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Mechanical Properties of SCC containing Metakoalin

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Abstract: The mechanical properties of self-consolidating concrete (SCC) containing various percentages of metakaolin (MK) are investigated in this study. The coarse/fine (C/F) aggregate ratio, coarse aggregate size, was varied to study the impact these parameters have on the mechanical properties of SCC mixtures. Twelve SCC mixtures with varying partial replacement of MK and various C/F aggregate ratio and size were investigated for the effects on compressive strength, modulus of elasticity (ME), splitting tensile strength (STS) and flexural strength (FS). From these results and the fresh property results the optimum SCC mixture was chosen and recommended. The results obtained in this investigation showed an increase of the compressive strength with the increase of the percentage of MK up to 20%. Increasing the percentage of MK also showed increases in the FS, ME and STS of the mixture. The results also indicated that increasing the coarse aggregate content/size tends to reduce all the mechanical properties of the tested mixtures.

1 Introduction

Mineral admixtures have been used successfully in SCC to improve the quality of both the fresh and mechanical properties of the mixture (Ding et al., 2003; 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 (MK) has been used in the production of normal concrete (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 such as 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).

It is also important when using SCM as a partial replacement of cement in SCC to obtain desirable results for the mechanical properties. SCMs can be used to improve the mechanical properties of SCC containing or they can be used to maintain the integrity of the SCC mixture with the addition of SCMs. Halit (2007) showed that by replacing cement with SF, it increased the STS when compared to the control mixture while using a SF replacement up to a 50% did not have any major impact on the ME. Halit (2007) also showed that the replacement with fly ash (FA) decreased the STS slightly and that high level replacements decreased the ME greatly. As well Xianyu et al. (2003) showed that the use of MK, SG, and SF increases the mechanical properties of NC.

In addition to using SCMs to obtain desirable mechanical properties, the mixture design can also have an impact on the mechanical properties. The volume and size of the coarse aggregate plays an important role on the Interfacial Transition Zone (ITZ) which is the bond between the aggregates and the surrounding paste matrix. Using larger aggregates or increasing the volume of the aggregates, increases the surface area of the ITZ, which may cause a weakness in the hardened concrete mixture in which failure can occur (Koehler et al., 2007). The ITZ has low density cement grains and contributes to reduce the overall strength of the concrete and the porosity (Larbi, 1993). As the volume of the coarse aggregate is increased the total volume of the ITZ increased which reduces the quality of the concrete and the compressive strength. As the coarse aggregate size is increased (while holding the C/F ratio constant) the thickness of the ITZ is increased which contributes to the reduction in the strength and strength development of the concrete. The ITZ also affects the STS and FS to a much larger extent than the compressive strength (Metha et al., 1993). The ME can also be affected by the ITZ and as well the SCM content. The ITZ and SCM content affect the cracking behaviour and porosity of the concrete mixture and can decrease or increase the ME (Metha et al., 1993).

There is limited information about the mechanical properties of SCC containing MK available in the literature and limited research into the effect of the mixture design (optimization) of SCC containing MK. The extent of this paper is to investigate the effect MK will have on the mechanical properties of SCC by varying the replacement percentage of cement with MK. After obtaining the optimum MK replacement percentage various mix design parameters will be varied in order to try and improve SCC containing MK. The mechanical properties to be studied include; strength development, 28 day compressive strength, STS, FS and ME. In addition to the SCC mixtures containing MK, similar mixtures using SF and SG replacements with cement using their optimum values based on other research will be mixed and used as a comparison to the mixtures using MK. Optimizing of SCC containing MK will be done by varying the C/F ratio and the coarse aggregate size.

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 10 and 20mm 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.

Table 2: Mixture Proportions for the 8 SCC Mixtures Containing MK

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	1.69
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	823.82	915.35	180	5.38
SG30	315	SG	135.0	821.8	913.1	180	1.39
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 for comparisons. 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 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.

