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Experimental Study on Ternary Blended Fast Setting High Early Strength Self Compacting Cement Mortars

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Abstract: *Concrete structures ages with time that repeatedly necessitates speedy and operative repair of deteriorated sections so as to improve the durability and put to reuse the concrete structures under repair at the earliest time. Supplementary cementitious materials(SCM)like metakaolin(MK)and nano sized alumina particles etc observed to be as prospective resources in developing formulations of cementitious matrix used for fast track durable repairs. Previous scholars contributed studies with an aim to formulate cementitious matrix for speedy repairs, instituting the effect of incorporation of many materials like calcium suplho-aluminate cements, magnesium phosphate cement, nano sized materials, mono fibres,hybrid combinations of various fibres etc.,into cementitious systems pointing to transmute some features of the repair materials. This paper presents the experimental analysis carried out on cementitious mortar prepared with OPC and various combinations of Metakaolin (MK), Ground Granulated Blast Furnace Slag (GGBFS),nano alumina(NA) and hybrid combinations of flexible Alkali Resistance(AR) glass fibres with an aim to develop fast track repair cement mortar matrix. Characteristics of Cementitious matrix-like flow(spread), flow time, setting time, chemical shrinkage, compressive strength at early ages like at 16hrs,1 day,3 day and 7 days age, bond strength, shrinkage, water absorption, porosity, sulphate resistance, temperature rise and abrasion resistance were analysed in order to arrive at a most favorable proportions (meeting the target values)for use in fast track repair of aged concrete structures.*

Keywords:
Ternary blend
Metakaolin
Hybrid fibres
Nano alumina

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I. Introduction

Cracking of concrete is a subject of foremost concern in infrastructure construction sector. Apart from the natural calamities effecting concrete service life, deterioration of concrete through corrosion, dissimilar shrinkage forms, freeze–thaw cycles, meagre workmanship, construction practices etc., effect the durability and there by lessens the service life of concrete [**1**]. Such decrease in concrete durability repeatedly necessitates speedy and operative repair of weakened sections [**2**]. Growing renovation, retrofit and repair costs of aged concrete structures is a matter of concern to all the stakeholders involved in infrastructure sectors of highly developed, developing and under-developed countries across the world[**3**]. Hence, approach of long-lasting and extraordinary performance of repair materials is particularly warranted for the sustainability of high traffic carrying different structure like bridges, pavements, toll plazas, parking bays, airport taxi ways,runways etc[**4**]. Thus prerequisites for an ideal repair material is to have free flowing for self compaction, exhibit fast setting, attain high strength at early ages in high traffic carrying congested structures[**1,5**], where repair/maintenance is mostly done during night time so that the structure/s can be reopened on the next morning peak hour i.e in less than 16 hours from the time of closure of the structure for warranted repair/maintenance[**6**].

Though extraordinary early age compressive strength is an requisite material characteristic for concrete repair, it furthermore effects an increase in the elastic modulus and brittleness of the material causing development of cracks [**7**].Repairs finished with conservative materials are prone to cracking(virtually half of routine concrete repairs fail owing to this practice) [**8**]. Adding to the untimely cracking of high early strength repair materials, cracks also originate due to autogenous shrinkage [**9**]. Variances in thermal gradients is one of the complicated issues for the robust repair materials[**10**]. Hence prime proposition of concrete repair material is essentially to improve compressive strength suitably at early ages[**11**], display sufficient flexural strength[**12,13**] and recompense for the development of cracks that are instigated owing to the properties of different shrinkage mechanisms [**14**].Also, high early strength concrete roots in decrease in ductility owing to improved paste maturity and its detrimental effects on the inter transition zone[**15**]. Adding to the above, improved early compressive strength might consequence in cracks that are triggered due to several types of shrinkage [**16**]. Over the years, several researchers focused their studies on fast-setting and high early strength concrete repair material proportions and published vital evidences on proportioning sustainable repair concrete/mortar matrix with various methodologies like partial replacement of OPC by moderate to high fineness SCMs such as Fly ash (FA), GGBFS, silica fume (SF)[**17**]. It is also well established that incorporation of hybrid combinations of flexible fibres in concrete or cement mortar significantly advances structural features, such as, flexural strength, impact strength, tensile strength, ductility and flexural toughness [**18**].By virtue of sustainable construction practices, scientific or conservational reasons, attention is shifting gradually towards the use of metakaolin[MK], an environmental-friendly material, in SCC [**19**]. As perceived by many earlier investigators, remarkable improvement of durability of hardened concrete mixtures achieved by incorporation of MK ,as mineral admixture, offers comprehensive opinions for the promising increase in future use of MK in SCC[**20**]. In the preceding studies on SCC incorporating GGBFS or MK, most of the researchers limited themselves to a less number of parameters [**11,20**]. The main attention was diverted in determining the properties of fresh mixtures and only few basic mechanical properties were measured in the hardened state[**11**]. Also there are less number of experimental investigations, carried out by past researchers , on shrinkage, water absorption ,sulphate resistance etc., properties of cementitious matrix prepared by use of combinations of SCMs like GGBFS ,MK etc[**21**] and use of various nano sized materials like nano silica(NS),nano alumina(NA), nano clays(NC) etc [**22**].Only few studies targeted the repair mortar matrix with rapid achievement of flowability combined with fast setting type besides high compressive strength and less shrinkage at early ages [**23-26**]. In this study, emphasis was placed on proportioning cementitious mortar matrix of fast setting, high early strength and self-compacting characteristics, which demonstrates features superior to other repair materials presently offered in the market. In this laboratory scale study, an experimental analysis was conducted for developing superior ternary blended cementitious mortar matrix as repair material and studying the performance of the same in fresh state and hardened state ,in early ages ,i.e from 16 Hrs to 7 days .Ternary blended cement mortar matrix was formulated with OPC and incorporating supplementary SCMs like MK, GGBFS,NA as part replacement of cement and with a fixed water to cementitious material ratio (w/cm) of 0.35 and 1.0% of PCE based high range water reducer as chemical admixture. Cementitious mortar matrix with different proportions of MK- ranging from 15 % to 30%, GGBFS- ranging from 20% to 30%, NA -ranging from 0.5 % to 2.0% and hybrid combinations 6mm and 12mm length AR flexible fibre- in combinations of different percentages ranging from 0.3% to 1.0%, were prepared and was analyzed in fresh state by slump flow, flow time ,chemical shrinkage, setting time and hardened ,at different periods of time from 16 hrs to 7 days, in terms of compressive strength, bond strength, shrinkage, water absorption, porosity , sulphate resistance , temperature rise and abrasion resistance.Tests results of the same presented and discussed in the subsequent sections.

