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MICROFINE GOUND GRANULATED BLAST FURNACE SLAG FOR HIGH PERFORMANCE CONCRETE

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ABSTRACT

The addition of activated cementitious / pozzolanic materials in high performance concrete is gaining importance in Indian construction industry due to their beneficial effects in improving performance characteristics. In this work, granulated blast furnace slag is activated by mechanical grinding and air cyclone separator to have a defined microfine particle size distribution in the final product called as 'Microfine granulated Blast Furnace Slag'(MFGGBS).

A high performance fly ash based concrete (M60) with MFGGBS/ silica fume/ Metakaoline is taken for their relative performance characteristics both in fresh and hardened states. The results indicate that MFGGBS addition in concrete improves cohesiveness, workability and workability retention in fresh state. The long term strength and permeability characteristics are also favourable. To have accrued benefits with MFGGBS, mix proportion is redesigned and trials are carried out to establish MFGGBS as a preferred additive for high performance fly ash based concretes.

KEYWORDS

Microfine, strength, impermeability, rheology

INTRODUCTION

The two major concerns that the Indian cement and construction industry facing in recent times are- reduction of CO_2 foot print of a cement and achieving sustainability. One of the ways to reduce CO_2 foot print is to use optimum content of cement (ordinary Portland cement) and its maximum replacement by pozzolana and / or cementitious materials of industrial by-products. Field applications indicated that up to 30% and 70% cement replacement is possible by fly ash and ground granulated blast furnace slag (GGBS) respectively. There are equal advantages and disadvantages by this replacement. The main disadvantages noticed in field are- reduction in early strength, early shrinkage cracks, more water demand, stiff mix etc. Several new techniques are developed to over come these difficulties by activating hydraulic activity of pozzolana / cementitious materials like- alkali addition, thermal treatment, addition of special additives, size reduction etc [Zi Qiao Jin et.al., 2010, Wang Bao-min and Wang Li-ji,2004].

In the present study, activation of GGBS has been carried out by further grinding granulated blast furnace slag. Such activated slag is referred as microfine GGBS (MFGGBS). Advantages of MGGBS in high performance concrete are studied by several experts [Nakamura et al, 1992, Darren T Y Lim et al, 2011,].

For production of MFGGBS, the granulated slag with value added material is ground in a ball mill attached with high efficiency classifier, which classifies the material and ensures that only the required micro size particle enters the final product. The entire process is operated by automatic process controller. A stringent QA scheme ensures consistent quality of product with a limited coefficient variation < 3.

This paper reports on experimental investigations on fresh and hardened properties of high performance concrete with special mineral additives. The other microfines used for study are- silica fume (SF) and Metakaoline (MK) from commercial sources.

EXPERIMENTAL DETAILS

Materials Characteristics. The physical and chemical properties of fly ash (FA), MFGGBS, SF and MK along with ordinary Portland cement (OPC 53 grade) are presented in Table 1. All the tests are carried out as per the Indian standards unless otherwise specified. The particle size distribution and micrographs (at the same magnification) of microfines m are presented in Fig. 1 and 2.

Table 1. Physical, chemical properties and particle size distribution of Cement, FA, MFGGBS, SF and MK

Characteristic	OPC	FA	MFGGBS	SF	MK
Physical Properties					
Specific gravity	3.16	2.20	2.90	2.20	2.60
Lime reactivity MPa (IS: 1727)	-	5.48	13.50	8.50	2.20
Chemical properties					
CaO	62.2	2.24	31.5	1.35	0.68
SiO_2	18.3	62.97	26.8	89.60	62.97
Al_2O_3	6.8	26.88	21.9	0.85	26.88
Fe_2O_3	7.7	3.60	2.0	1.99	3.60
MgO	1.3	0.77	1.0	1.00	0.77
SO_3	2.3	0.40	3.0	0.05	-
Loss on Ignition	1.4	0.31	1.9	0.59	3.02
Particle size distribution					
d10	4 µm	4 µm	2 µm	5 µm	2 µm
d50	22 µm	18 µm	5 µm	139 µm	8 µm
d90	61 µm	158 µm	9µm	260 µm	35 µm