For all mixtures, the strength development was determined using 1-, 3-, 7- and 28- day compressive strengths. The splitting tensile strength was measured using 100mm diameter by 200mm length cylinders according to ASTM C496-96. The flexural strength of 100mm x 100mm x 400mm prisms was also measured for all SCC mixtures as per ASTM C78-00. 100mm diameter by 200mm length cylinders with an attached 25mm strain gauge was used to test the modulus of elasticity of all mixtures. The mixtures are designated according to the type of SCM replacement (SF, slag [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.

2.2.2 Varying Coarse Aggregate Volume and Size

Table 4 shows the mixture proportions of SCC for varying the C/F ratio different coarse aggregate sizes.

Table 3 - Mixture Design for Varying Mixture Properties

Concrete Type	Cement (kg/m^3)	SCM Type	SCM (kg/m^3)	C/F Ratio	Stone Size (mm)	CA* (kg/m^3)	FA* (kg/m^3)	Water (L/m^3)	HRWR (L/m^3)
0.7C	450	-	-	0.7	10	724.94	1035.63	180	2.88
0.7MK	360	MK	90.0	0.7	10	717.89	1025.56	180	5.72
0.7SF	414	SF	36.0	0.7	10	719.66	1028.08	180	3.31
0.7SG	315	SG	135.0	0.7	10	720.81	1029.73	180	1.85
0.9C	450	-	-	0.9	10	833.90	926.60	180	1.69
0.9MK	360	MK	90.0	0.9	10	825.90	917.60	180	4.92
0.9SF	414	SF	36.0	0.9	10	821.80	913.10	180	1.39
0.9SG	315	SG	135.0	0.9	10	830.70	923.0	180	2.92
1.2C	450	-	-	1.2	10	960.31	800.26	180	2.27
1.2MK	360	MK	90.0	1.2	10	950.97	792.48	180	4.62
1.2SF	414	SF	36.0	1.2	10	953.31	794.43	180	3.02
1.2SG	315	SG	135.0	1.2	10	954.84	795.70	180	1.24
20C	450	-	-	0.9	20	833.95	926.62	180	1.78
20MK	360	MK	90.0	0.9	20	825.85	917.61	180	4.62
20SF	414	SF	36.0	0.9	20	827.88	919.86	180	2.54
20SG	315	SG	135.0	0.9	20	829.21	921.34	180	1.23

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

A total of 16 SCC mixtures were tested in this stage. From stage 1 the optimum MK replacement percentage was chosen based on the results for mechanical and fresh properties and then the C/F ratio and coarse aggregate size were varied to study their effect on the mechanical properties of SCC. Observing stage 1 the optimum MK replacement was 20% and was therefore used for the mixtures in Table 3. Twelve mixtures varied the C/F ratio from 0.7 to 1.2 while the remaining 4 mixtures used a larger coarse aggregate size of 20mm. 8% and 30% cement replacement levels were chosen for SF and SG respectively. The mixtures using a 20mm coarse aggregate had a C/F ratio of 0.9. All mixtures used a constant w/b 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. 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 same tests that were carried out for the mechanical properties in stage 1 were conducted for this stage. Therefore see stage 1 for a list of tests. The mixtures are designated according to the type of SCM replacement (SF, SG [SG] and MK) and the C/F ratio (0.7, 0.9 and 1.2) or the coarse aggregate size (20mm). For example a mixture with a C/F ratio of 0.7 and using a MK replacement would be designated as 0.7MK while a mixture using a 20mm coarse aggregate and using SF replacement would be labelled as 20SF.