1.1 Research significance

The scope and objectives of this experimental investigation was to formulate fast setting, early strength hybrid fibre reinforced self compacting cement mortar matrix prepared with OPC, GGBFS,MK,NA and hybrid flexible fibers in various combinations in order to achieve a targeted mini slump flow value of 200-250mm, mini 'V' funnel flow time of <8 seconds , final setting time of 4 hrs and 1 day compressive strength of 15-25 MPa[**27**]. Experimental investigations were carried out on the cementitious matrix in fresh state, mechanical properties on hardened state, in order to arrive at most favorable proportions (meeting the above set target values)for using the cement mortar matrix in repair of aged concrete structures. Thus, a comparative evaluation of the cement matrix was made based on the fresh state properties like flow(spread), flow time, setting time, chemical shrinkage, compressive strength at early ages like at 16hrs,1 day,3 day and 7 days, bond strength, shrinkage, water absorption , porosity , sulphate resistance, temperature rise and abrasion resistance. The experimental results are analyzed, discussed and accordingly conclusions, limitations and scope for further study presented.

II. Materials and mix proportions

2.1 Materials

The cement used in preparing mortar was OPC 53 Gr, confirming to IS 269:2015, having specific gravity 3.07 and Blaine's fineness 320m^2/kg, confirming to IS 269:2015, GGBFS having specific gravity 2.92 and Blaine's fineness 340m^2/kg, MK having specific gravity 2.26 ,Nano Alumina(NA) having specific gravity 3.82 ,P^H 8.43,purity 99.9%, PCE based chemical admixture and AR flexible fibres of 6mm and 12mm length, natural river sand, having Specific gravity 2.62 and water absorption 1.2% ,confirming to Zone-3 of IS

383:2016 .All the materials were procured locally. Characteristics of material used in this study is presented in Table 1.

Table 1-Material characterization

Compounds/ Property	MK	GGBFS
CaO	-	36.26
SiO_2	53.44	33.71
Al_2O_3	42.20	16.68
MgO	15.82	12.30
Fe_2O_3	1.19	0.59
LOI	1.46	1.87
IR	1.97	2.12
Chloride	0.074	0.004
MnO	3.28	4.38
Specification	IS16354 :2015	IS16714 :2018

2.2 Mix proportions

2.2.1 Flowable Hybrid Fibre Reinforced Mortar

Proportioning of control matrix with only OPC , in a fixed w/c ratio of 0.35 and PCE based chemical admixture in the ratio from 0.8% to 1.0% by weight of cement,was carried out in various ratios of cement and sand like 1:1,1:1.25,1:1.5,1:1.75 and 1:2 [**27-31**] . After several trials, the cement:sand ratio of 1:1.5 found to achieve the targeted criteria for flowable mortar. Hence keeping cementitious material(cm):sand in a ratio as 1:1.5, a total of thirteen cementitious mortar mixes were proportioned and were designated as Mx1 to Mx13 and divided into four categories i.e category 1 (i.e 100% OPC as control mix) with mix id Mx1; category2(50% OPC+ 50% in combinations of (MK+GGBFS)) with mix ids Mx2,Mx3,Mx4 andMx5; category3(50% OPC+ 48% to 49.5% in combinations of (MK+GGBFS)+0.5% to 2.0% of NA)) with mix ids Mx6,Mx7,Mx8 and Mx9; and category 4 (50% OPC+ 48% in combinations of (MK+GGBFS)+1.0% of NA+1% of AR Fibres in combinations of 6mm and 12mm)) with mix ids Mx10,Mx11,Mx12 and Mx13. Table-2 presents the mix proportions of cementitious matrix , prepared using cementitious material(cm) : sand in a ratio of 1:1.5 ,water/cm ratio of 0.35 , and other material proportions .The chemical admixture was of PCE based superplasticizer ,varied from 0.8% to 1.0 % by weight of cementitious material to maintain appropriate flowability for all the mortar matrix.

Table 2
Mix proportions of cementitious mortar mixes

*Cementitious Mortar Matrix ID	Description of the matrix 'Mix Category'	OPC	MK	GGBFS	NA	AR Fibre 6mm	AR Fibre 12mm
		%	%	%	%	%	%
Mx1	**Category 1**- Control Mix(OPC)	100	0	0	0	0	0
Mx2	**Category 2**- Cement(OPC) + Cementitious materials(MK+GGBFS)	50	15	35	0	0	0
Mx3		50	20	30	0	0	0
Mx4		50	25	25	0	0	0
Mx5		50	30	20	0	0	0
Mx6	**Category 3**- Cement(OPC) + Cementitious materials(MK+GGBFS)+ Nano Alumina	50	24	25.5	0.5	0	0
Mx7		50	24	25	1.0	0	0
Mx8		50	24	24.5	1.5	0	0
Mx9		50	24	24	2.0	0	0
Mx10	**Category 4**- Cement(OPC)+ Cementitious materials(MK+GGBFS)+ Nano Alumina+ AR Fibres	50	22.5	25.5	1	0.7	0.3
Mx11		50	22.5	25.5	1	0.6	0.4
Mx12		50	22.5	25.5	1	0.5	0.5
Mx13		50	22.5	25.5	1	0.3	0.7

