to 7%.

3.4.3 HRWR Demand

No significant difference in the HRWR demand was noticed for any mixture when the air content was increased from 0 to 7%. From Table 4 it can be seen the demand decreased by 6% (from 4.92 to 4.62 L/m^3) with increasing the air content from 0 to 7% respectively for the mixture using 20% MK replacement. The control mixture and SCC containing SF and SG shows little to no difference in the amount of HRWR required as the air content was increased from 0 to 7%. For mixtures using SF replacement, the HRWR demand decreased from (3.12 to 3.08 L/m^3), around a 1% increase when the air content was increased from 0 to 7% respectively while mixtures using SG replacement decreased by 3.6% from (1.38 to 1.33 L/m^3) as the air percentage was increased from 0 to 7% respectively.

4 Conclusions

The effect of MK replacement on the fresh properties of SCC were studied and compared to SCC containing no MK and to SCC with optimum SF and SG percentages. In addition, the C/F ratio, the binder content, HRWR dosage and the air content were all varied to study the effect of the mixture design on the fresh properties of SCC using the optimum replacement percentage of MK. The fresh properties were investigated using the slump flow, T_{500}, V-funnel, L-Box and J-Ring tests. The following conclusions can be made from the results discussed in the paper and are as followed:

- Increasing the percentage of MK in SCC has a direct impact on the fresh properties of the mixtures. The addition of MK shows to increase the viscosity of the mixtures while the flow ability of the mixtures decreased. The passing ability and segregation factor both increased with the addition of MK compared to SCC containing no MK.
- As the C/F ratio was increased from 0.7 to 1.2 in SCC mixtures containing MK, the passing ability decreased and the segregation factor increase. SCC mixtures made with no SCMs showed a decrease in the passing ability as the C/F ratio was increased from 0.7 to 0.9 while further increasing the C/F ratio increased the passing ability. The segregation factor for SCC mixtures made with no SCMs increased with an increasing C/F ratio from 0.7 to 1.2.
- Using a larger binder content of 500 kg/m^3 (compared to 450 kg/m^3) decreases the viscosity and increases the flow ability of all SCC mixtures. Larger binder content also increases the passing ability and improves the segregation factor regardless of the SCC mixture.
- All SCC mixtures investigated shows a decrease in the viscosity and increases in the flow ability as the air content rose from 0 to 7%. The passing ability for all SCC mixtures as the air content was increased from 0 to 7% increased while there was a reduction in the segregation factor.
- The HRWR demand for SCC containing MK increased with increasing MK replacement percentage from 0 to 25%.
- As the C/F ratio was increased from 0.7 to 1.2 the HRWR demand to produce the desired slump flow of 650 ± 50mm decreased for all SCC mixtures.
- Increasing the binder content of SCC mixtures shows to decrease the HRWR demand for SCC containing no SCMs and SCC containing SF and SG. SCC mixtures using MK showed no additional HRWR demand when the binder content was increased.
- There was no noticeable difference in the HRWR demand for SCC mixtures using SCMs or containing no SCMs as the air content was increased from 0 to 7%.

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