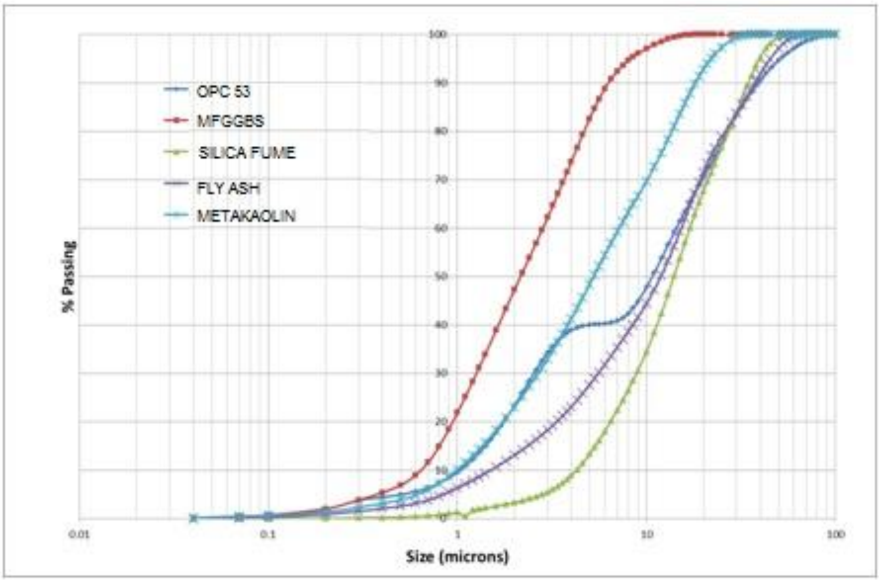
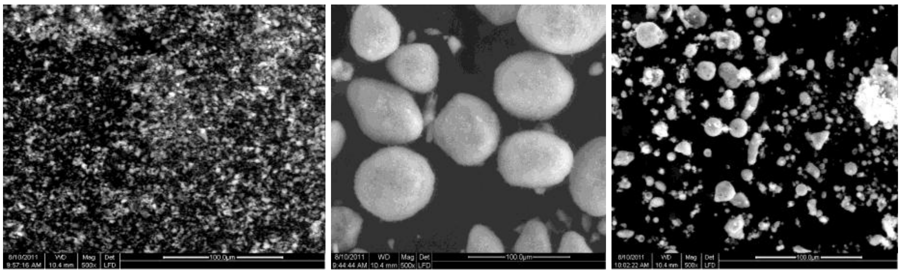


Fig.1 Particle size distribution of microfine mineral additives and OPC



MFGGBS SF MK

Fig 2. Microphotographs of microfine mineral additives at 100x magnification

It must be noted that the particle size data, and the microphotographs, for silica fume are based on the condensed form of silica fume.

The coarse (12 and 20 mm) and fine aggregates used are of granite and river sand (zone II) respectively available at Chennai. Results of bulk density, specific gravity and water absorption tests carried out as pr IS 2386 (Part III)-1963 and are presented in Table 2.

Mix Proportions

For the studies of the fresh and hardened properties, high strength concrete M60 is selected and accordingly mix proportions are developed through extensive trials and the test results reported in the Table 2. The following points may be noted with respect to the mixture proportions:

- The W/b is fixed based on the reference concrete; this W/b is maintained in all the mixes as 0.35 with the cement partially replaced with fine fly ash 25%.

