



Fly Ash Selection and Mix Proportioning for Ambient Cured High Strength In-situ Cast Mono Component Geopolymer Concrete

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Abstract: Potential valorisation of fly ash powders is examined for scalable production of in-situ cast structural member with ambient cured alkali-activated geopolymer concrete. The critical issue of strength variation has been investigated by correlating with the physical and chemical properties of the original fly ash affecting water demand in mix proportion. A Class-F fly ash having fineness of 680 m²/kg Blaine's specific surface area (SSA) and a low w/b down to 0.16 showed the 28-day strength of 99 MPa. In contrast, medium sized (416-464 m²/kg) fly ash-based mono component concrete produced the strength between 40-47 MPa and that of the coarse (157-326 m²/kg) grade < 20 MPa in the 28-day test. Lower strength was observed in Class-C fly ash containing high proportion of quartz sand exhibiting higher water demand. Results of mix proportioning suggest a higher strength gain with 20-30% increase in fly ash over the minimum cement content specified in the mix design guidelines of IS 456 : 2000 while replacing 15-20% of coarse aggregates by fine aggregates. Unconfined flexural load applied on the three M40 reinforced concrete (RC) beams, viz. mono component, bi-component geopolymer and Portland pozzolana cement showed similar deflection up to 20 kN load.

Keywords: Fly ash, geopolymer, alkali activator, slag, strength, RC beam

1. Introduction

Fly ash (FA) based alkali-activated geopolymers offer a sustainable solution in constructions by cutting down greenhouse gas emission in Portland cement manufacture (Palomo, Grutzeck, & Blanco, 1999). Using this form of binder, products such as bricks, precast slabs and paver blocks are manufactured and adopted in road construction, pavement toppings and railway sleeper fabrication (Provis, 2018). However fly ash based geopolymer concrete (FGPC) still faces some technical and regulatory obstacles against large scale deployment despite improved durability (Provis, 2018). Consistency in strength of fly ash based geopolymer concrete (FGPC) is a key driver for the rapid introduction into commercial space as an economic alternative to Portland cement concrete (CC).

FA is inherently heterogeneous with varied chemical composition and structural components in the micro or nano scale from source. Our previous work showed that all FAs are not readily suitable for FGPC even with slag administration or by adopting mechanical activation (Goswami & Reddy 2017, Goswami, 2020). On the other hand GGBS forms an excellent geopolymer solid binder in alkali environment due to its easy activation (Shi & Day, 1999). Commercial prospect of FGPC is linked to GGBS addition in 65:35 ratio by mass of FA and referred here as bi-component. FGPC prepared from mono component i.e., using FA as sole resource binder material will however avoid long hauling of GGBS from far-off steel plant avoiding cost and saving energy. Most FGPC reported so far are heat-cured at elevated temperature

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in between 60-95°C. Strength gain was highest by curing at 60°C temperature (Huynh, Hwang, & Lin, 2017). Bakharev (2005) showed that increase in resting period prior to heat curing resulted in higher compressive strength particularly for Class-F (ASTM C618) based FGPC. However, prolonged heat curing raises the cost of FGPC and impedes the possibility of large-scale introduction in the field. Ambient cured mono component FGPC will be convenient to produce and scalable, however the associated problems of strength variation and/or prolonged setting time need to be resolved with economic mix proportion which is the objective of the present work.

Strength of FGPC is influenced by physical and chemical properties of reactive ingredients, H₂O/Na₂O ratio in the activator, water to geopolymer solid binder ratio (w/b) or liquid alkali activator to solid binder ratio (L:S) in the mix proportions. For an economic mix, the ratio of L/S and the amount of solid binder i.e., FA both are to be optimised for the target strength. Palomo et al. (1999) studied the geopolymerization of low-calcium Class F (ASTM C618) FA using four different L/S by mass of 0.25 to 0.30 and concluded that the elevated curing temperature is responsible for higher strength gain. Xu & van Deventer (2000) also reported that the proportion of alkaline solution to alumino-silicate powder by mass should be approximately 0.33 to allow the geopolymeric reactions to occur. Barbosa et al. (2000) found that mixture of high molar H₂O/Na₂O ratio beyond 10 reduces the strength.

Generally, a finer FA is expected to be more reactive due to larger area of contact with chemical reactant and hence can lead to faster geopolymerisation. Therefore, FA with relatively finer particle size or higher specific surface area (SSA) can result in high strength concrete with dense structure. The 28-day compressive strength of geopolymer mortar cured at 30°C improved from about 22 MPa to about 35 MPa by classifying original high calcium FA of about 200 µm size to 20 µm size (Chindaprasirt, Chareerat, Hatanaka, & Cao 2011). However, the strength improvement in a NaOH activated FGPC cured at elevated temperature is reported to be lower than 10% using finer part of 2.79 µm sized median particles (D₅₀) drawn from the as-received coarse FA of 36.20 µm sized D₅₀ by mechanical classification of a Class-F FA (Kumar, Kumar, Alex, Bandopadhyay, & Mehotra, 2007). A very high strength (> 80 MPa) is reported by administering optimum GGBS and ultrafine (UF) low calcium FA of 3.4 µm of D₅₀ in ambient curing although no improvement was seen by blending the original Class-F Australian FA with UF part in 50:50 ratio (Khan, Shaikh, Hao, & Hao, 2016). The effect of finer particle size in monocomponent FGPC prepared from as-received FA is rarely reported particularly in ambient curing condition.