***Cementitious material(Cm): Sand = 1:1.5 ,W/Cm =0.35 ,Chemical Admixture ranging from 0.8% to 1.0% of Cm**

All the samples intended for use in different tests were cured using a controlled temperature of 27 °C±2 °C in water tank. The flow test for mortar matrix was performed according to EFNARC guidelines [**32**]with a targeted mini slump flow spread of 200-250mm and mini 'V' funnel flow time of <8 seconds. Normal consistency of cementitious matrix was carried according to IS 4031 (P-4)[**33**]. Initial setting time and final setting time test for cementitious matrix was performed according to IS 4031 (P-5)[**34**].Three numbers of cube specimens, each having 50 cm^2 surface area ,were used for each age and for each type of mix to test the compressive strength at various ages (16 hrs,1d,3d,7d) according to IS 4031 Part 6 [**35**] , mixing of mortar matrix was carried out using laboratory scale mechanical mixer and moulding of specimens was carried out with the resulting self compacting mortar matrix i.e without any vibration. The cube specimens were left in the moulds for 12 h at 27 °C±2 °C and after demoulding the cube specimens were kept in curing tank at 27 °C±2 °C till the time of testing at different ages up to 7days . Table 3 presents the results of mini slump flow spread, mini 'V' funnel flow time , initial setting time and final setting time, compressive strength tests conducted at various age of cementitious matrix. The specimen preparation used to determine the shrinkage of different cementitious mortar matrix was done according to the sizes of moulds as given IS 4031 part 10[**36**] but the age of test was from 16hrs,1,3 and 7days[**37**].Results of flow(spread), flow time, setting time, chemical shrinkage, compressive strength at early ages of 16hrs,1 day,3 day and 7 days age, bond strength, shrinkage, water absorption , porosity , sulphate resistance, temperature rise and abrasion resistance are presented and discussed here under in subsequent sections.

Table 3
Fresh state properties of cementitious mortar matrix

*Cementitious Mortar Matrix	Description of the matrix	Normal Consistency	IST	FST	Mini Slump Cone Flow 'mm'	Mini 'V' Funnel flow time 'Sec'	Whether meeting Set Targeted Values (IST,FST,Flow and Flow time)
ID	**Mix Category**	**%**	**Minutes**	**Minutes**	**Mortar**	**Mortar**	
Mx1	**Category 1** Control Mix (OPC)	28.00	185	230	120	16.68	Control Mix (Reference)
Mx2	**Category 2** Cement(OPC)+ Cementitious materials(MK+GGBFS)	31.00	120	190	190	14.51	No
Mx3		31.50	120	185	210	12.87	No
Mx4		31.80	100	154	220	7.62	Yes
Mx5		38.60	100	129	220	7.58	Yes
Mx6	**Category 3** Cement(OPC)+ Cementitious materials(MK+GGBFS)+Nano Alumina	32.00	120	160	210	7.32	Yes
Mx7		32.50	120	140	220	7.94	Yes
Mx8		32.80	100	140	220	12.58	No
Mx9		32.90	100	130	185	21.47	No
Mx10	**Category 4** Cement(OPC) + Cementitious materials(MK+GGBFS)+ Nano Alumina+ AR Fibres	34.60	120	130	190	7.06	Yes
Mx11		35.10	120	150	200	7.82	Yes
Mx12		35.20	110	140	210	7.87	Yes
Mx13		35.80	110	140	160	16.94	No

*Based on the meeting criteria of targeted values, the cementitious matrix Mx1,Mx4,Mx5,Mx6,Mx7,Mx10,Mx11 and Mx12 are tested for compressive strength, slant shear bond strength, shrinkage, water absorption , porosity and sulphate resistance. Test results are analysed and discussed in subsequent paras.

III. Results and discussion

3.1 Flowability of cementitious matrix

SCM's incorporation, as part replacement of cement, in cementitious matrix significantly effects the flow and flow time of the mortar matrix compared to control mix (Mx1)prepared with OPC only. It can be seen from the Table 3 that, for mix category 2 ,with mix ids Mx3,Mx4 and Mx5, when 50% of cement is replaced by GGBFS and MK either in equal proportions of 25% each or 20% and 30% respectively-the flow of matrix was increased by 58.33 % to 83.33%.Also the mini 'V' funnel flow times reduced by 13.00 % to 54.55% ,this is due to the fact that SCM incorporation in cementitious matrix lessens the water demand for workable matrix and eases the mixed water to be available to most of the cementitious grains in the matrix and also by virtue of use of PCE based chemical admixtures with a proven reduction of water demand by 30% to 40 % [**38-42**] .It can also be seen from the Table 3 that for mix category 3,with mix ids Mx6 and Mx7,in addition to the combinations of GGBFS+MK, incorporation of NA, in the ratio of 0.5% to 1.0% of cementitious material , there is practically no change in the flow and flow time and outcome agrees with the earlier findings of similar studies[**7**] but in contrast , incorporation of NA from 1.5% to 2.0% ,flow time of the mortar matrix was significantly increased by 28.71%, due to higher dosage and agglomeration of tiny sized NA particles and incorporation of NA beyond 1.5% significantly increases the water demand owing to greater surface area of nano sized materials[**43-45**].Also to maintain the desired flow characteristics of matrix prepared with inclusion of NA, percentage of PCE admixture was increased from 0.8% to 1.0% by weight of cementitious material[**46-50**].The cementitious mortars flow and flow time significantly effected by the consequence of fibre incorporation beyond 1.0%, either in mono or in hybrid combinations [**47**].Hence in this study fibre incorporation is restricted to 1.0% ,this is in contrast with the polymer fibre dosage limit of maximum 0.6% for desirable flow [**29**]. It can also be seen from Table 3 that the inclusion of flexible fibres in cementitious matrix increases the flowtime by 1.5% which can be suitably compensated by slight modification of proportions.