- 10% of different microfine mineral additives are used.
- The super plasticizer dosage is fixed based on an initial slump in the range 170–200 mm; as far as possible, the SP dosage is maintained constant for the mixes with the same replacement levels of mineral additives. Glenium B233 chemical admixture is used. Final slump and flow is measured after 2 hrs.
- As the dosage of chemical admixture is fixed with all microfine materials, inevitably slump retention variation is observed. UFGGBS had slump retention for a longer period.
- Replacement is carried out on a mass basis, without the appropriate adjustments in the aggregate content, which was maintained constant for all concrete mixes; thus, the yield for different mixtures is expected to be slightly different.
- Thus, the proportions kept constant are: FA 25%, UFGGBS/SF/Mk 10%;water 149 kg/m^3;Fine aggregates 728 kg/m^3; Coarse aggregates (both20 & 12 mm) 546 kg/m^3; Chemical admixture 0.36 and 0.73% for cement concrete and concrete with mineral admixtures respectively..
- For all concretes, the workability after mixing and after 120 min of mixing is evaluated using slump and flow table tests. After 1 day, specimens were removed from the moulds and stored in a 100% RH room until the age of test. The compressive strengths were determined from 100 mm cubes as per IS 516 at the ages of 1, 3, 7, 28, and 56 days.
- OPC based concrete is taken as reference mix.
- The elastic modulus is tested in accordance with ASTM C469, using three extensometers, on 150 x 300 mm cylinder specimens at 28 days in a Controls Advantest servo controlled machine of 3 MN capacities.
- The workability, flow, compressive strengths at different ages (3, 7, 28 and 56 days), and modulus elasticity results of fly ash based concrete with different mineral additives along with ref.mix are presented in the Table 4.

Table 2. Mix proportions of reference mix and fly ash based concrete with different microfine mineral additives.

Concrete type	Cement Kg/m^3	Fly ash Kg/m^3	MFGGBS/ SF/MK Kg/m^3	Aggregate kg/m3 20 mm	Aggregate kg/m3 12 mm	Sand Kg/m^3	Water kg	W/ Binder
Ref. mix OPC	430	-	-	546	546	728	149	0.35
OPC+FA+MFGGBS/SF/MK	280	108	43	546	546	728	149	0.35

Durability studies

In the present study, durability characteristics are studied by carrying out two significant tests namely water absorption, sorptivity and RCPT and chloride diffusivity tests and results are presented in Tables 3 and 4 respectively.

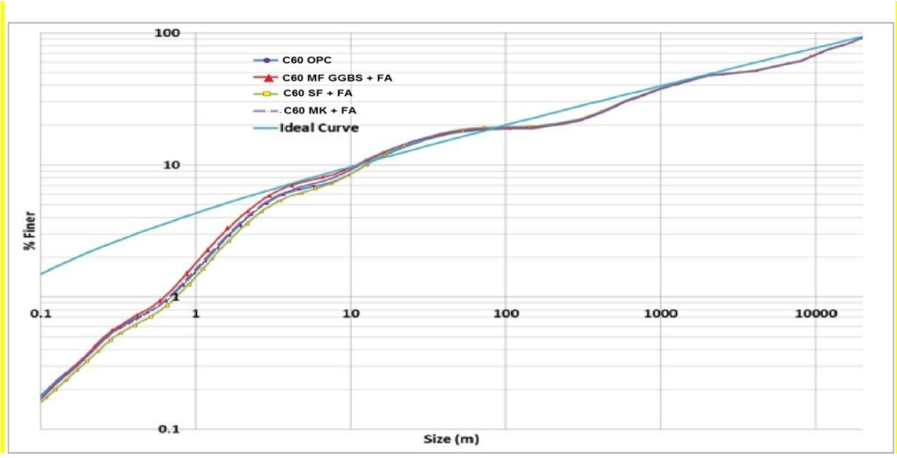
The water sorptivity studies are done as per ASTM C1585. The water absorption and sorptivity index were calculated as per the standard procedures.

The chloride ingression is tested by RCPT and Pond ‘tests as per ASTM C1202 and ASTM C1556 respectively.

