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Synergetic Effect of Met kaolin for Developing Fast Setting Early Strength Self-Compacting Concrete

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Abstract
One of the chief apprehensions in the construction industry is utilisation of industrial waste by-products which are mostly industrial waste by-products like fly ash(FA), ground granulated blast furnace slag(GGBFS), micro silica(MS), etc, having potential pozzolanic nature in concrete as supplementary cementitious materials(SCMs)for attaining the sustainability in concrete construction and also improving structural properties of concrete. The addition of various types of SCMs in concrete enhances the performance, decreases the calcium hydroxide quantity by ingesting it through a pozzolanic reaction. SCMs are vital constituents of self-compacting concrete(SCC) mixes which are characterised by free-flowing, high workable nature producing a pleasing surface finish. It is well established that with the addition of SCMs, in concrete, enormous nucleation locations are formed owing to the dissipation of fine pozzolana particles in the paste causing compact filling of the pores formed within the cement and thereby diminishing the barrier effect in the transition zone between the paste and aggregate thereby enhancing uniformity of mix. Previous studies directed towards the effects of SCMs particularly metakaolin(MK) in concrete where a significant augmentation of the mechanical characteristics and durability properties of the hardened concrete specimens was observed, providing sound opinions regarding the need for further investigation of the effects of MK and its resourcefulness as a promising SCM for increased future use. MK is slowly gaining its place as an extremely resourceful pozzolanic material, through its high pozzolanic response, to yield calcium silicate hydrates(CSH) and stratlingate(C2ASH8) and hydro garnet(C3AH6) thereby enhancing the early strength and durability of concrete. In this experimental investigation two types of ternary blended sustainable early strength M50 grade SCC mixes were formulated one with part replacement OPC with MK, in various proportions ranging from 2.5% to 20%, and with 25% FA (designated as FMK0,2.5,5 …20 series mix). Another SCC mix was with similar OPC+MK combinations as above but with 25% GGBFS (designated as GMK0,2.5,5 …20 series mix). A comparative analysis was made for the synergetic effect of MK in FMK series mix and GMK series mix with reference to controlled mixes in the fresh and hardened state, and analyzed by a comprehensive set of rheological parameters like flow, flow time, L box flow, segregation resistance, initial setting and final setting time in a fresh state of concrete; mechanical properties, durability characteristics in the hardened state in order to optimize the combinations for establishing the suitability of blends for developing fast setting early strength SCCs

Key Words : Metakaolin, Synergy, Early strength SCC, Durability

1.0 Introduction:

Concrete ,the second most consumingmaterial after water by mankind , is being preferred all over the world as construction material in most of infrastructure facilities over the past few decades.This has resulted in development ofmany types of concreteslike high performance concrete,high strength concrete,self-compacting concrete(SCC) etc[1].SCC is characterised with free flowing behaviour, highly workable, homogenous, dense /compact and yielding aesthetically pleasing surface finish, planned to escalate the speed of construction as well as quality of concrete in the same [2]. SCC utilises good amount powder materials (< 125 micron size) like supplementary cementitious materials (SCMs) i.e industrial waste by productshaving potential pozzolanic nature like flyash(FA),ground granulated blast furnace slag(GGBFS) ,microsilica(MS) etc[3]. It is well documented that addingthese pozzolanic materials results in improvement of various characteristics of concrete like consistency, mechanical strength, confrontation to cracks and reduced permeability[4-7].Performance of numerouscontemporary concrete mixes are improved with addition of these SCMs, which decreases the calcium hydroxide quantity by consumption through its pozzolanic reaction[8]. The consequentof SCM addition in concrete alters the microstructure and there byenhances the mechanical strength, durability and results in increases the servicelife of concrete structures [9-10].SCM inclusions in concrete results in enormous nucleation locations that are formed due to the dissipation of fine pozzolanic particles in the paste causingcompact filling of the pores formed within the cement and thereby diminishes the barrier effect in the transition zone between the paste and aggregates thus enhancing uniformity of mix[11-14].Consequently, part replacement ofordinary portland cement(OPC)with pozzolanic materialsupsurges its mechanical strength and durability as compared to the control mixes, because of the refinement of interface[15].Metakaolin(MK)an industrialproduct produced by calcination of designated kaolin($Al_2O_3.2SiO_2.2H_2O$)to temperatures of 650-900°C, under specific conditions, has attracted the attention of many researchers,during past three decades especially during the last decade, due to its high pozzolanic potential[16-20].Calcination of kaolin assists in breaking down the structure of kaolin wherein bound hydroxyl ions get detached ensuing disordered alumina and silica layers thereby produces a highly reactive, an amorphous aluminosilicate ($Al_2O_3.2SiO_2$), known as MK with pozzolanic and dormant hydraulic reactivity, appropriate for use as potential replacement material in cement concrete construction[21-22].MKis slowly gaining its place as an extremelyresourceful pozzolanic material, through its pozzolanic response,as it reacts quickly with the surplus calcium hydroxide,which is consequential from hydration of OPC to yield calcium silicate hydrates(CSH) and stratlingate(C_2ASH_8) and hydro garnet(C_3AH_6) thereby enhancing early strength and durability of concrete[23-25].

Ground Granulated Blast Furnace Slag(GGBFS), non-metallic industrial waste by-product of steel plants, consisting of silicates and aluminosilicates of calcium and others has wide adoptability as an SCM over the past several decades in construction industry due to its chemical composition[26-28]. Early age strength gains of concrete comprising GGBFS reported to be lower compared to concrete made with OPC but GGBFS nclusion in concrete reduces water demand for workability,enhancesrheologyand later age hardened properties of SCC like compressive strength ,flexural strength ,split tensile strength ,modulus of elasticity(MoE) etc and encourages sustainability[29-30]. GGBFS use in concrete reduces the setting process as well as lowering heat liberation during hydration process and increases resistance against sulphate and chloride attacks thus making it appropriate for use in concrete construction in marine environments[31-33].