3.2 Chemical Shrinkage of cementitious pastes

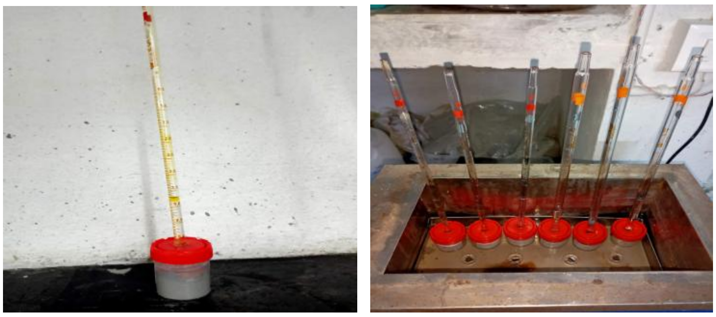
Chemical shrinkage(CS) of cementitious pastes was measured following the procedure as stated in ASTM C1608 [20]. Glass vials of 30 ml capacity were filled with approximately 20g of cementitious material paste prepared as per the proportions (pastes-falling in the mix category 1 to 3) mentioned in Table 2 and compacted by gentle tapping on a rubber mat for 10 s. Distilled water was gently discharged up to the top into the glass vial. A graduated pipette was hosted into a rubber cap of the glass vial and the assembly carefully sealed, recorded the weights to the nearest 0.0001 g and placed in a water bath at controlled temperature 27 ± 2^0C (Fig.1). The chemical shrinkage readings were recorded from 90 min after the contact of water and cementitious material in order to attain temperature equilibrium of assembly in the water bath. The chemical shrinkage is considered as the measured captivated water in 'ml' per gram of cementitious binder. Mass(M) of the cementitious material in the vial is given by:

$$M_{\text{Cementitious material}} = (M_{\text{Vial + Paste}} - M_{\text{empty Vial}})/(1+w/cm)$$

Chemical shrinkage(CS) in ml/g of cementitious material at any time 't' is calculated using the following formulae:

$$CS_{(t)} = (h_{(t)} - h_{(90min.)}) / M_{\text{Cementitious material}}$$

Where $h_{(t)}$= Water level in pipette at time 't' minutes , $h_{(90min.)}$ = Water level in pipette at time '90' minutes i.e initial water level reading in pipette .



(a) Initial -at 90 minutes (b) at 16 hours

Fig.1- Chemical shrinkage at 90 minutes to 16hrs

Chemical shrinkage ,from 16hrs to 168 hrs i.e 7 days, of prepared cementitious pastes of mix category 1 to 3 i.e Mix1 to Mix9 from is presented in Fig.2

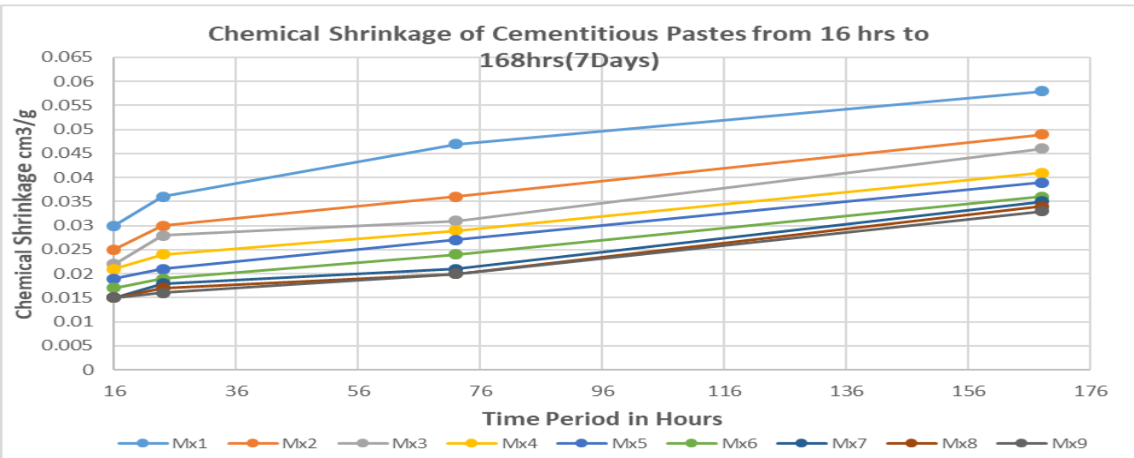


Fig.2

It can be seen from the Fig.2 that chemical shrinkage of control paste i.e mix category 1 with mix id Mx1,was maximum for all the time periods(16 hrs to 7 days) . For mix category 2 (Mx2 to Mx5) where MK,GGBFS added in various proportions to prepare cement mortar ,chemical shrinkage reduced considerably for the all the time periods due to densification of matrix. For mix category 3(Mx6 to Mx9) incorporation of nano sized alumina ,chemical shrinkage further reduced. This reduction is due to further densification of matrix.

3.3 Initial setting time (IST)and final setting time(FST) of cementitious pastes

Incorporation of GGBFS+MK as supplementary cementitious materials as part replacement of OPC in cementitious matrix significantly affected initial and final setting time of pastes compared to control mix prepared with OPC only. It can be seen from the Table 3 that, for mix category 2 ,with mix ids Mx3,Mx4 and Mx5 ,when 50% of cement is replaced by GGBFS and MK either in equal proportions of 25% each or 20% and 30% respectively , the initial setting time reduced by 35.13 % to 45.94% and the final setting time reduced by 17.39 % to 43.48%. Similarly as can be seen from the Table 3 that for mix category 3 ,with mix ids Mx6,Mx7,Mx8 and Mx9, incorporation of NA, in addition to the combinations of GGBFS+MK ,in the ratio of 0.5% to 2.0% there is practically no significant change in the initial setting time of paste but there observed significant change in the final setting times by the order of 30.43% at 0.5% NA to 43.48% at 2.0% NA. The reduction in final setting time may be due to the quick hydration reactions caused by tiny sized alumina particles[38].In contrast to the above observation, for mix category 3,with mix ids Mx10,Mx11,Mx12 and Mx13,in addition to GGBFS+MK+NA when flexible fibre in hybrid combinations of 1.0% is incorporated in the cementitious paste, the initial setting time reduced from 35.15 % to 40.14 .Less reduction in initial setting time over the control mix can be attributed to higher water demand of fibres , and owing to the size and shape of fibres, in producing the targeted flow of paste. However, with the above percentage inclusion of hybrid combinations of fibre- the final setting time observed to be reduced by 34.78 % to 43.48%.