Particle Packing

The particle packing software ‘EMMA’ (www.elkem.com) is used to compare the combined packing of granular ingredients of the mixes. The particle packing analysis as per the model for the mix is presented in Figure 2.

Fig 2: Particle packing curves for mixes of different mineral admixtures



RESULTS AND DISCUSSION

Effect of pozzolana materials and microfine GGBS on durability and mechanical properties of concrete were reviewed by several experts [Malhotra and Mehta, 1996, Swamy, 1999, Rajamane et.al, 2003, ACI.233R, 1995]. In the present study (Table 1), except MFGGBS, all other mineral additives are siliceous in nature and their secondary strength gain is due to pozzolana reaction. MFGGBS being calcareous and siliceous, has both cementitious and pozzolana reactivity respectively. This leads to more quantity of hydrated products and enhances strength and durability of concrete. It is also reported that the bondage between aggregates and cement paste at interfacial zone is further strengthened due to pozzolana reactivity [Swamy, 1999].

Table 3. Workability, compressive strength, Modulus of Elasticity, sorptivity, chloride diffusion of concrete mixes with different ultrafine additives

Concrete Type	Slump mm		Flow mm		Strength days MPa					Modulus of Elasticity GPa	Sorptivity Mm/√s	Water absorption (%)
	Initial	Final	Initial	Final At 2 hrs	1 d	3d	7 d	28 d	56 d			
Ref. concrete OPC	205	45	600	455	33.0	50.9	65.8	72.1	-	39	0.001898	1.67
OPC+FA+ MFGGBS (10%)	Collapse	220	Collapse	590	29.3	48.5	59.4	67.2	73.3	52	0.001691	1.96
OPC+ FA+ SF (10%)	210	45	510	380	34.6	57.8	60.1	63.9	71.8	51	0.001472	1.69
OPC+ FA+ MK (10%)	220	65	565	395	32.6	49.4	60.3	68.4	72.1	45	0.001084	1.32

Table 4. RCPT and chloride diffusion coefficient of concrete mixes with different ultrafine additives

Concrete mix	RCPT value coulombs	Classification as per ASTM 1202	Chloride apparent diffusion Co-efficient($x10^{-12}$ m^2/s	Resistance to chloride penetration
Ref .concrete OPC	2400	Moderate	9.11	High
OPC + FA + MFGGBS (10%)	440	Very Low	2.13	Extremely High
OPC + FA + SF (10%)	160	Very Low	1.86	Extremely High
OPC + FA + MK (10%)	320	Very Low	2.85	Very High

Recent studies on granulometry of cement and cementitious materials [Huiwen et.al,2004] indicated that not only fineness but also particle size distribution that influences the strength gain and packing efficiency and hence reduces permeability and increases strength of concrete. Particle range of microfine slag lies between 2 and 9 microns helps to fill in the gaps between cement hydrated particles or between cement and other fine pozzolana material. The use of different particle sizes below 45 microns improves particle packing of concrete. Particle packing plays crucial role in concrete and improves concrete performance characteristics like cohesiveness, compressive strength, im-permeability, resistance to aggressive chemicals and moisture ingression etc. Improvement in particle packing at macro level is achieved by following standard grading aggregates and at micro level by judiciously adding additive/s of different PSDs along with cement and other ingredients [Dordi and Vyasa Rao, 2011]. Use of ternary and quaternary cementitious systems in concrete satisfies all essential requirements for high performance including sustainability and economy [Mehta and Burrows, 2001] and possibly the future norm. Thus a combination of fine and microfine mineral additives (triple blends) i.e. fly ash of normal Blaine and microfine mineral additives like MFGGBS,SF and MK is preferred in the present study to establish their relative merits. In the present study (Fig 2), no clear cut differences are visible in particle packing between the mixes with different additives except MFGGBS gradation curve is closer to the ideal one. One of the reasons may be the percentage addition of particular fraction is relatively low. However, further studies between 0.1-10 microns are needed to have firm conclusions of particle packing effect. Based on limited data, it can be assumed that the performance characteristics would primarily depend on the reactivity of the mineral admixture, rather than on the particle packing when the size ranges are approximately the same.