Flyash(FA) ,industrial waste by-product from thermal power plants, has found its use SCM in various types of concretes. FA’s usage, because of its pozzolanic properties, as a partial replacement of OPC in SCC is proven over last three decades[34-38] . FA’s incorporation in SCC, because of its spherical shape, found to reduce water demand for workability, thus advances its rheological characteristics,reduces bleeding and also improves hardened properties[39-40]. OPC can be replaced with Fly ash from 15 to 35 percent by mass but gain of strength observed to be slower when compared to control mixes[41-44].

Previous studies directed towards the effects of SCMs particularly MK in concrete where a significant augmentation of the mechanical characteristics and durability properties of the hardened concrete specimens was observed [45-50], providing sound opinions regarding the need for further investigations on the effects of MK and its prospectiveness as a promising SCM for increased future use. Numerous investigators have testified that a notable advancement in compressive strength, tensile strength of both conventional concrete and SCC mixtures, wherein MK was used, at various percentage levels, as part replacement of cement [9,15,16,19,23–28]. In direction to assess the durability of concrete, a number of laboratory methods have been applied in earlier pertinent studies, primarily regarding the ability of ions and fluids to transport through its pore system[24]. Cement replacement with MK , upto 20% as SCM, ,resulted in reduced capillary rise in conventional concrete samples[26].Reduction in the initial surface absorption, sorptivity, chloride permeability, gas permeability of conventional concrete was observed at 10% replacement of cement by MK which was attributed to the filler effect of MK particles thereby reducing the porosity of concrete[26].In contrast, an upsurge in the sorptivity was observed for a replacement level of 15%[32-38]. 50% of reduction in gas permeability was observed in concrete with 20% cement replacement by MK[36] which is in contrast with the findings of[32-38] with respect to increase in % MK ,as replacement of cement, beyond 15%.These research on inclusion MK in concrete revealed improvement in hardened properties of concrete at an early age[34-38],while GGBFS,Flyashincorporation in concreteshownan improvementin the fresh properties as well as continuing strength development over extended period of time[39-40]. In the previous studies of SCC containing GGBFS,Flyash or MK, most of the researchers narrowed their attention to a limited number of parameters [17,20,21] of fresh mixtures and basic mechanical properties in the hardened state. In spite of the expediency of such scholarships, the global view of the material was time and again restricted by a deficiency of evidence for case of setting and hardening behaviour, early development of strength ,gain of strength with age ,temperature gradient between near surface and interior core temperature of concrete, shrinkage,sulphate and chloride ion penetration resistance .Thereforefurther research is required to explore on the optimum combinations of slow reactive SCM (like Flyash and GGBFS) and high reactive SCMs(like MK,Microsilica etc) in development of early strength SCCs.

2.0 Research Significance

One of the chief apprehensions in construction industries is utilisation of industrial waste by-products like Flyash, GGBFS etc in concrete as SCM’s for attaining the sustainability in concrete construction and also improving structural properties of concrete. The resourcefulness of MK as a highly reactive SCM can be used to compensate the slow reactiveness of Flyash ,GGBFS etc in development of early strength concretes for fast track repairs and also for fast constructions of new infrastructure facilities .Thus, this experimental analysis was aimed to develop a ternary blended sustainable early strength M50 grade SCC proportioned,with a total powder quantity, including cementitious material content,of 540kg/cum, w/cementitious materials(cm) ratio of 0.35, as per provisions of IS 10262:2019[41]- with a targeted final setting time of 10 hours and a 1 day targeted compressive strength of 20N/mm^2, meeting SF1(slump flow 550mm-650 mm), V2 class(V Funnel flow 9 -25 Seconds) and SR2 class(Segregation Resistance<15%)[42] ,by OPC with replacements by incorporating combination of MK and 25%GGBFS ; combinations of MK and 25% Fly ash .Proportion of MK in the above mix started from 2.5% and for each successive trial MK’s addition wasvaried by 2.5%.Thus MK’s proportion of 2.5%, 5%,7.5%10%,12.5% 15% ,17.5% and 20% added in each successive trial so that the combined replacement of GGBFS+MK will be from 27.5% to 45% by weight of OPC. Similarly in Flyash based mix ,Flyash+MK combinations will be from 27.5% to 45% by weight of OPC by keeping 25% FA content and varying MK’s proportion from 2.5%, 5%,7.5%10%,12.5% 15% ,17.5% and 20% in each successive trial. Evaluation of above SCC mixes, i.e combinations of GGBFS+MK (designated as GMK series)and Fly ash +MK(designated as FMK series), in fresh and hardened state carried, compared and analysed by a comprehensive set of rheological parameters like flow, flow time ,L box flow,segregation resistance, initial setting and final setting time of fresh state of concrete; mechanical properties, durability characteristics in hardened state in order to optimise the combinations for establishing the suitability of blends for developing fast setting early strength SCCs .

3.0 Materials and methods

3.1. Cement

Locally available Ordinary Portland Cement (OPC) 53Gr complying with IS 269-2015 was used in this study. Specific gravity of the cement was 3.14 and blaine's fineness was 340m^2/kg.

3.2 GGBFS

Locally available reputed brand GGBFS confirming to IS 16714:2018 was used in this study.GGBFS's specific gravity was 2.91 and Blaine's fineness 350m^2/kg.

3.3 Fly ash

Locally available fly ash supplied from near by thermal power station was used in this study, and was confirming to IS 3812:2013.Specific gravity of flyash was 2.08 and Blaine's fineness 330m^2/kg.

3.4 Metakaolin (MK)

Locally available MK, complying to IS 16354:2018, was used in this study.MK 's specific gravity was 2.26.Particle size of MK was D_{10} = 0.9 microns, D_{50}= 5.9 microns and D_{90}= 13.59 microns.

3.5 Coarse and fine aggregates

Locally available crushed angular coarse aggregate 10 mm MSA and natural fine aggregate having a powder content(<125 Micron) of 6% was used in this study. Coarse and fine aggregates were complying with the requirements of IS3 383:2016.

3.6 Water

Tap water confirming to IS 456:2000 was used in proportioning the SCC mixes.

3.7 Super-plasticizer (SP)

Locally available reputed brand of PCE based high range water reducing(HRWR) SP complying to IS 9103:1999(RA) having a water reduction capacity of 35% was used in this study. SP's specific gravity was 1.14.

Material characteristics of OPC,GGBFS,MK and Flyash is presented in Table 1.