Pietersen & Bijen (1991) reported that FA reactivity is proportional to glass content. The chemistry of glassy phase in FA and its dissolution kinetics in alkaline medium is known to play a profound role in strength gain (Fernández-Jime'nez, Palomo, & Criado, 2005). The effect of glass content on the present FGPC will be evaluated here while effect of chemistry in the geopolymer and effect of size reduction of FA by mechanical activation have been reported elsewhere (Goswami, 2000).

Amidst various claims of superior strength, FGPC prepared following mix design guidelines of IS 10262:2009 show a far lower 28-day strength in the vicinity of 23-33 MPa for oven cured geopolymers (Anuradha, Sreevidya, Venkatasubramani, & Rangan, 2012). In the present study, granulometry has been analysed in detail with a view to determine the influence on L/S or w/b and strength gain therein. Furthermore, the mechanical performance of the reinforced concrete (RC) beam of mono component FGPC is compared with bi-component FGPC and Portland pozzolana cement (PCC) concrete beams in load-deflection study.

Table 1 - Typical chemical analysis of various binders used for synthesis of geopolymer

Constituents (%)*	NLC-II Coarse	NLC-III Medium	RTPS Medium/1	RTPS Medium/3	YTPS D-Pass	Mettur Fine	Mettur Medium	Koradi Medium	Koradi Pond ash	GGBS JSW
SiO ₂	54.26	48.73	61.68	62.09	59.80	57.39	58.91	61.25	62.97	37.63
Al ₂ O ₃	28.44	26.78	27.36	27.97	29.77	31.39	29.98	27.95	28.41	14.38
Fe ₂ O ₃	2.04	3.03	4.45	3.63	4.50	4.80	5.09	4.68	4.47	1.11
CaO	10.99	14.56	2.35	2.14	2.03	1.54	1.49	1.91	0.87	37.21
MgO	1.71	2.42	0.69	0.93	0.77	0.81	0.90	0.91	0.54	8.65
K ₂ O	0.04	0.02	0.84	1.00	1.02	1.10	1.03	1.02	0.84	0.55
Na ₂ O	0.24	0.37	0.80	0.29	0.16	0.29	0.31	0.28	0.06	0.23
SO ₃	0.53	2.70	0.00	0.07	0.02	0.22	0.07	0.09	0.00	0.38
P ₂ O ₅	0.11	0.14	0.22	0.30	0.37	0.58	0.45	0.27	0.25	-
TiO ₂	1.54	1.12	1.49	1.39	1.53	1.69	1.65	1.56	1.60	-
Cl	0.005	0.005	0.004	0.007	0.004	0.023	0.006	0.006	0.005	-
Total	99.89	99.88	99.90	99.82	99.97	99.83	99.89	99.92	100.01	100.14
Carbon**	0.70	1.69	2.02	0.07	nd	1.74	nd	0.05	1.66	nd

Moisture loss***	0.16	0.52	0.21	0.13	0.05	0.32	0.19	0.15	12.5	0.11
Insoluble residue	64.89	42.6	91.63	-	88.44	-	-	-	90.3	10.9

*on loss free basis at 1000°C, **loss at 600°C, ***110°C, 1 hour, nd – not detected

2. Materials Used

FA sample is collected from seven major thermal power plants in India located at Neyveli, Raichur, Yeramur, Mettur, Koradi, Sipat and Vindhyachal for this study. FA powders were drawn from a storage silo of a 210 MW thermal power plant in NLCIL (TPS-II) at different period to represent possible variations at source. NLCIL uses lignite from their nearby mines in and around Neyveli, Tamil Nadu, India. Rest of the FA powders are generated from coal. FA samples were collected at various locations of 800 MW super-critical thermal power stations at Yermarus (YTPS) and a specimen collected from the point nearest to the chimney, D-pass is selected for the purpose of reporting here. FA is usually received in moisture-free condition but rarely shows moisture up to ~2% which is dried at 110°C before usage. Koradi 'pond ash' is received with moisture content of 12.5% but dried in the laboratory. GGBS is collected from local outlets of JSW Cement.

2.1 Characterization of Fly Ash and GGBS

Physical and chemical properties of as-received FAs were thoroughly characterized. Bulk chemical composition is determined by X-ray fluorescence instrument (EDSXRf, Bruker AXA, S2 Ranger). Insoluble residue is determined by dissolving FA in acid medium and subsequently in alkali as per IS 4032-1985. Table 1 shows that the chemical composition of FAs with respective variations in SiO₂, Al₂O₃, CaO, MgO content. Al₂O₃ is the highest in Mettur FAs and lowest in NLC-III. NLC FAs are classified as Class-C due to higher CaO varying in the range of 10.99-14.56 wt%. Rest all belong to the category of ASTM C618 Class-F, defined as having (SiO₂ + Al₂O₃ + Fe₂O₃) ≥ 70 wt% while CaO is found to be in the range of 0.87-2.35 wt%. GGBS on the other hand contains CaO as high as 37.21 wt% with SiO₂ as low as 37.63 wt%.