3 Discussion of Test Results

3.1 Effect of Metakaolin

Table 4 - Mechanical Properties for Mixtures Containing Metakaolin

Concrete Type	f'_c, MPa				FS (kN)	FS / $f'_c{}^{0.5}$	STS (kN)	STS / f'_c	ME (GPa)	ME / $f'_c{}^{0.5}$
	1 Day	3 Day	7 Day	28 Day						
MK0	7.0	16.8	23.1	31.1	3.72	0.566	3.40	0.092	39.0	4.24
MK5	8.4	21.6	31.1	41.3	3.82	0.581	3.41	0.083	41.3	4.34
MK10	9.1	23.1	34.0	42.1	3.98	0.602	3.68	0.080	42.1	4.54
MK15	7.8	22.8	39.6	47.6	4.24	0.615	3.92	0.073	47.6	4.83
MK20	10.0	25.5	38.6	50.6	4.50	0.620	4.27	0.087	50.6	4.45
MK25	8.3	23.5	38.2	43.5	4.04	0.675	4.05	0.093	43.5	4.25
SF8	9.7	23.1	34.0	44.4	4.12	0.558	3.86	0.096	42.8	4.67
SG30	5.5	15.9	27.9	37.0	3.93	0.550	3.50	0.094	37.0	4.56

3.1.1 Compressive Strength

3.1.1.1 28 Day Compressive Strength

Table 4 shows the 28 compressive strengths for all MK partial replacements percentages. From this table it can be seen that the 28 day compressive strength increased by 29.8% as the MK replacement level was increased to 20%. Further increasing the MK replacement level from 20 to 25% decreased the 28 day strength by 13.4%. Khatib et al. (1996) showed similar results in which the 28 day compressive strength increases up to a 20% MK replacement and further increasing the MK content decreases the compressive strength. All partial MK replacement percentages showed a higher 28 day compressive strength compared to the control mixture. Also, all partial MK replacement levels had a higher 28 day compressive strength compared to 30% SG replacement while only the 15%, 20% and 25% partial MK replacements had a 28 day compressive strength that was higher compared to 8% SF as a partial replacement. 10% partial MK replacement showed a similar 28 day compressive strength to 8% partial SF replacement.

3.1.1.2 Strength Development

Table 5 - Strength Development for SCC Mixtures Containing Metakaolin

Concrete Type	f'_c, MPa		
	1 Day	3 Day	7 Day
MK0	0.22	0.45	0.69
MK5	0.20	0.52	0.75
MK10	0.22	0.55	0.81
MK15	0.16	0.48	0.83
MK20	0.20	0.50	0.77
MK25	0.19	0.54	0.88

SF8	0.22	0.51	0.76
SG30	0.17	0.45	0.72

To account for the variations in the compressive strengths, the 1, 3 and 7 day compressive strengths were divided by their respective 28 day compressive strengths to normalize the results. The normalized 1, 3 and 7 day compressive strengths are shown in Table 5. All MK mixtures (except MK10) had a 1 day strength developments lower than the control mixture. The 1 day strength development increased from 5% to 10% MK replacements then decreased when the percentage was further increased to 15% and finally increased as the MK replacement percentage was further increased to 20%. Using a MK replacement of greater than 25% yielded no additional benefits towards the 1 day strength development. Compared to the other SCMs, all MK replacement percentages had a higher 1 day strength development when compared to the mixture using 30% SG as a partial cement replacement. Compared to 8% SF, only the 10% MK replacement percentage had a comparable 1 day strength development while all other MK percentages had a lower 1 day strength development.

The 3 day strength development increased up to 10% MK partial replacement and then decreased when the MK replacement level was increased to 15%. As the MK replacement level was further increased from 15% to 25 the strength development after 3 days increased. All mixtures using MK as a partial cement replacement showed a higher 3 day strength development when compared to the control mixture. All MK replacement percentages showed 3 strength developments greater than 30% SG as a partial replacement. Only the 10% and 25% MK replacement levels had a higher 3 day strength development compared to SF partial cement replacement.

The 7 day strength development increased with increasing the partial MK replacement up to 15%. Further increasing the partial replacement percentage from 15 to 20% decreased the strength development, while increasing from 20% to 25% increased the strength development. All MK partial replacement percentages had larger 7 day strength developments compared to the mixture using no cement replacement. All mixtures using MK, except for 5% partial replacement, showed a higher 7 day strength development when compared to a mixture using 8% SF as a partial cement replacement. 5% partial MK replacement showed similar 7 day strength to that of SF as a partial cement replacement. All MK mixtures showed a 7 day strength development greater than using 30% SG partial replacement.