4.0 Experimental procedure

The methodology adopted in this study for arriving mix propositions of SCC was structured in two distinct stages. The first step consisted in studying thebehaviour of cementitious pastes (i.e mixture of combinations of OPC+GGBFS+MK and water (GMK series); combinations of OPC+Flyash +MK and water(FMK series)) and cementitious mortar with the pastes.The cementitious mixes were investigated by the mini-slump flow test and mini Vfunnel flow test to determine superplasticizer saturation quantity by weight of cementitious material for the targeted flow. In the Second step, the effect of combinations of GGBFS +MK ; Fly ash +MKin SCC (mixture of cementitious material , water, sand and coarse aggregate) was investigated. Various combinations of coarse aggregate and sand combinations were tried for qualifying the SCC characteristics and the combination finalised were coarse aggregate as45% and sand as 55% in total aggregate content.In case of Flyash incorporated SCC mixes, control mix (Flyash as SCM)was prepared keeping cementitious materials combination as OPC at 75% and Flyash at 25% and the same being designated as FMK0. In the subsequent SCC mixes of FMK series(with constant flyash at 25%) OPC was replaced with MK from 2.5% to 20% and the resulted SCC mixes were designated as FMK2.5,FMK5,FMK7.5,FMK10,FMK12.5, FMK15,FMK17.5 and FMK20.Similarly in case of GGBFS incorporated mixes, control mix (with GGBFS as SCM) was prepared keeping cementitious materials OPC at 75% and GGBFS at 25% and the same designated as GMK0. Accordingly in the subsequent SCC mixes of GMK series (with constant GGBFS at 25%) OPC was replaced with MK from 2.5% to 20% and the resulted SCC mixes were designatedasGMK2.5,GMK5,GMK7.5,GMK10,GMK12.5,GMK15,GMK17.5 and GMK20. Thus a total of 18 no.s of SCC mixes consisting of 9 nos. of FMK series and 9 nos. of GMK series proportioned and investigated in this study and the mix proportions of the same are presented in Table 2(FMK series) and Table 3(GMK series) respectively.All the FMK and GMK series SCC mixes were evaluated for the rheological parameters like flow, flow time ,segregation resistance, initial setting and final setting time in fresh state of concrete. Table 4(FMK series) and Table 5(GMK series) presents test results of SCC in fresh state. Mechanical properties of all the proportioned SCC mixes(FMK series and GMK series), in hardened state, were evaluated as per the provisions of IS 516 for properties like compressive strength, split tensile strength,durability characteristics such as shrinkage ,sorptivity, resistance to ingression of Cl^- ion ,as per the provisions of ASTM C 1543and resistance to sulphates tested as per the provisions of ASTM C1012.Mechanical and durability test results of the above SCC mixes were analysed and the same is discussed in subsequent sections.

Table 1: Material characterization

Compounds/ Property	MK	GGBFS	Flyash
	%		
CaO	-	36.29	5.11
SiO_2	53.21	32.70	63.86
Al_2O_3	42.14	16.10	22.57
MgO	0.42	11.80	0.19
Fe_2O_3	0.16	0.54	6.25
LOI	1.44	1.72	0.26
Chloride	0.070	0.004	0.007
Specification	IS16354 :2015	IS16714 :2018	IS3182 :2013

5.0 Results and Discussions

5.1 Fresh state properties of SCC

5.1.1 Slump Flow

Mineral admixtures (SCMs) additions, as part replacement of cement, in producing SCC mixes reduces the water demand as compared to control SCCmix(in this caseFMK0,GMK0).Chemical composition and fineness of SCMs are the main properties that effects the water requirement for flowable mix .Fig.1 represents the slump flow of various SCC mixes experimented in this study and variations in slump flow with reference to % MK is presented in Fig.2.When %MK varied from 2.5% to 12.5% i.e for the mixes FMK2.5 to FMK12.5 ,slump flow was reduced from 3.17% to 12.70% as compared to control mix FMK0.Whereasreduction in slump flow was from 1.56% to 14.06% as observed for similar variations of %MK in GMK series SCC mixes. Thus higher reduction in slump flow in SCC consisting of GMK series can be attributed to quickness in reaction of MK in presence of GGBFS than the reaction of MK in company of Flyash .This reduction of slump flow was more when %MK increased beyond 12.5% in both the FMK series and GMK seriesmixes.The maximum replacement level of MK was found to be 12.5% for achieving the targeted slump flow category of SF1 (i.e 550-650mm)in both the FMK series and GMK series mixes.

Table 2 Mix Proportion of FMK Series SCC Mixes

Sl. No	Mix ID	Cementitious Materials composition			Concrete Making Materials (Kg/Cum)				
		OPC 53 Gr (%)	Flyash (%)	MK (%)	Total Cementitious Materials	CA 10	Sand	PCE Admixture	Water
1	FMK0	75.00	25.00	0	540	750	915	5.5	190
2	FMK2.5	72.50	25.00	2.50	540	750	915	5.5	190
3	FMK5	70.00	25.00	5.00	540	750	915	5.5	190
4	FMK7.5	67.50	25.00	7.50	540	750	915	5.5	190
5	FMK10	65.50	25.00	10.00	540	750	915	5.5	190
6	FMK12.5	62.50	25.00	12.50	540	750	915	5.5	190
7	FMK15	60.00	25.00	15.00	540	750	915	5.5	190
8	FMK17.5	57.50	25.00	17.50	540	750	915	5.5	190
9	FMK20	55.00	25.00	20.00	540	750	915	5.5	190

Table 3 Mix Proportion of GMK Series SCC Mixes

Sl.	Mix ID	Cementitious Materials	Concrete Making Materials

No		composition			(Kg/Cum)				
		OPC 53 Gr (%)	Flyash (%)	MK (%)	Total Cementitious Materials	CA 10mm	Sand	PCE Admixture	Water
1	GMK0	75.00	25.00	0	540	750	915	5.5	190
2	GMK2.5	72.50	25.00	2.50	540	750	915	5.5	190
3	GMK5	70.00	25.00	5.00	540	750	915	5.5	190
4	GMK7.5	67.50	25.00	7.50	540	750	915	5.5	190
5	GMK10	65.50	25.00	10.00	540	750	915	5.5	190
6	GMK12.5	62.50	25.00	12.50	540	750	915	5.5	190
7	GMK15	60.00	25.00	15.00	540	750	915	5.5	190
8	GMK17.5	57.50	25.00	17.50	540	750	915	5.5	190
9	GMK20	55.00	25.00	20.00	540	750	915	5.5	190