Table 2 - Physical properties of the solid binders used for geopolymer synthesis

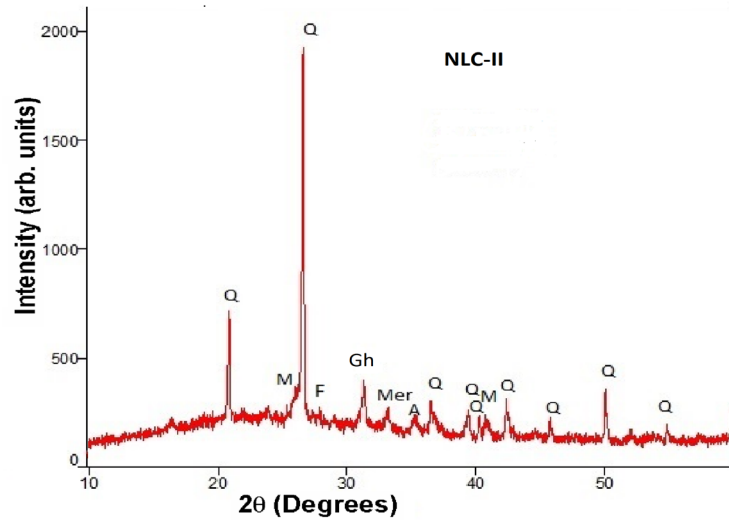
Property	NLC-II Coarse	NLC-III Medium	RTPS Medium/1	RTPS Medium/3	YTPS D-Pass	Mettur Fine	Mettur Medium	Koradi, Pond ash	JSW GGBS
Specific Gravity	2.59	2.58	2.11	2.15	2.32	2.21	2.13	2.06	2.86
Blaine's SSA, m ² /kg	157	431	416	489	680	594	464	326	371
Residue over 45 μm, %	57.75	34.22	41.83	26.18	2.54	9.61	28.36	45.54	nil
Tap density, kg/m ³	-	1000	1240	1280	1240	1040	1150	1040	1450
Glass content, %	37.20	41.98	-	33.15	37.92	38.41	37.30	34.13	94 (Q-XRD)

Specific surface area (SSA) was measured using Blaine's apparatus and specific gravity was evaluated by Le Chatelier flask. Table 2 shows that specific gravity of FA varied significantly between NLC and Raichur in the range of 2.10-2.59. NLC-II FA shows lowest Blaine's SSA although fineness in the two NLC FAs varied widely in the range of 157-431 m²/kg of SSA as the specimens were collected at different time interval from the same thermal power plant. Highest fineness of 680 m²/kg is observed in the YTPS FA collected from D-Pass near chimney. Two samples received from Mettur also have different fineness (594 m²/kg and 464 m²/kg). Raichur (RTPS) FA specimens showed SSA in the range of 416-489 m²/kg. For the purpose of discussions here we have called SSA between 400-500 m²/kg as 'medium', SSA above 550 m²/kg as 'fine' and less than 350 m²/kg as 'coarse'. Behaviour of Koradi FA is similar to a relatively finer variety of Raichur called as medium/3 (RTPS M3), hence not included. However pond ash from Koradi is reported here to show the variations in the ultimate strength. Vindhyachal and Sipat FAs fall into the category of 'coarse' hence not included. Tap density is calculated by dividing the mass of dry FA with the volume occupied in a plastic graduated cylinder after gentle tapping for 2 minutes.

Glass content of FA powders are determined by reacting with 1% HF solution as described by previous authors [16]. Glass content in these FAs is found to be varying in the band of 33.15-41.98% by HF treatment. GGBS shows higher

glass content in the order of 94% with lowest insoluble residue in the series (Table 1 and 2). Scanning electron microscopy (SEM) was conducted using FEI, Nano Nova 450. X-ray powder diffraction (XRD) in selected FA and geopolymers using Bruker, D8 Discover instrument in steps of 0.022 degree/s with the set parameters of voltage at 40 kV, current at 30 mA, antiscatter of 0.5°.

(a)



(b)

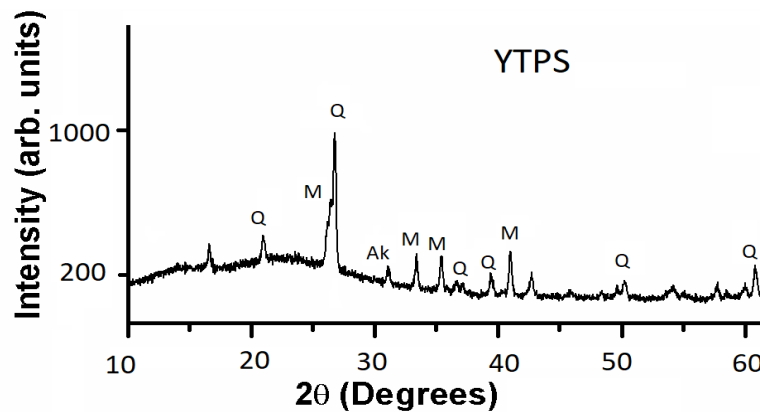


Fig. 1 - XRD pattern of fly ashes (a) NLC-II coarse; Class-C; (b) D-pass Yermarus TPS Fine, Class-F, Q- quartz, M- mullite, Gh- gehlenite, F- feldspar, Ak- akermanite, Mer- merwinite, A- alumina