3.4 Temperature Rise of cementitious matrix

Cementitious mortar, prepared as per the proportions presented in Table-1, placed in an insulated box having the size 400cmX400cmX400cm, sealed completely, to measure rise in temperature, which is an indirect indication of strength gain, by placing the 'K' type thermocouple into the cementitious mortar as shown in the Fig.3 .Temperature rise in various mortars as prepared above were monitored, after 30 minutes after the contact of water and cementitious material , from the period 16 Hrs to 7 days. Temperature rise in cementitious mortars are presented in Fig.4.

(a) Thermocouples (b) Mx1 at14.63 hrs (c) Mx2at 15.93hr (c) Mx3at 16.17hr

Fig.3

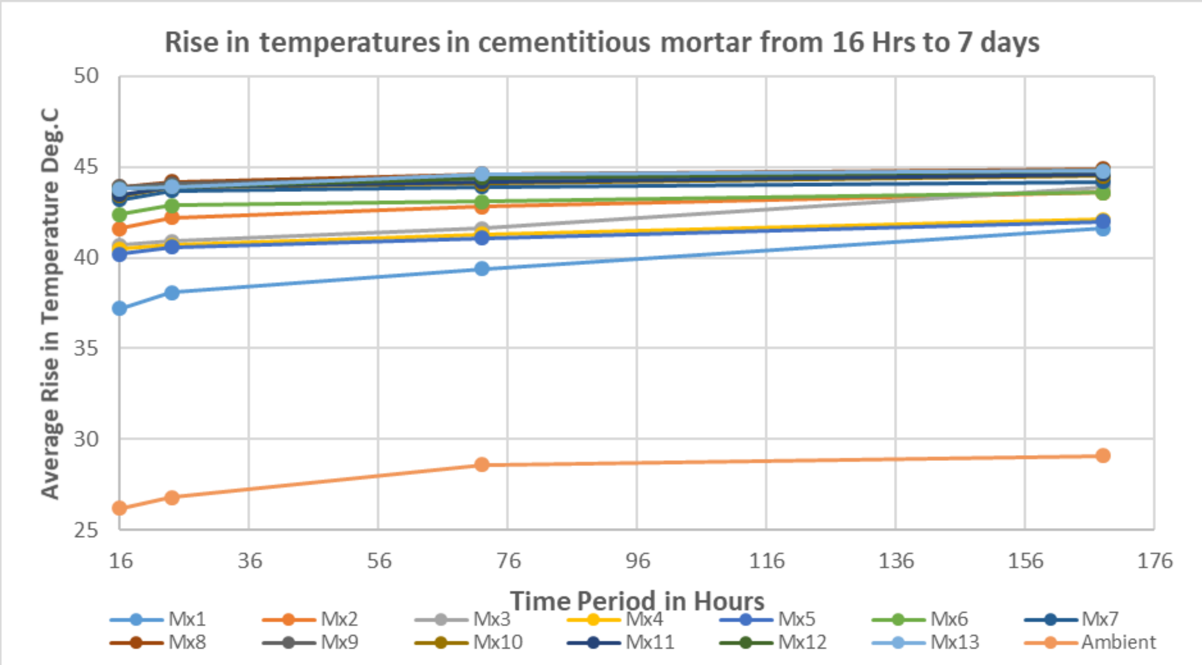


Fig.4

It can be seen from the Fig.4 that average rise in temperature of control mortar(Category 1-Mx1)is minimum for all the time periods(16 hrs to 7 days) . For mix category 2 (Mx2 to Mx5) where MK,GGBFS added in various proportions in cement mortar , average rise in temperature increased considerably in the initial ages of 16 hrs and 24 hrs indicating increase in reactions due to fineness of MK and GGBFS. For mix category 3(Mx6 to Mx9) incorporation of NA , average rise in temperature increased notably than mix category2 in the initial ages of 16hrs and 24 hrs. This sudden increase in temperature is due to fast reactions of NA and promoting early reactions. For mix category 4(Mx10 to Mx13) with the incorporation of fibres in various proportions average rise in temperature reduced marginally than the mix category3 in the initial ages of 16hrs and 24 hrs. This decrease in temperature may be due to fibre distribution effect causing somewhat slower reactions in the early ages.

3.5 Compressive strength of cementitious matrix

The results of the compressive strength for the different mortar mixes are presented in Table 4. It can be seen from Table 4 that for mix category 2, with mix ids Mx4 and Mx5 ,when 50% of cement is replaced by GGBFS and MK either in equal proportions of 25% each or 20% and 30% respectively the cube compressive strength increased gradually from 16.79 N/mm^{2}at 16 hrs age to 22.27 N/mm^{2}at 3 days age ie 32.64 % increase in compressive strength at 3 days over the compressive strength at 16 hrs age.Whereas increase in compressive strength at 7days age was 30.40% over the compressive strength at 3 days age. This is because of the slowing down in secondary hydration reactions of GGBFS+MK in the cement matrix in the later ages than 3 days. As can be seen from Table 4, for mix category 3, with mix ids Mx6 and Mx7, on combining the NA at 0.5% in the cement mortar,increase in compressive strength at 3days over the compressive strength of 16 hrs age was 44.18 %. While for the same mix the increase in compressive strength at 7days over the compressive strength at 3 days age was 24.43%. Higher percentage of increase in compressive strength at 3 days is due to the quick reactions caused by the NA particles in the cementitious matrix. In contrast to the above observation, for mix category 4, with mix ids Mx10,Mx11 and Mx12, in addition to GGBFS+MK+NA when flexible fibre, in hybrid combinations of 1.0%, is incorporated in the cementitious matrix the cube compressive strength increased gradually from 18.76 N/mm^{2}at 16 hrs age to 25.68 N/mm^2 at 3days age to 32.05 N/mm^{2}at 7 days age i.e 37.84 % increase in compressive strength at 3 days over compressive strength at 16 hrs age. Whereas for the same mix ,increase in compressive strength at 7 days age was 18.06 % over the compressive strength at 3 days age. Higher compressive strengths at early ages of 16hrs to 3days age can be attributed to improved microstructure and to the better bonding due to NA and hybrid fibre combinations.