FMK10 GMK10 GMK15

Fig.1 Slump Flow Test of SCC Mixes

Table 4Fresh State Properties of FMK Series SCC Mixes

Sl.No	Mix ID	Fresh state properties					
		Slump flow	'V'funnel flow time	L box flow	Segregation Resistance (SR)	Initial setting time (IST)	Final setting time (FST)
		mm	seconds	h2/h1	%	Minutes	Minutes
1	FMK0	630	16	0.94	12	490	560
2	FMK2.5	610	20	0.92	12.3	460	520
3	FMK5	608	21	0.91	12.1	400	505
4	FMK7.5	595	23	0.9	11.5	380	490
5	FMK10	580	24	0.88	11.5	340	460
6	FMK12.5	550	38	0.74	22	300	410
7	FMK15	530	40	0.71	22	280	380
8	FMK17.5	500	49	0.68	23	270	360
9	FMK20	460	54	0.65	25	240	320

Table 5

Fresh State Properties of GMK Series SCC Mixes

Sl.No	Mix ID	Fresh state properties					
		Slump flow	'V'funnel flow time	L box flow	Segregation resistance	Initial setting time	Final setting time
		mm	seconds	h2/h1	%	Minutes	Minutes
1	GMK0	640	15	0.96	14	460	540
2	GMK2.5	630	17	0.91	14.2	440	530
3	GMK5	610	19	0.88	14.8	390	490
4	GMK7.5	590	22	0.85	15.1	370	460
5	GMK10	560	24	0.81	16.4	350	440
6	GMK12.5	550	25	0.72	22	310	390
7	GMK15	500	40	0.68	22	300	370
8	GMK17.5	490	46	0.68	22	280	340
9	GMK20	440	52	0.68	22	260	320

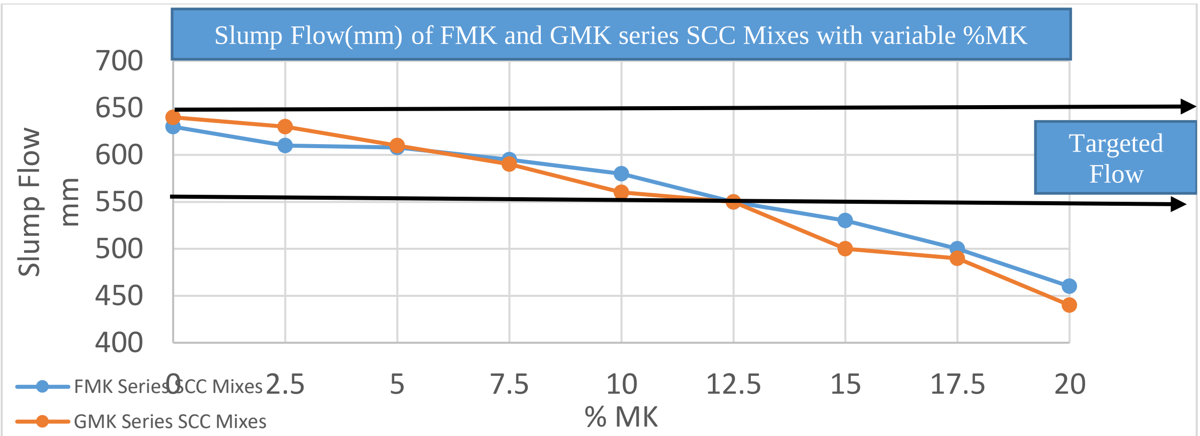

Fig.2

5.1.2 V Funnel Flow

From Table 4 ,it can be seen that when %MK varied from 2.5% to 10% i.e for the mixes FMK2.5 to FMK10 ,the V funnel flow time increased from 25.00% to 50% as compared to FMK0.Whereas referring to Table 5, for similar variations of %MK in GMK series increase in V funnel flow time observed was from 13.33% to 60.00% .Thus higher increase in V funnel flow in GMK series can be attributed to swiftness in reaction of MK in company of GGBFS than the reaction of MK in in company of Flyash .This increase of V funnel flow was more when %MK increased beyond 10% in both the FMK series and GMK series mixes. The maximum replacement level of MK was observed to be 10% for achieving the targeted V funnel flow of V2class(i.e 9-25 sec) in both the in both the FMK series and GMK series mixes.

5.1.3 L Box Flow

From Table 4, it can be seen that decrease in the depth ratio in L box test, conducted as per EFNARC guidelines[43], of SCC mixof FMK series, was observed with the % increase in MK in the mix.When %MK varied from 2.5% to 10.0% i.e for the mixes FMK2.5 to FMK10,depth ratio in L box test decreased from 2.13% to 6.38% as compared to FMK0.Whereasfrom Table 5 it can be observed that decrease in the depth ratio in L box test was from 5.21% to 15.62% for similar variations of %MK in GMK series mixes,. Thus higher decrease in the depth ratio in L box test in GMK series can be attributed to fastness in reaction of MK in concern of GGBFS than the reaction of MK in concern of

Flyash.This decrease in the depth ratio in L box test was more when %MK increased beyond 10.0% in both the FMK series and GMK series mixes.The maximum replacement level of MK was observed to be 10.0% for achieving the qualifying depth ratio(i.eh2/h1=0.8) in L box test for SCC's in both the FMK series and GMK series mixes.

5.1.4 Segregation Resistance(SR)

From Table 4 it can be perceived thatwhen %MK varied from 2.5% to 10.0% i.e for the mixes FMK2.5 to FMK10,SR increased from 2.50% to 4.17% as compared to FMK0.Whereas from Table 5,the observed increase in the SRfor similar variations of %MK in GMK series , was from 1.43% to 7.86% .Thus higher increase in the SRin GMK series can be attributed to high degree of reaction of MK in presence of GGBFS than the reaction of MK in presence of Flyash.This increase in the SRwas more when %MK increased beyond 10% in the FMK series,whereas the increase in SR was observed to be more beyond 7.5%MK in GMK series.For achieving the qualifying class SR2(i.e SR,15%), The maximum replacement level of MK was observed to be 10.0% and 7.5% for FMK series and GMK series mixes respectively.