Experiments showed that [Wang Ling et.al, 2004, Khayat et.al. 2008] blast furnace slag has both filling and dispersing effect and hence addition of MFGGBS had improved workability and workability retention than other mineral admixtures. Although MFGGBS particles are relatively angular to sub-angular (Fig.1), their smooth surface texture helps to improve flowability properties. Slump test results (Table 3) clearly indicates that slump and flow retention is more with MFGGBS. Laboratory trials also confirmed that a dosage of 0.05-0.1% chemical admixture can be reduced if MFGGBS is used. This distinct property of MFGGBS has made it preferred material than other mineral additives.

The trends of the compression test results indicate that the strength of the mix with MFGGBS continues to increase significantly even after 28 days, as in some other mineral additives (Table 3). Such long term strength gain is noticed in concretes with supplementary materials[Neville, 2009, Swamy, 2007].

To judge durability of concretes with different mineral additives, sorptivity and chloride ingression tests are conducted. Although there are no guidelines in use internationally to distinguish between good and bad concretes based on the sorptivity performance, several research studies have shown that concrete with w/c of 0.35 – 0.40 would have sorptivity values in the range 1–8 x 10^{-3} mm/ $s^{1/2}$. It is clear from the results (Table 3) that all sorptivity indices are within 2 x 10^{-3} mm/$s^{1/2}$ and is considerably very high in reference mix. The same trend is noticed in water absorption values. The low values of chloride diffusion less than 2. X 10^{-12} m^2/s indicates triple mix concretes have extremely high/ very high resistance to chloride penetration (Darren et.al, 2011). Rapid chloride test results indicate that reference mix is more prone to chloride permeability than triple mixes. This confirms that triple mixes are better choices for high performance concrete [Thomas and Shehata, 2000, Roland et.al, 2002, Mullick, 2007].

The distinct properties - high workability , long slump retention and gradual strength gain properties of MFGGBS has been used beneficially at field by modifying mix proportion of concrete originally designed. In the case study presented below mix proportion 'A' is the mix with other microfine. Mix 'B' is the modified mix for the same grade of concrete with MFGGBS. Test results clearly indicate that use of MFGGBS in high strength fly ash based concrete is highly economical.

Table 5. Cost benefit analysis of high strength concrete with MFGGBS/ SF

Mix Proportions	A	B	Cost per kg of material (Rs)	Cost of mix (Rs) A	Cost of mix (Rs) B
Grade	M-60	M-60			
Cement	395	350	6.5	2567.5	2275
Fly ash P 60	100	100	2.1	210	210
MFGGBS	--	15	17.5	---	262.5
Micro Silica	15	-	17.5	262.5	-
Crushed Sand	777	811	0.73	567.21	592.03
10 mm	585	599	0.63	368.55	377.37
20 mm	560	568	0.63	352.8	357.84
Water	150	146	0.80	120	116.8
Admixture PC	5.1	4.18	160	816	668.8
				5264.56*	4860.34**
Workability, Slump, mm					
0 mts	Collapse	Collapse			
30 mts	Collapse	180			
60 mts	170	150			
90 mts	150	140			
120 mts	100	130			
Compressive Strength, N/mm^2					
3 days	40.0	42.9			
7 days	52.9	55.4			
28 days	70.2	72.3			

* Equals to 9305.74 Japanese yen / 95.93 US$
** Equals to 8591.23 Japanese yen / 88.56 US$

CONCLUSIONS

Use of fine and microfine mineral additives in high performance concrete is a must to have improved characteristics both in fresh and hardened states. Microfine ground granulated blast furnace slag is the preferred material in fly ash based high strength concrete as it has three distinct advantages such as improving workability and its retention in fresh state and durability and high strength in hardened state.

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