Typical XRD patterns of FA in Figures 1 (a) and (b) show that quartz is the dominant crystalline phase present in FA typically. A comparison of relative intensities at 26.6° 2θ shows that D-Pass YTPS has the lowest quartz content while the mullite phase is significantly higher. SEM image in Fig. 2 (a) shows that particles in NLC-II FA are coarse as compared to that of the NLC-III in Fig. 2(b) which has more of finer particles and agglomerates. Coarse sand particles with sharp edges are found to be distributed in the matrix of glassy spheres or cusps.

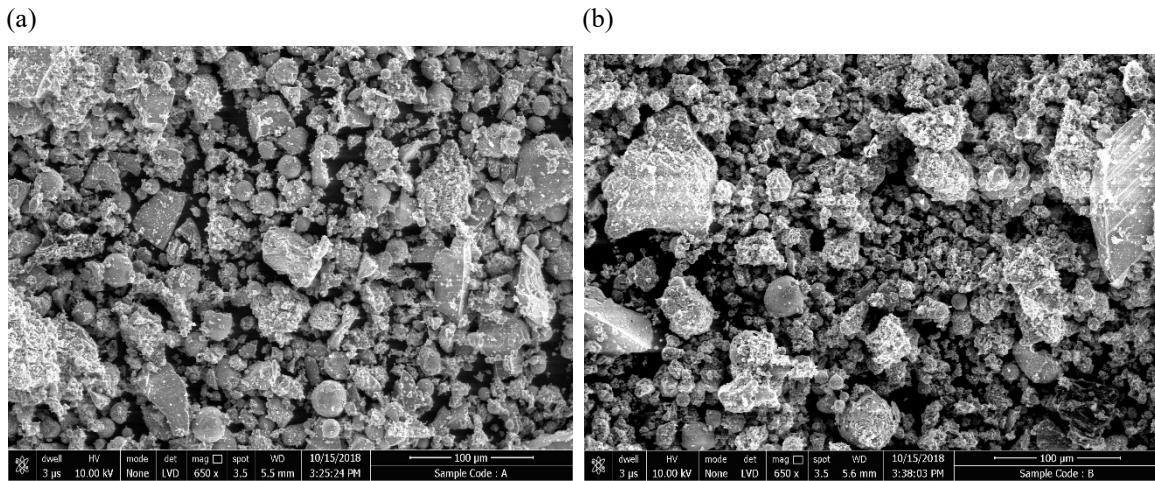


Fig. 2 - SEM images of original fly ashes from NLCIL showing round shaped fly ash particles in coarse sized NLC-II, (a) and medium sized agglomerated NLC-III; (b) powders with large irregular sized sand particles

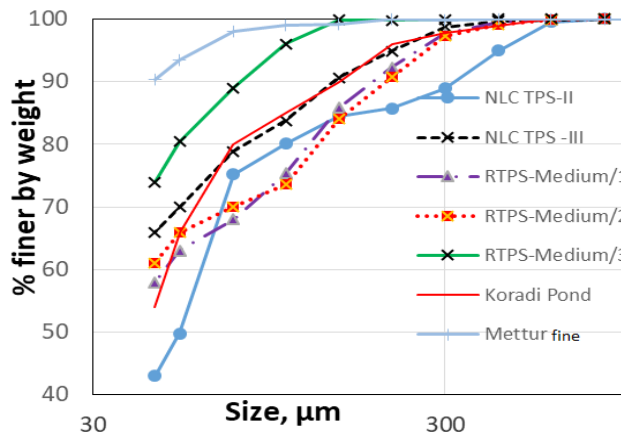


Fig. 3 - Sieve analysis of original fly ash powders from four major thermal power plants in India at Neyveli, Raichur, Koradi and Mettur

Dry sieve analysis was performed on as-received powders using a set of sieves in the size range of 1700 – 75 µm while wet sieve analysis was conducted in the finer range of 53-45 µm. Sieve analysis results have been plotted in Fig. 3 showing cumulative % finer by mass against size in semi-log scale for comparison. It shows that FA powders have dissimilar size distribution, more particularly in the finer fraction of less than 53 µm size. NLC-II FA is a coarse sized powder considering all the sources with retention over 45 µm as high as 57.75% in comparison to 9.61% of Mettur fine FA and 2.54% in D-Pass YTPS (Table 2). The size variation among the RTPS FA powders is also wide with 45 µm retention varying between 26.18-41.83%. In NLC-II FA, the specific gravity of the fraction higher than 150 µm size is 2.59 while it is found to be 2.52 in the size fraction of finer than 53 µm. The coarser fraction (>150 µm) of 14.2 % appears to be quartz sand due to matching density and is more clearly understood from the block shape with sharp edges seen in the SEM images of fig. 2.