5.1.5 Initial Setting Time (IST)

From Table 4,it can be comprehendedthat when %MK varied from 2.5% to 10.0% i.e for the mixes FMK2.5 to FMK10,IST decreased from 6.12% to 30.61% as compared to FMK0.Whereas from Table 5 , it can be observed that decrease in the IST was from 4.34% to 23.91% for similar variations of %MK in GMK series mixes.Thus higher decreasein the initial setting time in FMK series can be attributed to dense packing of matrix owed to spherical nature of Flyash particlesas compared to non spherical nature of GGBFS.This decrease in the ISTwas more when %MK increased beyond 10% in the FMK series whereas decrease in the ISTwas observed to be more beyond 7.5% MK in GMK series mixes .For achieving higher decrease in the initial setting time ,the maximum replacement level of MK was observed to be 10.0% and 7.5% in SCC mixes of FMK series and GMK series respectively.

5.1.6Final Setting Time(FST)

Fig.3 represents the setting time test of various SCC mixes experimented in this study.It can be viewed from Table 4thatwhen %MK varied from 2.5% to 10.0% i.e for the mixes FMK2.5 to FMK10, FST of SCC mix decreased from 7.14% to 17.85% as compared to FMK0.Whereas in GMK series mixes,the observed decrease in the FST was from 1.85% to 18.51% for similar variations of %MK.Thus higher decrease in the final setting time in SCC consisting of SCM combinations of GGBFS+MK can be attributed to high degree of reaction of MK in presence of GGBFS than the reaction of MK in presence of Flyash This decrease in the FST was more when %MK increased beyond 10% in both the mixes of FMK series and GMK series.For achieving higher decrease in the FST ,the maximum replacement level of MK was observed to be 10.0% in both the mixes of FMK series and GMK series.

Concrete Setting Time Test

Final Setting Time of FMK17.5

Fig.3 Setting Time Test of SCC Mixes

5.2 Hardened state properties of SCC

5.2.1 Compressive Strength

Compressive strength test results for the experimented SCC mixes presentedFig.4,Table 6 and Table 7.It can be seen from Fig.4that early age(1 day) compressive strength of FMK0 was 22.14 N/mm^2 whereas for GMK0 1day compressive strength was 23.18N/mm^2. When in FMK series mixes where MK from increased from 2.5% to 20%, mix has resulted in increase in compressive strength for all the periods i.e from 1day to 90days. For mix FMK12.5,compressive strength observed at 1day was 24.22 N/mm^{2}whereas the same for GMK12.5was 25.16 N/mm^2.It can be seen from the Table 6 and Table 7 that as the %MK increases from 2.5% to 20% ,the increase in 1 day compressive strength was observed to be marginal beyond 12.5% of MK in both FMK series and GMK series mixes. MK's performance in presence of GGBFS observed to be superior than in presence of flyash for attaining higher early age strength.

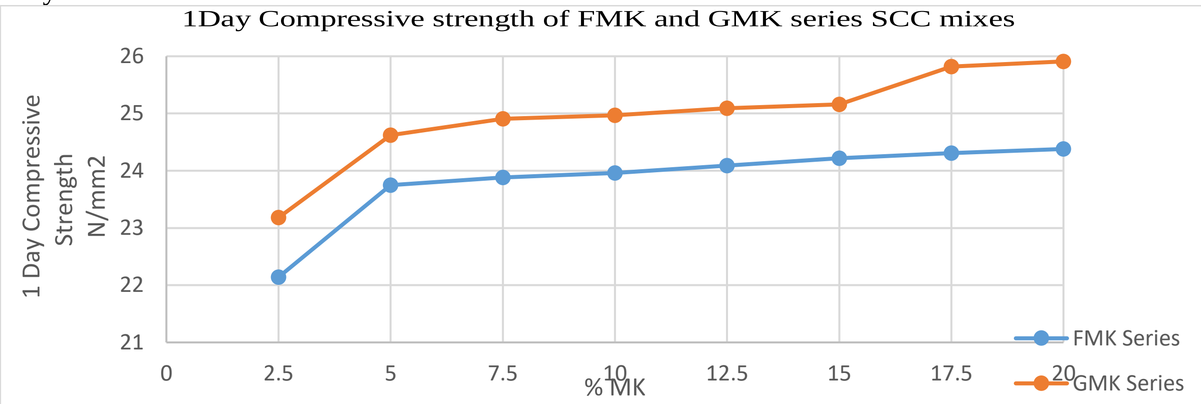

Fig.4

5.2.2 Split Tensile Strength

Split tensile strength test results for the experimented SCC mixes presented in Table 6 and Table 7. Early age(1 day) split tensile strength of FMK0 and GMK0 was almost similar. When in subsequent FMK series mixes where MK varied from 2.5% to 20%, SCC mix has resulted in increase in split strength for all the periods i.e from 1day to 90days. For mix FMK12.5 wherein OPC was replaced with 12.5%MK , split tensile strength observed at 1day was 2.08 N/mm^2, whereas the split tensile strength was2.18 N/mm^{2}for GMK12.5.It can also be seen from the Table 6 and Table 7 that as the %MK increases from 2.5% to 20% , the increase in 1 day Split tensile strength was observed to be marginal beyond 12.5% of MK in both FMK series and GMK series of mixes. MK's performance in presence of GGBFs observed to be superior than in presence of flyash for attaining higher early age split tensile strength.