3.1.2 Flexural Strength

The flexural strength (FS) for all mixtures was normalized to account for differences in the compressive strength. Since the FS is proportional to the square root of the compressive strength all FS values were divided by the square root of the 28 day compressive strength. This was done so that a comparison could be done between various SCM types. From Table 4 it can be seen that using a 20% or greater partial MK replacement percentage results in a normalized FS that is higher compared to using 8% SF partial cement replacement. 30% SG partial cement replacement exhibited a higher normalized FS compared to 5, 10, 15 and 20% partial MK replacement and had a similar normalized FS compared to using a 25% partial MK replacement level.

Table 4 shows the FS for all mixtures. These values were not normalized to show the effect of MK partial replacement on the FS of SCC. From this table it can be seen that the FS increases as the partial MK replacement percentage is increased from 0 to 20%. Justice et al. (2005) showed that using MK content similar to 8% SF results in an increase in the FS at a similar w/b ratio. The FS increased by 20.9% as the partial MK replacement percentage was increased to 20%. Further increasing the partial replacement level from 20 to 25% resulted in a 10% decrease in the FS.

3.1.3 Modulus of Elasticity

Table 4 shows the results for the normalized ME for the effect of MK partial cement replacement on SCC. As previously stated, the ME was normalized by diving it by its respective compressive strength. From this table it can be seen that using a 15% partial MK replacement results in a similar or higher normalized ME when compared to using 8% SF as a partial cement replacement. When using 30% partial cement replacement with SG, only 15% partial cement replacement with MK results in a higher normalized ME. All other replacement percentages resulted in a lower normalized ME when compared to using 30% SG partial replacement.

The results for the ME are shown in Table 4. These values were not normalized to show the effect of MK partial replacement on the ME of SCC. From this table it can be seen that increasing the partial MK percentage from 0 to 20% increases the ME. The ME increased by 20.8% with the addition of 20% MK as a partial cement replacement. As the MK partial replacement percentage was further increase from 20% to 25% the ME decreased by 5.3%. These results were similar to those obtained by Razak et al. (2001) showed that replacing 10% of cement with MK and SF results in an increase in the ME when compared to concrete containing no SCMs in NC.

3.1.4 Indirect Tensile Strength

The results for the normalized STS for the effect of MK partial cement replacement on SCC are shown in Table 4. From this table it can be seen that when using 8% SF and 30% SG as partial cement replacements, these mixtures results in a higher normalized STS compared to all partial MK replacement mixtures used.

Examining Table 4 which shows the results for the STS of all tested mixtures, it can be seen that increasing the partial MK percentage from 0 to 20% increases the STS. Using a 20% MK as a partial cement replacement resulted in an increase of 25.4% in the STS. Further increasing the MK replacement from 20 to 25% slightly decreases the STS by 5.2%. However, all partial cement replacements with MK results in a higher STS when compared to the control mixture

3.2 Effect of Coarse Aggregate Volume and Size

Table 6 - Mechanical Properties for Varying Mixture Proportions

Concrete Type	f'_c, MPa				FS	STS	ME
	1 Day	3 Day	7 Day	28 Day			
0.7C	6.1	13.2	20.7	28.5	4.39	3.54	28.1
0.7MK	8.8	20.3	34.1	45.5	5.25	4.8	33.2
0.7SF	8.0	18.2	29.0	38.5	4.45	4.25	31.8
0.7SG	5.0	13.5	24.3	32.8	4.23	3.93	29.7
0.9C	7.0	16.8	23.1	31.1	3.72	3.4	26.9
0.9MK	10.0	25.5	38.5	50.6	4.5	4.27	32.5
0.9SF	9.7	23.1	34.0	44.4	4.12	3.86	30.3
0.9SG	5.5	15.9	27.9	37.0	3.93	3.5	28.3
1.2C	7.4	18.1	23.8	31.6	3.59	3.19	26.1
1.2MK	11.2	28.1	42.3	55.0	4.04	4.03	31.4
1.2SF	10.1	24.4	35.8	46.8	3.99	3.52	29.2
1.2SG	6.9	18.5	31.0	41.0	3.44	3.15	27.6
20C	8.1	17.6	24.2	32.1	3.56	3.28	25.9
20MK	10.8	24.8	40.3	51.9	4.1	4.14	30.2
20SF	9.6	22.6	35.0	44.4	3.84	3.83	28.0
20SG	6.3	15.9	29.2	38.6	3.62	3.38	26.0