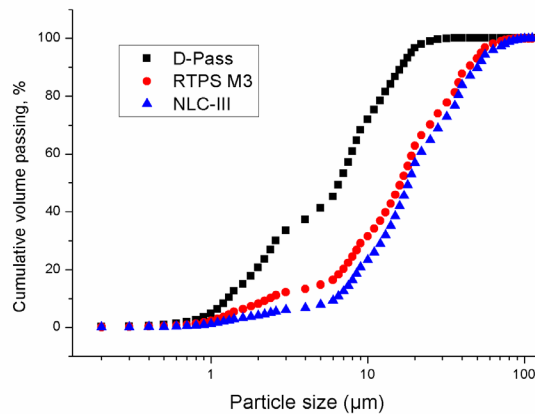


Fig. 4 - Cilas particle size distribution showing differences between medium and fine sized fly ash powders (Medium: RTPS medium/3 and NLC-III, Fine: YTPS D-Pass)

Furthermore, a complete particle size distribution analysis is conducted by laser diffraction method using a Cilas 990 instrument which gave the distribution up to the range of 0.1 µm for selected FA. Cilas particle size distribution by laser diffraction method shows wide variation in the particle size distribution by volume fraction between medium and fine sized FAs as seen in Fig. 4. D-pass YTPS has the lowest D50 size of 4.5 µm in the series with 71.93% finer less than 10 µm sized. In contrast D50 value is as high as 38.42 µm in the coarse NLC-II and 20.34 µm in RTPS medium/2. RTPS medium/2 FA has 66% finer than 53 µm in sieve analysis but 29.33% finer than 10 µm. Correspondingly in coarse NLC-II FA with 50% finer than 53 µm shows only 9.55% finer sized than 10 µm. It shows that gap widens in finer range i.e., RTPS FA has more of finer particle size in the finer range of below 10 µm than that of the NLC-II. Considering the entire series, most significant variation is seen in the vicinity of 10 µm which is between 9.5-71.9%. D50 falls in the range of 15-20 µm for medium sized FA with finer than 10µm size of 23-32%. GGBS is another fine material with D50 of 4.81 µm and 71.35% less than 10 µm sized particles similar to D-pass YTPS. GGBS also has a sizable proportion of submicron sized particles of 18.39 % to account for its high reactivity in addition to low insoluble residue (Table 1).

2.2 Aggregates

Aggregates normally used for ordinary Portland cement concrete is also used for geopolymer concrete manufacture. Coarse aggregate is crushed angular of 20 mm maximum nominal size with flakiness index of 8.6% tested as per IS 2386 Part I. Fine aggregate used is conforming to grading Zone II of Table 4 of IS 383. River sand clean from mud, silt and organic constituents is used as fine aggregate and graded hard granite jelly obtained from local crusher is used as coarse aggregate. The fineness modulus and specific gravity of fine aggregate are 2.66 and 2.59 respectively as whereas it is 7.26 and 2.62 for coarse aggregate. Test data on aggregates are presented in Table 3 following the test procedure given in IS 2388 Part III. Packing density of fine aggregate was found to be 1640 kg/m³ by gently tapping a known volume of dry river sand in a graduated measuring cylinder. Coarse aggregates were made wet by sprinkling water (2%) on it which helps to avoid absorption of water from alkaline solution and compensate internal water absorption capacity determined previously.

Table 3 - Test data on aggregates

	Specific gravity	Water absorption, %	Surface moisture, %	Fineness modulus
Fine aggregate	2.59	nil	0.1	2.66
Coarse aggregate	2.62	1.8	0	7.26

2.3 Preparation of Alkaline Activator (L):

- A. Sodium silicate: Sodium silicate solution is obtained from commercial source (National Industries, Karnataka). The chemical composition of the sodium silicate solution was Na₂O=12.6%, SiO₂=25.5%, water 39.42% by mass, specific gravity = 1.513 and appearance is colourless.

- B. Sodium hydroxide solution: Sodium hydroxide pellets are taken from commercial grade (98% purity) and dissolved in distilled water. Volume is made up as required for 8 and 16 molar concentrations. Sodium hydroxide solutions were prepared 12 hours prior to use.

Using two different molarity, 8M and 16M NaOH, alkali activator solutions were prepared by mixing sodium hydroxide solution with sodium silicate liquid at the room temperature ($\sim 28^\circ\text{C}$) in the weight ratio of 1:2.5 following the procedure laid down in the literature [15]. After mixing the resultant specific gravity is found to be 1.497 and 1.420 for 16M and 8M concentration of alkali activator solutions respectively. They were allowed to cool down overnight in sealed condition and used within 48 hours.