Table 6

Hardened State Properties of FMK Series SCC Mixes

Compressive Strength(N/mm^2)								Split Tensile Strength(N/mm^2)					
Sl .No	Mx ID	1 Day	3 Days	7 Days	28 Days	56 Days	90 Days	1 Day	3 Days	7 Days	28 Days	56 Days	90 Days
1	FMK0	22.14	32.71	40.76	52.14	53.87	53.91	1.86	1.97	3.16	5.24	5.3	5.32
2	FMK2.5	23.75	36.37	48.34	58.04	58.76	58.79	1.94	2.08	3.62	5.28	5.34	5.36
3	FMK5	23.88	37.62	49.4	58.61	58.94	59.02	1.98	2.41	3.71	5.41	5.46	5.47
4	FMK7.5	23.96	38.43	49.86	59.66	59.8	59.85	1.99	2.46	3.88	5.56	5.61	5.63
5	FMK10	24.09	38.68	50.26	59.78	59.9	59.92	2.01	2.52	3.94	5.59	5.64	5.68
6	FMK12.5	24.22	38.76	50.44	59.81	59.97	60.05	2.08	2.59	3.98	5.61	5.68	5.76
7	FMK15	24.3	38.8	50.5	59.8	60.0	60.1	2.10	2.6	4.01	5.63	5.74	5.79

		1	1	1	3	2	1		1				
8	FMK17.5	24.38	38.86	50.72	59.86	60.09	60.16	2.11	2.64	4.08	5.65	5.76	5.81
9	FMK20	24.47	39.05	50.89	59.09	60.15	60.18	2.13	2.67	4.12	5.66	5.79	5.86

Table 7

Hardened State Properties of GMK Series SCC Mixes

		Compressive Strength(N/mm^2)						Split Tensile Strength(N/mm^2)					
Sl No	Mix ID	1 Day	3 Days	7 Days	28 Days	56 Days	90 Days	1 Day	3 Days	7 Days	28 Days	56 Days	90 Days
1	GMK0	23.18	33.68	40.98	53.06	53.94	53.96	1.91	1.99	3.19	5.29	5.36	5.42
2	GMK2.5	24.62	36.82	48.69	58.67	58.81	58.87	1.97	2.16	3.76	5.37	5.39	5.48
3	GMK5	24.91	37.94	49.76	58.84	59.06	59.09	2.01	2.47	3.86	5.64	5.51	5.56
4	GMK7.5	24.97	38.19	49.92	59.81	59.94	60.02	2.06	2.53	3.91	5.69	5.69	5.72
5	GMK10	25.09	38.9	50.98	60.02	60.25	60.29	2.13	2.58	4.06	5.73	5.74	5.78
6	GMK12.5	25.16	39.21	51.06	60.84	60.46	60.87	2.19	2.67	4.19	5.81	5.81	5.81
7	GMK15	25.82	39.82	51.16	60.96	60.67	60.92	2.22	2.68	4.24	5.91	5.89	5.93
8	GMK17.5	25.91	39.96	51.54	61.02	61.09	61.18	2.28	2.71	4.31	5.96	5.92	5.97
9	GMK20	25.97	40.02	51.67	61.09	61.12	61.19	2.31	2.76	4.36	5.98	5.96	6.02

5.2.3 Drying Shrinkage

Fig.5, Table 8 and Table 9 represents the drying shrinkage test of various SCC mixes experimented in this study.Drying shrinkage % variation over the control mix for the experimented SCC mixes presented in Table 8 and Table 9. Early age(1 day) % drying shrinkage of GMK0 was decreased by 20% than drying shrinkage of FMK0 . When in subsequent FMK series SCC mixes where MK varied from 2.5% to 20%, SCC mix has resulted in marginal increase in drying shrinkage for all the periods i.e from 1day to 90days. .The % drying shrinkageat 1 day of FMK12.5 was 0.0476% and the same for FMK12.5 was 0.0142%over the control mix. In terms of reduced % drying shrinkage over control mix , MK's replacement from 2.5% to 20% performed well in mixes GMK2.5 to GMK20than in mixes FMK2.5 to FMK20 .It can be stated that in reduction of % drying shrinkage MK's performance in presence of GGBFS observed to be more than in presence of flyash.This can be attributed to fast reaction of MK in GMK series than in FMK series .

Table 8 % Shrinkage of FMK Series SCC Mixes

Sl.No	Mix ID	MK %	Shrinkage (%) compared to Standard Reference Bar of 30 cm length (-)					
			1 Day	3 Days	7 Days	28 Days	56 Days	90 Days
1	FMK0	0	0.0090	0.0110	0.0124	0.0152	0.0163	0.0166
2	FMK2.5	2.5	0.0104	0.0128	0.0136	0.0169	0.0172	0.0173
3	FMK5	5	0.0182	0.0219	0.0238	0.0247	0.0249	0.0254

4	FMK7.5	7.5	0.0264	0.0317	0.0372	0.0402	0.0408	0.412
5	FMK10	10	0.0362	0.0442	0.0448	0.0472	0.0477	0.482
6	FMK12.5	12.5	0.0476	0.0519	0.0571	0.0681	0.0689	0.0692
7	FMK15	15	0.0482	0.0616	0.0337	0.0424	0.0426	0.0431
8	FMK17.5	17.5	0.0486	0.0619	0.0339	0.0435	0.0439	0.0446
9	FMK20	20	0.0491	0.0622	0.346	0.0453	0.0441	0.0449

Table 9 % Shrinkage of GMK Series SCC Mixes

Sl.No	Mix ID	MK %	Shrinkage (%) compared to Standard Reference Bar of 30 cm length (-)					
			1 Day	3 Days	7 Days	28 Days	56 Days	90 Days
1	GMK0	0	0.0072	0.0079	0.0089	0.0091	0.0103	0.0108
2	GMK2.5	2.5	0.0087	0.0092	0.0098	0.0104	0.0112	0.0116
3	GMK5	5	0.0094	0.0098	0.0109	0.0134	0.0136	0.0139
4	GMK7.5	7.5	0.0104	0.0117	0.0189	0.0196	0.0204	0.0209
5	GMK10	10	0.0127	0.0139	0.0152	0.0169	0.0178	0.0181
6	GMK12.5	12.5	0.0142	0.0167	0.0185	0.0198	0.0206	0.0212
7	GMK15	15	0.0168	0.0206	0.0246	0.0268	0.0426	0.0432
8	GMK17.5	17.5	0.0172	0.0209	0.0262	0.0276	0.0442	0.0451
9	GMK20	20	0.0181	0.0216	0.0263	0.0281	0.0449	0.0465