3.2.1 Compressive Strength

3.2.1.1 28 Day Compressive Strength

The results for the 28 day compressive strengths for varying C/F ratios are shown in Table 6. It can be seen from this table that the 28 day compressive strengths decrease as the C/F ratio is changed from 0.7 to 1.2. Examining the control mixture, there was a 6.5% decrease in the 28 day compressive strengths as the C/F ratio was increased from 0.7 to 1.2. When using 20% MK mixture, the 28 day compressive strengths decreased by 6.3% with the increase of the C/F ratio from 0.7 to 1.2. Both 8% silica fume and 30% SG as partial cement replacements showed decreases of 6.4% and 3.8% for the 28 day compressive strength respectively with the increase of the C/F ratio from 0.7 to 1.2.

Table 6 shows the results for the 28 compressive strengths when using a 20mm coarse aggregate. The 28 day compressive strength for the control mixture decreased by 5.6% as the coarse aggregate size was increased from 10mm to 20mm. Neptune et al. (2010) observed similar results in which increasing the maximum nominal aggregate size show a small reduction in the compressive strength. 20% MK mixture also had a decrease in the 28 day compressive strength of 6.7% from 50.63 to 47.22 MPa when the coarse aggregate size was increased. The 8% SF mixture had a decrease of 7.6% in the 28 day compressive strength with increasing coarse aggregate size, while the 30% SG mixture had a decrease of 8.9% when using a larger coarse aggregate size of 20mm.

As previously mentioned the mechanical properties of concrete are dependent on the ITZ. As the volume of the coarse aggregate was increased as the C/F ratio rose the surface area of the ITZ also increased and caused a reduction in the compressive strength. The same happened as the coarse aggregate size was increased while the C/F ratio was held constant. The size of the ITZ also increased and contributed to the loss in compressive strength.

3.2.1.2 Strength Development

Table 7 - Strength Development for Varying C/F ratios and Coarse Aggregate Size

Concrete Type	Strength Development		
	1 Day	3 Day	7 Day
0.7C	0.23	0.47	0.70
0.7MK	0.21	0.51	0.81
0.7SF	0.23	0.52	0.77
0.7SG	0.20	0.46	0.73
0.9C	0.22	0.45	0.69
0.9MK	0.20	0.50	0.77
0.9SF	0.22	0.51	0.76
0.9SG	0.17	0.45	0.72
1.2C	0.21	0.44	0.68
1.2MK	0.20	0.47	0.76
1.2SF	0.21	0.49	0.77
1.2SG	0.17	0.43	0.72
20C	0.20	0.44	0.65
20MK	0.20	0.49	0.75
20SF	0.21	0.48	0.74

20SG	0.17	0.42	0.71

The strength development results for varying C/F ratios are shown in Table 7. From this table it can be seen that as the C/F ratio increases, the 1, 3 and 7 day strength development decreases for all mixtures. The mixture using MK as a partial replacement had a 4.8%, 7.3%, and 6.5% decrease in the 1, 3 and 7 day strength developments when the C/F ratio was increased from 0.7 to 1.2. Raising the C/F ratio from 0.7 to 1.2 decreased the 1, 3 and 7 strength developments by 5.7%, 6.5% and 3% respectively compared to the control mixture. 8% SF and 30% SG mixtures also showed a similar trend as those of the control and MK mixtures, where the 1, 3 and 7 day strength developments decrease as the C/F ratio is increased from 0.7 to 1.2.