Table 4
Compressive strength of cementitious mortar matrix from16 hrs to 7 days

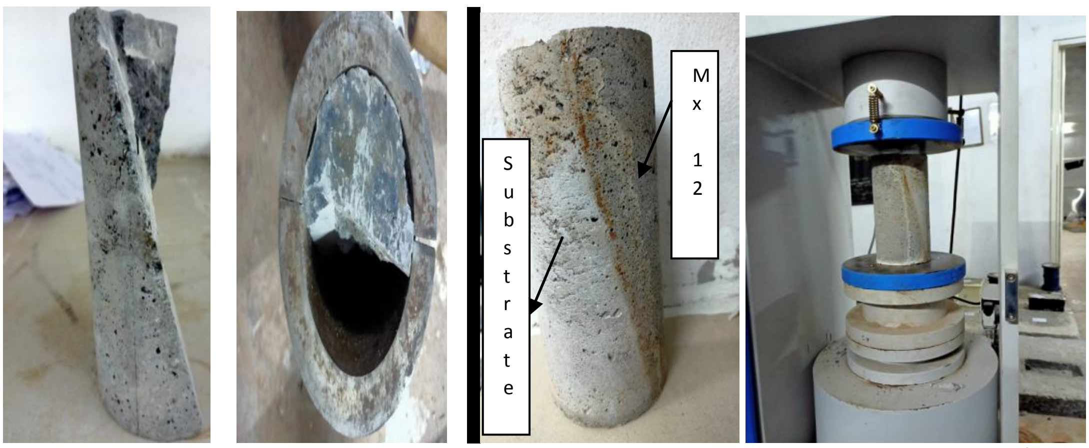
*Cementitious Mortar Matrix	Description of the matrix	Compressive Strength N/mm^2			
ID	**Mix Category**	**16 Hrs**	**1Day**	**3Days**	**7Days**
Mx1	**Category 1**-Control Mix(OPC)	6.24	8.5	14.82	25.49
Mx4	**Category 2** Cement(OPC)+ Cementitious materials(MK+GGBFS)	16.79	18.22	22.27	29.04
Mx5		16.81	18.74	22.65	29.57
Mx6	**Category 3** Cement(OPC)+ Cementitious materials(MK+GGBFS)+ Nano Alumina	16.86	19.29	24.31	30.25
Mx7		18.24	19.75	24.39	31.27
Mx10	**Category 4** Cement(OPC)+ Cementitious materials(MK+GGBFS)+ Nano Alumina+ AR Fibres	18.63	20.21	26.68	31.98
Mx11		18.76	20.84	25.86	32.05
Mx12		18.78	21.27	25.92	32.16

3.6 Bond strength of cementitious matrix with substrate concrete

Bond strength between prepared cementitious repair mortars and concrete substrate (C) tested as per the slant shear test following the provisions of ASTM C882. The samples used in the slant-shear test comprised of two splits of a cylindrical shape bonded at 30°.Substrate cylindrical concrete specimens is cut to rough surface having required area and placed into the 100mmx200mm diameter cylindrical mould and prepared combinations of repair mortar under study i.e category 1 to 4 ,with mix ids Mx1,Mx4,Mx5,Mx6,Mx7,Mx10,Mx11 and Mx12, is placed to get bonded with the substrate. After demolding and curing ,the composite specimens tested in axial compression at ages 16hrs,1 day,3 day and 7 days(Fig 4). The bond strength(Mpa) in the slant-shear test calculated using the below mentioned formulae:

$$\sigma_{\textbf{Bond strength}} = \{P/((\pi/4))Xd^2)\}XSin30^0$$

P= Load at failure in KN ; d=Diameter of cylinder in mm



(a) Substrate cut section (b) Substrate in the mould (c) Composite section (d) Slant shear test of composite

Fig 4 - Substrate and repair mortar slant shear bond strength test

Slant shear bond strength test results are presented in Fig.5.