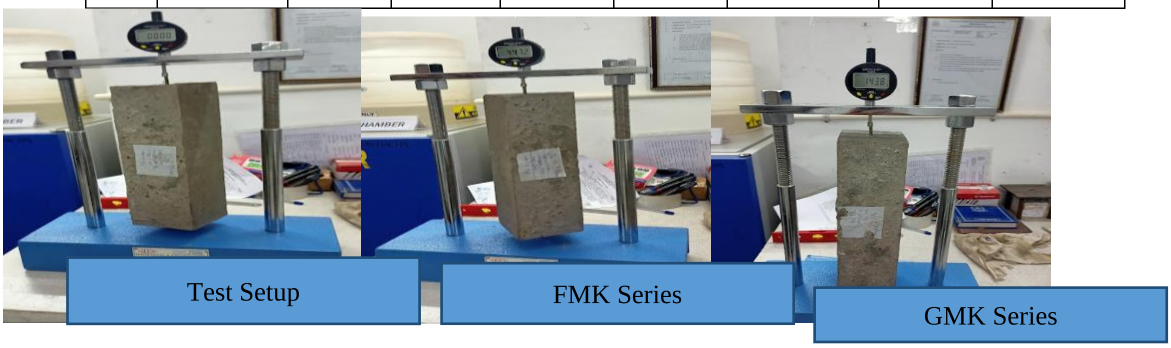

Fig.5 Shrinkage Test of SCC Mixes

5.2.4 Sorptivity

Sorptivity test of various SCC mixes experimented in this study are presented in Fig.6,Table 10 and Table 11.It can be seen thatin the of FMK series SCC mixes ,with the % increase of MK in the mix ,decrease of sorptivity(10^{-4} g/mm^2/min$^{1/2}$)observed. Sorptivitydecreased from 5.13% to 60.68% as compared to FMK0 when %MK varied from 2.5% to 12.5% i.e for the mixes FMK2.5 to FMK12.5.Whereas for similar variations of %MK in SCC of GMK series, decrease in sorptivity observed was from 14.05% to 70.25% . Thus higher decrease in sorptivity in SCC mixes of GMK series can be attributed to fast reaction of MK in company of GGBFS than the similar reaction of MK in company of Fly ash .This decrease in sorptivity was marginal when %MK increased beyond 12.5% in both the FMK and GMK series SCC mixes. The maximum replacement level of MK was observed to be 12.5% for achieving lower sorptivity values in both the FMK series and GMK series SCC mixes.

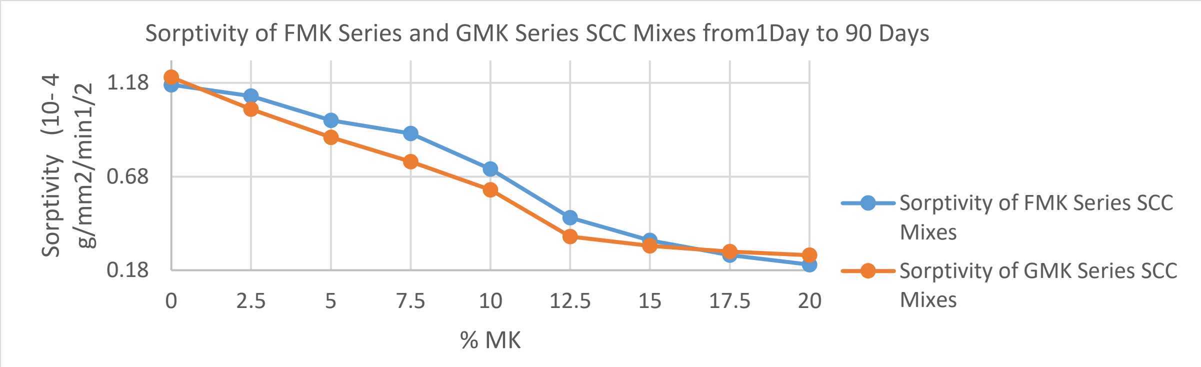

Fig.6 Sorptivity of FMK Series and GMK Series SCC Mixes from1Day to 90 Days

5.2.5 Temperature Gradient(Difference in Temperature from Core to near surface):

Thermocouples of PT100 with a temperature change sensing of 0.1^{0}C accuracy and Data logger CT716U was used in this study to capture the temperature history[44-48] of FMK and GMK series of SCC mixes. Mould size used for the study was 300mmx300mmx300mm.2No.s of PT 100 thermocouples securely fixed ,one at core area and other at near surface area ,were placed in each mould prior to placing the designated SCC. Polystyrene pads were placed in the moulds all around the moulds in order to insulate the mould and ensure no leakage of heat to surrounding environment. Temperature history was continually captured after the addition of water to cementitious mix from 30 minutes to 30 hrs duration. The temperature gradient,.i.e temperature difference between inner core and near surface of concrete, for the experimented FMK series and GMK series SCC mixes presented in Fig.7,Table 10 and Table 11.Early age(1 day) temperature increase in inner core of FMK0 was 48.2^{0}C whereas the same for GMK0 was 48.8^{0}C .When in subsequent FMK series SCC mixes with MK varying from 2.5% to 20%, the mix has resulted in increase in rise in temperature of inner core for all the periods i.e from 20 hours to 30 hours. The least temperature gradient observed at 26 hrs for mix FMK15 was 15.9^{0}C whereas the least temperature gradient observed at 26 hrs for GMK15 was 14.3^{0}C. It can also be observed that there was marginal increase in temperature gradient beyond 12.5% of MK in both FMK series as well as GMK series of SCC Mixes. MK's performance in presence of GGBFS observed to be superior than in presence of flyash interns of early rise in temperature and as a consequence for attaining higher early age strength by GMK series mixes as compared to FMK series SCC mixes.