The strength development results for varying coarse aggregate size are shown in Table 7. From Table 7 it can be seen that increasing the coarse aggregate size from 10 to 20mm, the 1, 3 and 7 strength developments for all mixtures decreases. The 1, 3 and 7 day strength developments for mixtures using MK as a partial cement replacement had a decrease of 4%, 2.7% and 3% respectively as the aggregate size was increased from 10 to 20mm. As well, increasing the coarse aggregate size from 10 to 20mm for the control mixture showed a decrease of 6.5%, 2.1% and 5.2% in the 1, 3 and 7 day strength developments respectively. Mixture using 8% SF as a partial replacement showed decreases of 5.2%, 6% and 2.7% for 1, 3 and 7 day strength development respectively, while 30% SG as a partial replacement showed a reduction of 4.1%, 6.3% and 0.44% for the 1, 3 and 7 day strength development respectively when using a 20mm coarse aggregate size.

These results could be related to the effect of the ITZ as mentioned before. Increasing the C/F ratio or using larger coarse aggregates, increases the volume/thickness of the ITZ which reduces the quality of the mixture resulting in a lower strength development for these mixtures.

3.2.2 Flexural Strength

The results for the FS for varying C/F ratios are shown in Table 5. From Table 6 it can be seen that the FS decreases for all mixtures as the C/F aggregate ratio was increased from 0.7 to 1.2. Using 20% MK mixtures showed a large decrease in the FS of 23% with the increase of the C/F ratio from 0.7 to 1.2. SCC containing no SCMs had a decrease in the FS of 18.2% with the increase of the C/F ratio from 0.7 to 1.2. Both partial replacements with 8% SF and 30% SG showed decreases in the FS of 10.3% and 18.6% with increasing C/F ratio from 0.7 to 1.2. Looking at the compressive strengths for these values it can be seen that as the compressive strength decreased the FS also decreased. This relationship between compressive strength and FS was observed by Mindess et al. (2002) as well as confirmed by Neptune et al. (2010).

The results for FS for varying the coarse aggregate size can be seen in Table 5. From this table it can be seen that using a larger coarse aggregate size of 20mm decreases the FS for all four mixtures. The control mixture had a decrease of 4.3% and partial replacement of cement with 20% MK showed a reduction of 8.9%. Using 8% SF and 30% SG as partial replacements also showed decreases in the FS of 6.7% and 7.9% respectively when the coarse aggregate size is increased from 10mm to 20mm. Neptune et al. (2010) showed that increasing the size of the aggregate in single sized gradations reduced the flexural strength.

3.2.3 Modulus of Elasticity

The results for the MEs are shown in Table 6. From this table it can be seen as the C/F ratio was increased from 0.7 to 1.2 for all mixtures the ME decreases. The control mixture had a decrease of 6.8% with an increasing C/F ratio from 0.7 to 1.2. Increasing the C/F ratio when using 20% MK mixtures showed a 5.4% decrease in the ME as the C/F ratio was increased to 1.2. Also both partial cement replacements with 8% SF and 30% SG showed decreased in the ME of 8.2% and 7.4% respectively when the C/F ratio was increased from 0.7 to 1.2

Table 6 shows the ME results for varying coarse aggregate sizes. The table shows that all mixtures experience a decrease in the ME when the coarse aggregate size was increased from 10mm to 20mm. 20% MK partial replacement showed a 7.1% increase in the ME when using a larger coarse aggregate size. The control mixture also showed a 3.6% increase in the ME when using a 20mm coarse aggregate size. Partial cement replacements with 8% SF and 30% SG had increases in their respective MEs of 7.8% and 8.0% respectively as the coarse aggregate size was increased from 10mm to 20mm.