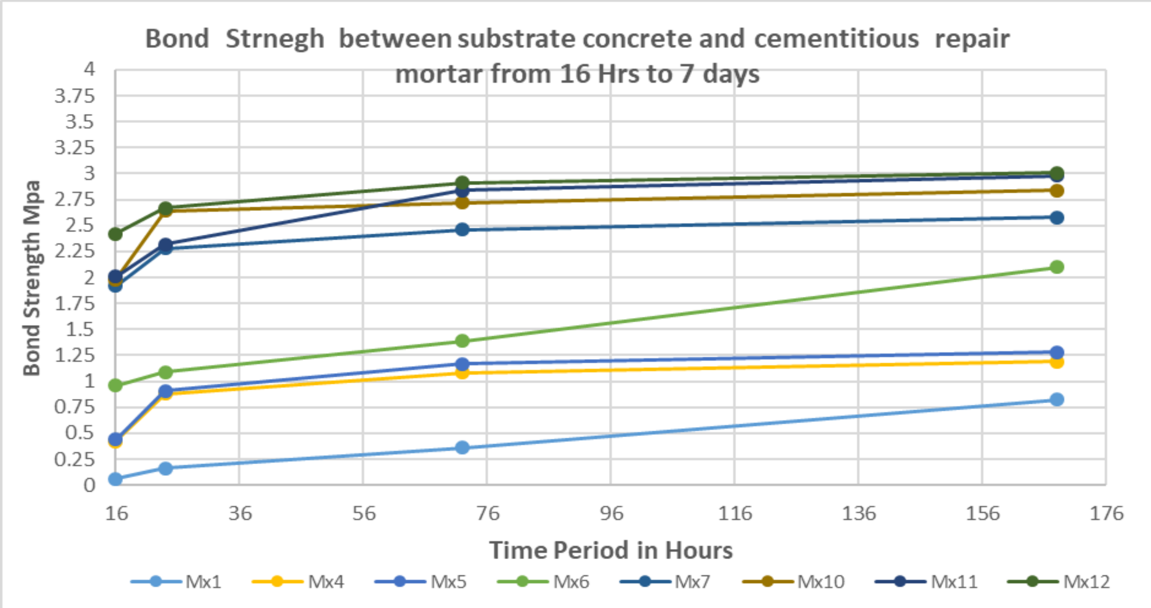


Fig.5

It can be seen from that for the Fig.5 for category 1 with mix id Mx1, bond strength between substrate concrete and control mortar is minimum for all the time periods(16 hrs to 7 days) . For mix category 2, with mix ids Mx4 and Mx5, where MK,GGBFS added in various proportions , bond strength increased for the all the time periods due to densification of matrix and improvement in the adhesion of mortar with substrate. For mix category 3,with ids Mx6 and Mx7, incorporation of NA ,bond strength further increased indicating early age reactions and thereby increase in the bond strength . For mix category 4,with mix ids Mx10 ,Mx11 and Mx12, incorporation of fibres in various proportions ,bond strength further increased indicating development in good adhesion with substrate at early age.Mx12 attained maximum adhesion and the bond strength range from 16hrs to 7 days is from 2.42 Mpa to 3.01 Mpa.

3.7 Shrinkage of cementitious matrix

The shrinkage results of cementitious matrix are presented in Table 5. The results indicates that for control mix ,mix id Mx1, the reduction in shrinkage from 1day age to 28 days of is 35.50 % .While for the mix of category 2, with mix id Mx4, when 50% of cement is replaced by GGBFS and MK in equal proportions of 25% each for the same over the same period ,reduction in shrinkage was 29.25%. For mix category 3 with mix id Mx7, where part replacement of cement done with MK by 24% and GGBFS by 25 % respectively, and 1% NA ,the reduction in shrinkage over the same period was 32.08%. In contrast to the above observation, for mix category 4, with mix id Mx10,Mx11 and Mx12, when hybrid combinations of flexible fibre is used with a total hybrid fibre combination of 1% , the reduction in shrinkage, over the same period of 1day to 28days , was significantly began to change from 24.32 % to 16.60%.

Table 5
Shrinkage, water absorption and porosity of cementitious mortar matrix

*Cementitious Mortar Matrix	Description of the matrix	Shrinkage %				Reduction in shrinkage (1 Day to 28 Days)	Water Absorption %	Porosity %	Change in length % (specimens exposed to sulphate solution)
ID	Mix Category	1 Day	3 Days	7 Days	28 Days	%	28 Days	28 Days	7 Days Vs 28 Days
Mx1	Category1	0.0109	0.0137	0.0134	0.0169	35.50	3.52	8.56	0.0462
Mx4	Category2	0.0179	0.0236	0.0241	0.0253	29.25	2.86	7.23	0.0417
Mx5		0.0271	0.0325	0.0384	0.0399	32.08	2.28	5.28	0.0398
Mx6	Category3	0.0329	0.0462	0.0476	0.0492	33.13	2.36	5.62	0.0320
Mx7		0.0462	0.0537	0.0564	0.0664	30.42	2.42	5.84	0.0294

Mx10	Category4	0.0501	0.0647	0.0672	0.0662	24.32	2.38	5.67	0.0288
Mx11		0.0301	0.0324	0.0381	0.0392	23.21	2.39	5.81	0.0221
Mx12		0.0427	0.0418	0.0524	0.0529	19.28	2.36	5.22	0.0205

3.8 Water Absorption of cementitious matrix

The water absorption ,conducted as per the provisions of ASTM C948, test results of cementitious matrix at 28 days of age is presented in Table 5. The results indicates that for mix category 4, with mix id Mx4, when 50% of cement is replaced by GGBFS and MK in equal proportions of 25% each, the reduction in water absorption was 18.75 % over control matrix. While for mix category 3,with mix id Mx7, when 1% NA is mixed in the cementitious mortar,the reduction in water absorption was 35.23 % .In contrast to the above observations for mix category 4, with mix ids Mx10,Mx11 and Mx12,when hybrid fibre is incorporated in the cementitious mortar ,the reduction in water absorption was from 32.38 to 32.95 % .

3.9 Porosity of cementitious matrix

The porosity ,conducted as per the provisions of ASTM C948,test results of cementitious matrix at 28 days of age is presented in Table 5. The results indicates that for mix category 4, with mix id Mx4, when 50% of cement is replaced by GGBFS and MK in equal proportions of 25% each, the reduction in porosity was 15.54 % over control matrix. While for mix category 3, with mix id Mx7, when 1% of NA is incorporated in the cementitious mortar ,the reduction in porosity was 38.32 % .In contrast to the above observations, for mix category 4, with mix ids Mx10,Mx11 and Mx12, when hybrid fibre is incorporated ,the reduction in porosity was 33.76% to 39.01%.

IV. Abrasion Resistance of cementitious matrix

Abrasive loss of cementitious mortars, prepared as per the proportions presented in Table-1, tested as per IS: 9284 (comparative wear resistance of surfaces) by judging abrasion loss subjected to abrasive charge. Mortar cube specimens of 100 mm was exposed to the impingement of air driven silica sand in pneumatic sand blast cabinet. Mortar surface was applied by abrasive force by 4000 grams of impingement at a pressure of 0.14 N/mm^2 ,which results in the loss of mass from the surface. Mass loss expressed as percentage loss, which is abrasion resistance, for that particulars surface. Surface of mortars after application of abrasive charge is presented in Fig.6.