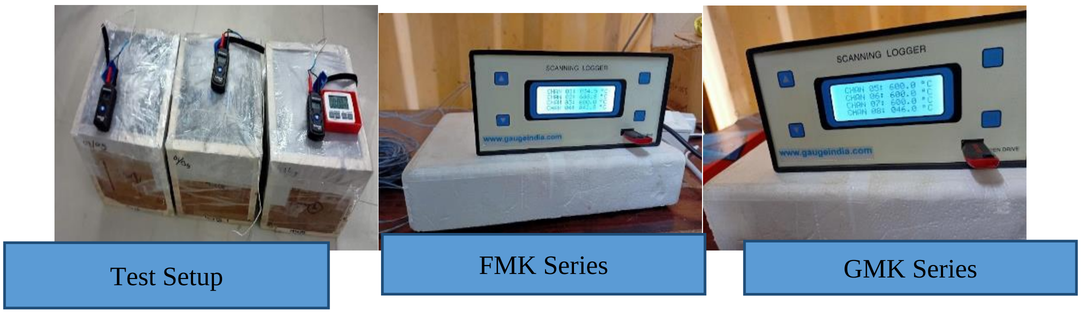

Fig.7 Temperature Gradient Test of SCC Mixes

Table 10 Durability Properties of FMK Series SCC Mixes

Sl.No	Mix ID	MK %	Maximum Core Temperature ^{0}C	Time for reaching Maximum core Temperature	Temp Gradient ^{0}C	Sorptivity (10^{-4} g/mm2/min$^{1/2}$)	Sulphate Resistance Length @ 1d/28d	Chloride resistance

				Hrs				
1	FMK0	0	46.6	29.8	20.8	1.17	1.21	0.96
2	FMK2.5	2.5	48.2	29.6	20.6	1.11	1.16	0.87
3	FMK5	5	49.6	26.8	19.8	0.98	1.12	0.81
4	FMK7.5	7.5	49.9	26.2	19.2	0.91	1.1	0.72
5	FMK10	10	50.6	24.6	18.4	0.72	1.06	0.61
6	FMK12.5	12.5	51.2	22.7	16.6	0.46	1.02	0.34
7	FMK15	15	51.8	22.1	15.9	0.34	1.01	0.31
8	FMK17.5	17.5	52.1	22.1	16.8	0.26	0.91	0.26
9	FMK20	20	52.6	22.4	17.2	0.21	0.82	0.22

Table 11
Durability Properties of GMK Series SCC Mixes

Sl.No	Mix ID	% MK	Maximum core Temperature ^{0}C	Time for reaching Maximum core Temperature Hrs	Temp Gradient ^{0}C	Sorptivity (10^{-4} g/mm2/min$^{1/2}$)	Sulphate Resistance Length @ 1d/28d	Chloride resistance
1	GMK0	0	47.6	29.1	19.8	1.21	1.16	0.82
2	GMK2.5	2.5	48.8	28.9	19.6	1.04	1.09	0.68
3	GMK5	5	49.7	26.2	18.9	0.89	1.06	0.51
4	GMK7.5	7.5	50.3	25.8	18.4	0.76	1.04	0.44
5	GMK10	10	50.6	24.1	17.1	0.61	1.01	0.37
6	GMK12.5	12.5	51.8	22.1	15.6	0.36	0.96	0.28
7	GMK15	15	51.9	21.8	14.3	0.31	0.92	0.26
8	GMK17.5	17.5	60.2	21.1	14.1	0.28	0.88	0.21
9	GMK20	20	60.8	20.6	13.9	0.26	0.82	0.16

5.2.6 Sulphate Resistance

As can be seen from the Table 10 and Table 11 that increase in sulphate resistance observed with the % increase of MK in the mix of FMK series.Sulphate resistance was increased from 4.13 % to 15.70% as compared to FMK0 when %MK varied from 2.5% to 12.5% i.e for the mixes FMK2.5 to FMK12.5.Whereas for similar variations of %MK in GMK series mixes the observed increase in sulphate resistance was from 6.03 % to 17.24%. Thus higher increase in sulphate resistance in SCC mixes of GMK series can be attributed to fast reaction of MK in company of GGBFS than the similar reaction of MK in company of Flyash.This increase in sulphate resistance was marginal when %MK increased beyond 12.5% in both the FMK and GMK series mixesThe maximum replacement level of MK was observed to be 12.5% for achieving increase in sulphate resistance in both the FMK series and GMK series SCC mixes.

5.2.7 Chloride Resistance

As can be seen from the Table 10 and Table 11 that increase observed in resistance to chlorideion penetration with the % increase of MK in the SCC mixesof FMK series. The resistance to chloride ion penetration was increased from 9.37 % to 64.58% as compared to FMK0 when %MK varied from 2.5% to 12.5% i.e for the mixes FMK2.5 to FMK12.5.Whereas for similar variations of %MK in SCC mixes of GMK series, observed increase in resistance to chloride ion penetration was from 17.07 % to 68.29%. Thus higher increase in chloride ion penetration in GMK series can be attributed to fast reaction of MK at early ages in company of GGBFS than the similar reaction of MK in company of Flyash .This increase in resistance to chloride ion penetration was marginal when %MK increased beyond 12.5% in both the FMK series and GMK series mixes. The maximum replacement level of MK was observed to be 12.5% for achieving increase in chloride ion penetration values both the FMK series and GMK series SCC mixes.

6.0 Conclusions

The following conclusions can be drawn from the conducted experimental study :

1) Fast reaction of MK in company of GGBFS was observed than the similar reaction of MK in company of Flyash.
2) Slump flow reduction was more when %MK increased beyond 12.5% in both the FMK series and GMK series mixes.
3) V funnel flow time increase was more when %MK increased beyond 10% in both the FMK series and GMK series mixes.
4) Decrease in the depth ratio in L box test was more when %MK increased beyond 10.0% in both the FMK series and GMK series mixes.
5) Decrease in the FST was more when %MK increased beyond 10% in both the mixes of FMK series and GMK series.
6) MK's performance in presence of GGBFS observed to be superior than in presence of flyash for attaining higher early age strength .
7) Increase in 1day age strength was marginal beyond 12.5% of MK in both FMK series and GMK series mixes..
8) Sorptivity decreased with the increase in % MK in both the FMK and GMK series mixes.
9) Resistance against chloride ion penetration and sulphate ion penetration was more in GMK series mixes compared to FMK series of mixes.

Conflicts of Interest

Authors declare that they have no conflicts of interest.

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