3. Experimental Methods

3.1 Mixing and Proportioning

Concentration and proportion of alkali activator are both determined from paste trials conducted earlier [3-4]. It is revealed that water demand for paste consistency differs widely between the geopolymer solid binders. Wherever low water: geopolymer solid binder ratio (w/b) is possible, 16M solution is selected. As far as possible Na-ion content in the geopolymer solution is retained at a comparable level to that of the previous investigations [1,8,15]. Initial trials on mix proportions were conducted using FA and GGBS in 65:35 mass ratio i.e, bi-component FGPC denoted by 'FG' (FGR1, FGR2, FGNII, FGR40) with $360\text{--}385\text{ kg/m}^3$ of solid binder presented in Table 4. The ratio of fine and coarse aggregates was calculated following the mix design guidelines of IS 10262:2009 [17] and further optimised using dry mixing trials in a measuring cylinder so as to minimise voids and hence low w/b ratio in mix proportion. Typically, coarse aggregate is reduced by 15-20 wt.% and compensated by fine aggregate. Calculated values of course and fine aggregates are indicated in the parenthesis below each of the mix proportions (Table 4). Mix proportion was further optimised with increased weight of FA and GGBS to 457 kg/m^3 and reduced w/b to 0.27 in the mix proportion, FGR3. With the view to reduce water further, a trial was conducted with increased proportion of finer geopolymer solid binder to 487 kg/m^3 in mix proportion, FY with YTPS D-pass FA. This FA has a higher specific gravity of 2.32 hence increased loading did not change the volume fraction. In order to evaluate the effect of w/b, trials were conducted in the optimised mix proportion, FR3 with RTPS FA adding extra water during mixing. The calculation of water content is done considering water available in sodium silicate liquid and fresh water added to sodium hydroxide pallet. Guideline of IS 10262:2009 is followed for arriving at the concrete mix proportions viz., mono component geopolymer with Mettur/medium FA (FM40M), bi-component geopolymer with RTPS medium/3 FA and GGBS in 65:35 ratio by mass (FGR40), for load-deflection studies of reinforced beams. Geopolymer binders used were 10% more than the recommended quantity of cement in Table 5 of IS 456: 2000. A control mix was prepared with 350 kg of PPC from local source (Bharthi) for M40 grade RC beam (PPC M40) and prism (PCM40) as per guidelines of IS 10262-2009. Proportioning of coarse and fine aggregates was selected as 0.576: 0.424 applying 10% reduction in coarse aggregate for pumpable concrete with water:cement ratio of 0.40 as per the standard.

Fly ash was first mixed with fine aggregate in a 30 kg capacity Pan mixer for about 2 minutes for uniform mixing. Alkali activator solution was added in the dry mixture of fly ash and fine aggregate and allowed to get mixed for 5 minutes further. Surface dry saturated coarse aggregate is added to the mixture and mixed for another 15 minutes. When 16M activator solution is used, supplementary addition of sodium silicate and water were administered sufficient for homogenous mixing or otherwise for slump requirement.

3.2 Placing of Fresh Concrete and Curing

Workability test was conducted by usual slump test as per IS 1199-1959. When flow value is very low it is reported as harsh mix in Table 4. Specimens for compressive strength test were cast in $15 \times 15 \times 15$ cm mold and compacted in the usual method followed for CC described in IS 516-1959 and vibrated for 3 minute minimum on a vibrating table. Extended vibration time up to 2 minute was adopted for harsh mix. Density of the prisms are also measured as a cross-check for internal voids. Three reinforced concrete (RC) beams of size $80 \times 25 \times 20$ cm were cast in M40 mix design PPC M40, FM40M and FGR40. HYSD steel bars in 8 mm dia are used for both longitudinal reinforcement and vertical stirrups at a spacing of 100 mm with clear cover of 20 mm concrete around. Sealed ambient curing method was adopted by wrapping the FGPC prisms and beams before and after demoulding.

Table 4 - Mix proportion of alkali activated geopolymer concrete with different sources of fly ash

Mix design	Fly ash source, grade	Fly ash (kg/m ³)	GGBS (kg/m ³)	Conc. of NaOH solution	NaOH solution (kg/m ³)	Na ₂ SiO ₃ liquid (kg/m ³)	Extra Water (kg/m ³)	Alkali activator:solid binder (L/S)	Coarse aggregate (kg/m ³)	Fine aggregate (kg/m ³)
FGR1	RTPS, M1	244	131	8M	64.3	160.7	32.7	0.60+0.09#	972 (1117)	795 (599)