3.2.4 Indirect Tensile Strength

The results for the STS for varying C/F ratios are shown in Table 5. This table shows, increasing the C/F ratio from 0.7 to 1.2 reduced the STS for all mixtures. The control mixture had a reduction of 11.8% and using 20% MK partial replacement resulted in a decrease of 13.8% as the C/F ratio increased from 0.7 to 1.2. 8% SF and 30% SG partial replacements experienced a drop of 9.9% and 14% respectively as the C/F ratio was varied from 0.7 to 1.2.

Table 5 shows the STS results when using varying coarse aggregate sizes. From this table it can be seen that increasing the coarse aggregate size from 10mm to 20mm decreases the STS for all mixtures. This was also observed by Akcaoglu et al. (2002) where the loss in the tensile strength increased as the coarse aggregate size is increased. The control mixture showed a decrease in the STS of 6.2% with the use of the 20mm coarse aggregate. 20% partial replacement with MK resulted in a 5.6% decrease in the STS when using a 20mm coarse aggregate. In addition, both 8% SF and 30% SG partial replacements showed decreases of 8.8% and 10% respectively in the STS with the 20mm coarse aggregate.

4 Conclusions

The effect of MK replacement on the mechanical properties of SCC was studied and compared to SCC containing no MK and to optimum vales of various other SCMs. In addition the C/F ratio and the coarse aggregate size were varied to study their effect on the mechanical properties of SCC. The mechanical properties were investigated using FS, STS, the compressive strength development and ME tests. The following conclusions can be made from the results discussed in the paper; these conclusions are as follows:

- Increasing the percentage of MK up to 20% in SCC has a direct effect on the mechanical properties of the mixtures. The addition of MK shows to increase the compressive strength of SCC mixtures and increased the FS, STS and ME. Further increasing the MK percentage to 25% yielded no additional benefits for the mechanical properties. Using 20% MK replacement showed a 21% increase in the FS. Also, increasing the percentage of MK in SCC seems to improve the ME up to 15% replacement. However the addition of MK up to 15% MK replacement shows an increase in the STS of 26% when compared against the control mixture.
- Using a 20% MK replacement results in a 30% increase in the compressive strength compared to using no MK. Also, compared to SF, using a 15% or greater MK replacement results in a higher compressive strength. All MK replacement percentages obtained higher 28 day compressive strengths compared to SG.
- The 1 and 3 day strength development of mixtures containing MK appears to decrease as the percentage of MK replacement increased up to the 15%, while the 7 day strength development increased with increasing percentage of MK up to 15% replacement.
- Increasing the C/F ratio in SCC showed to have a negative impact on the compressive strength for all the mixtures. Also using a larger coarse aggregate size in SCC, results in a reduction in the compressive strength for all mixtures. Increasing the C/F ratio from 0.7 to 1.2 decreased the compressive strength by 6.5%, 6.3%, 6.4% and 3.8% when testing the control, MK, SF and SG mixtures respectively.
- The 1, 3 and 7 day strength developments decreased with increasing the C/F ratio from 0.7 to 1.2 regardless of the mixture. Using MK results in a 4.8%, 7.3% and 6.5% decrease in the 1, 3 and 7 day strength development respectively as the C/F ratio was increased from 0.7 to 1.2.

- Increasing the coarse aggregate size from 10 to 20mm shows to reduce the 1, 3 and 7 day strength developments. MK mixtures showed a reduction in the 1, 3 and 7 day strength developments by 4%, 2.7% and 3% respectively when the coarse aggregate size changed from 10 to 20mm. All other SCC mixtures had decreases in the strength development when using a larger coarse aggregate size.
- The FS, STS and ME all decreased by 23%, 14% and 5% respectively when the C/F ratio was increased from 0.7 to 1.2 for SCC mixtures using MK. All other SCC mixtures resulted in decreases in the FS, STS and ME as the C/F ratio was increased.
- Using a larger coarse aggregate size showed to decrease the FS, STS and ME by 9%, 6% and 7% for SCC mixtures using MK replacement. SCC containing SF and SG and SCC using no SCM showed similar decreases in the FS, STS and ME when using a 20mm coarse aggregate size compared to using a 10mm coarse aggregate.

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