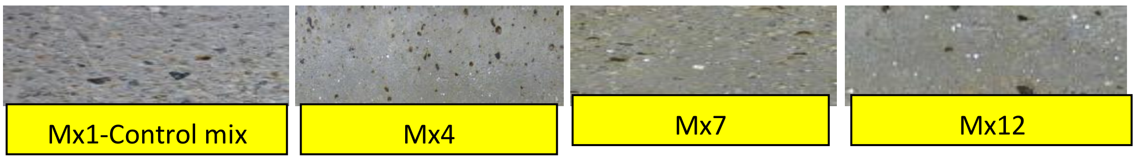


Fig.6

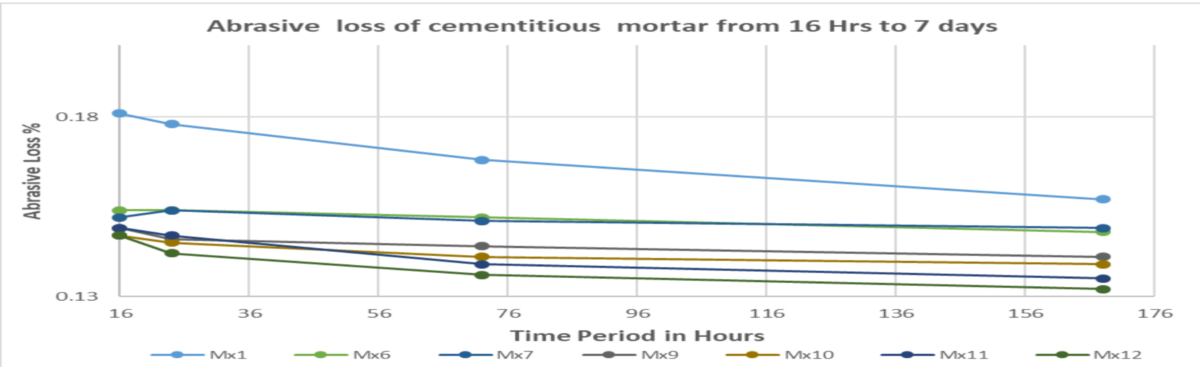


Fig.7

It can be seen from the Fig.7 that abrasive loss of control mortar i.e for category 1-with mix id Mx1, is maximum for all the time periods(16 hrs to 7 days) . For mix category 2 with mix ids Mx4 and Mx5, where MK,GGBFS added in various proportions , abrasive loss decreased for the all the time periods due to densification of matrix and improvement in the abrasion resistance. For mix category 3 ,with mix ids Mx6 and Mx7, with the incorporation of NA , abrasive loss further decreased indicating early age reactions and thereby increase in the abrasion resistance . For mix category 4 ,with mix ids Mx10 ,Mx11 and Mx12,with the incorporation of fibres in various proportions , abrasive loss further decreased indicating development in abrasion resistance at early age. Mx12 attained minimum abrasive loss and abrasion resistance ,from 16hrs to 7 days, and is in the range of 0.143 % to 0.131 % respectively. The lower abrasive loss may be due to the AR fiber's good adhesion with cementitious materials.

4.1 Sulphate resistance of cementitious matrix

Sulphate resistance test results of cementitious matrix at 28 days of age is presented in Table 5. Tests carried on the mortar bar specimens(similar dimensions as used in shrinkage test)after curing the same for 28 days completely immersed in 5% Na_2SO_4 solution. Length change readings noted after demoulding the specimens , before immersion, at 7^{th} day and at 28^{th} day. The results indicates that for mix category 2, with mix id Mx4, when 50% of cement is replaced by GGBFS and MK in equal proportions of 25% each, the reduction in sulphate resistance was 9.74 % over control matrix. While for mix category 3,with mix id Mx7, with the incorporation of 1% NA ,the reduction in sulphate resistance was 26.16%. In contrast to the above observations, for mix category 4, with mix ids Mx10,Mx11 and Mx12,on incorporation of hybrid fibre ,the reduction in sulphate resistance was 37.66% to 55.62% . Test results indicate a steady decrease in %length change of specimen from 7^{th} day of immersion to 28^{th} day of immersion due to the densification of microstructure not permitting sulphate ion penetration through the mortar matrix.

V. Conclusions

The experimental study on the cementitious material combinations of GGBFS+MK+NA reinforced with hybrid fibres reveals the following conclusions:

1. There is practically no change in the flow and flow time when 0.5% to 1.0% of NA is mixed in the cementitious mortar consisting of 49.0% to 49.5 % of GGBFS+MK and 50 % of OPC. But flow time of the cementitious mortar matrix significantly increased by 28.71 % when % of NA is increased by 1.5% to 2.0%.
2. Chemical shrinkage of cementitious pastes decreased when NA is incorporated at 0.5% to 2.0%.
3. Inclusion of hybrid flexible fibre in the cementitious pastes reduced final setting time by 34.78 % to 43.48% over the control mix. Hence fast setting mortar matrix can be prepared with combinations of OPC+GGBFS+MK+NA and Hybrid Fibre.
4. 32.64 % increase in compressive strength at 3 days over compressive strength at 16 hrs age was observed when 50% of cement is replaced by GGBFS and MK either in equal proportions of 25% each or 20% and 30% respectively.
5. Cementitious matrix M2 to M13 demonstrated increase in temperature in early ages from 16hrs to 72 hrs compared to control mix M1 indicating early reactions representing higher compressive strength and lower final setting times over control mix Mx1.
6. There was a gradual increase in the compressive strength of all cementitious matrix, as studied, over a period of time from 16 hrs to 7 days.
7. Incorporation of fibres and NA in small proportions of 1% in the cementitious matrix has demonstrated considerable improvement in mechanical properties.
8. Cementitious matrix prepared with 50% of OPC+ 25.5 % GGBFS +22.5% MK+ 1% of nano alumina and 1% AR flexible fibres (i.e hybrid-0.5% 6mm length and 0.5%12 mm length) appears to result in microstructure densification of the cementitious matrix over a period of time there by resulting reduction in water absorption , porosity ,abrasion resistance ,bond,sulphate resistance, which is an indirect result indicating improved durability of matrix.

Conflicts of Interest

Authors declare that they have no conflicts of interest.

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