FGR2	RTPS, M2	243	132	8M	75	187.5	21.1	0.70+0.06#	958 (1085)	784 (590)
FGR2	RTPS, M2	244	131	8M	75	187.5	10.9	0.70+0.03#	963 (1113)	788 (589)
FGR3	RTPS, M3	297	160	16M	45.6	134	45.7	0.35+0.04* +0.10#	947 (1116)	758 (553)
FR3	RTPS, M3	457	0	16M	45.6	113.9	40.3	0.35+0.09#	947 (1126)	758 (541)
FR3	RTPS, M3	457	0	16M	45.7	114.3	65.0	0.35+0.14#	947 (1063)	758 (539)
FR3	RTPS, M3	457	0	16M	45.7	114.3	113.0	0.35+0.25#	947 (950)	758 (526)
FGNII	NLCII, C	234	126	8M	55.5	138.9	105	0.54+0.29#	962	785
FNIII	NLCIII M	375	0	8M	58.9	147.3	60	0.55+0.16#	980 (1103)	808 (616)
FK _p	Koradi, Pond	460	0	16M	61.2	191.7	45.0	0.47+0.08* +0.10#	947 (964)	758 (502)
FY	YTPS, D-pass, F	487	0	16M	44.5	140.5	0	0.32+0.06*	949 (1204)	758 (533)
FMF	Mettur, F	457	0	16M	45.6	139.1	36.3	0.35+0.05* +0.08#	947 (1102)	758 (551)
FM40F	Mettur, F	385	0	16M	46.2	136.8	30.6	0.42+0.06* +0.07#	1042 (1171)	759 (586)
FM40 M Beam	Mettur, M	385	0	16M	46.2	136.8	30.6	0.42+0.06* +0.07#	1015 (1159)	739 (580)
FGR40 Beam	RTPS, M3	250	134	16M	38.4	126	32.0	0.35 +0.08* +0.08#	1050 (1208)	764 (604)
PCM40	PPC	350	0	SP=7 kg	-	-	140	SP @2%	1121	816

C:coarse, M:medium, F:fine, SP:superplasticizer, *,#:Extra Na₂SiO₃ & water added during mixing, (Calculated values as per IS 10262:2019)

3.3 Test Procedure for Hardened Properties

28-days sealed ambient cured prisms were subjected to compression test by applying load at the rate of 5.2 kN/s as prescribed in IS 516 in a 2000 kN capacity machine (Datacone). Minimum of three cubes were tested in each of the mix and the ultimate strength was calculated by dividing breaking load by area. Test data was discarded if the variation in the individual reading was found to be beyond 5% of the average ultimate strength. Load-deflection experiments for RC beams were conducted in a 100-tonne capacity programmable universal testing machine as per ‘center point’ flexural loading method, ASTM C293 and load was applied in steps of 2.4 kN on a 50 mm dia roller placed on the top surface across the RC beam at a point equidistant from the two bottom rollers supporting the beam on the test bed (span, L=600mm). Deflection was directly measured by a dial guage with 0.001 mm least count under the load points at mid span. Behaviour of the beam was carefully observed, and first crack was identified by a handheld microscope.

Table 5 - Fresh and hardened properties of ambient cured fly ash-based alkali activated geopolymer concrete

Mix design	Water:solid binder by wt. (w/b)	Consistency (slump)	Setting and hardening behaviour, time lag	Average strength, 28-day, MPa	Concrete density, kg/m ³
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FGR1	0.38	120 mm	Normal, 6 hr	55.2	(2399)
FGR2	0.40	150 mm	Normal, 6 hr	53.1	(2401)
FGR2	0.37	110 mm	Normal, 6 hr	56.0	(2399)
FGR3	0.27	Harsh mix	Normal, 6 hr <i>Expanded</i>	84.4	2401
FR3	0.24	Very harsh mix	Slow, 72 hr	47.3	2295
FR3	0.30	Harsh mix	Slow, 72 hr	40.0	2394
FR3	0.40	Zero slump	Bleeding in 1 hr, 72 hr	14.7	2256
FGNII	0.55	100 mm	Slow, 24 hr	15.5	-
FNIII	0.43	Initially lean	Fast setting, 3 minute	19.0	(2429)
FK _p	0.33	Harsh mix	Slow, 72 hr	15.0	2264
FY	0.16	Harsh mix	Slow, 24 hr	99	2439
FMF	0.25	Harsh mix	Slow, 24 hr	75.0	2388
FM40F	0.28	Harsh mix	Slow, 24 hr	50.0	2277
FM40M Beam	0.28	Harsh mix	Slow, 72 hr	40.1	(2352)
FGR40 Beam	0.27	Harsh mix	Slow, 72 hr	-	(2395)
PCM40	w/c = 0.40	100 mm	Normal, 6 hr	50.3	(2427)

Slow:slow initial setting, hr:hour; w/c-water/cement; (Calculated values of fresh concrete as per IS 10262: 2009)

4. Results

4.1 Fresh and Hardened Properties of Concrete

Variations in specific size area, particle size spectrum and granulometry in FA powders showed wide variation in the fresh and hardened properties of concrete presented in Table 5. Geopolymer concrete was initially prepared with higher proportion of liquid activator, L/S=0.7 using 8M NaOH solution for 100 mm of slump. However harsh mix with lower proportion of L/S=0.38 with 16M NaOH solution was successfully placed with vibration of 5 minute; defect-free and dense FGPC was produced using mono component low calcium FA. Class-F FGPC exhibited slow initial setting time of 1-3 days although strength results after 28 days of curing was higher (Table 5). When GGBS is added initial setting is faster. In the mix designs of RTPS FA with GGBS, setting time reduced to the level of PPC concrete, however the harsh mix (FGR3) expanded in the mould. NLC-III FA exhibited fast setting (within 3 minute) as it posed difficulties in placing although the mix appeared lean initially.

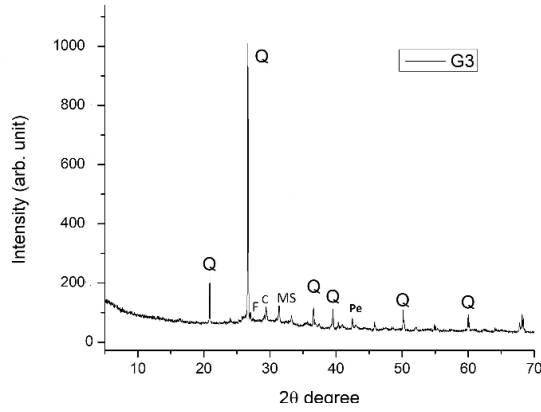


Fig. 5 - XRD pattern in a typical fly ash based alkali-activated geopolymer paste cured in sealed ambient condition. Q-quartz, F-feldspar, MS-magnesium silicate, Pe-periclase and C-hydrated cementitious phases C-S-H or M-S-H

4.2 Mono Component and Bi-Component FGPC

XRD pattern of the geopolymer paste produced in the same proportion of mix design FNIII without aggregates is presented in Fig. 5. Sharp quartz peak at $26.6^\circ 2\theta$ in the 28-day cured geopolymer paste (G3) indicates presence of unreacted quartz that is unaffected by action of alkali activators. In the geopolymers of high calcium containing NLC FA or the geopolymers of low calcium fly ash with added GGBS, a peak at $29.3^\circ 2\theta$ is noticed and identified as hydrated cementing phase (C-S-H or M-S-H) which is responsible for strength development. The other crystalline phases detected are feldspar $[\text{NaAlSi}_3\text{O}_8]$ / plagioclase $[\text{Ca}_{0.65}\text{Na}_{0.35}(\text{Al}_{1.65}\text{Si}_{2.35}\text{O}_8)]$ followed by minor phases like magnesium silicate (MgSiO_3), periclase (MgO) as seen in Fig. 5. Crystalline phases viz., mullite, gehlenite $[\text{Ca}_2\text{Al}(\text{Al},\text{SiO}_7)]$, akermanite, $[\text{Ca}_2\text{MgSi}_2\text{O}_7]$, merwinite $[\text{Ca}_3\text{Mg}(\text{SiO}_4)_2]$, Augite $[\text{Ca}(\text{Fe},\text{Mg})\text{Si}_2\text{O}_6]$ and diopside $[\text{Ca}(\text{Mg},\text{Fe},\text{Al})(\text{Si},\text{Al})_2\text{O}_6]$ were detected in the same proportion as in original FA indicating that these phases were not reacted by the activator solution.



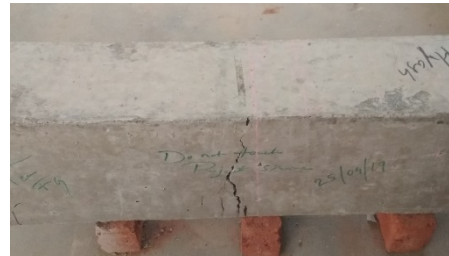
(a) Geometry of rebar and form work for beam



(b) Reinforced PPC M40 concrete beam



(c) FM40M



(d) FGR40

Fig. 6 - Showing geometry of rebar (a) and crack patterns in reinforced beams of PPC M40 concrete (b), mono component geopolymer (FM40M) concrete with medium sized fly ash (c), bi-component (FGR40) with fly ash and GGBS (d)

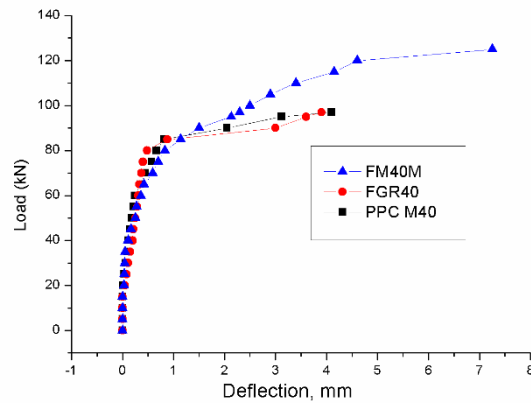


Fig. 7 - Load-deflection curves of reinforced M40-concrete beam with PPC (PPC M40), mono component (FM40M) and bi-component with fly ash:GGBS in 65:35 mass ratio FGPC (FGR40)

4.3 Deflection in Reinforced Beam

Fig. 6(a) shows the formwork with the rebars, and Fig. 6(c) shows the top roller used for applying load on beams. The results of unconfined ‘center point’ flexural load test exhibit similar load-deflection behavior for all the three types of RC beams up to 20 kN load. First cracking load for the two reinforced beams, PPC M40 and GGBS administered bi-component geopolymer, FGR40 are found to be 50 kN while it is 45 kN for mono component medium sized FA beam, FM40M. Figures 6 (b, c and d) show the crack pattern at maximum load exhibiting higher crack width in the case of FM40M while multiple cracks is seen in FGR40 implying lower fracture resistance. Fig. 7 shows the plot of deflection against applied load for all the three beams. Deflection after first cracking load was higher in the case of FM40M as compared to FGR40 and PPC M40. However, FM40M beam exhibited higher load bearing capacity and higher energy absorption with enhanced flaw tolerance.

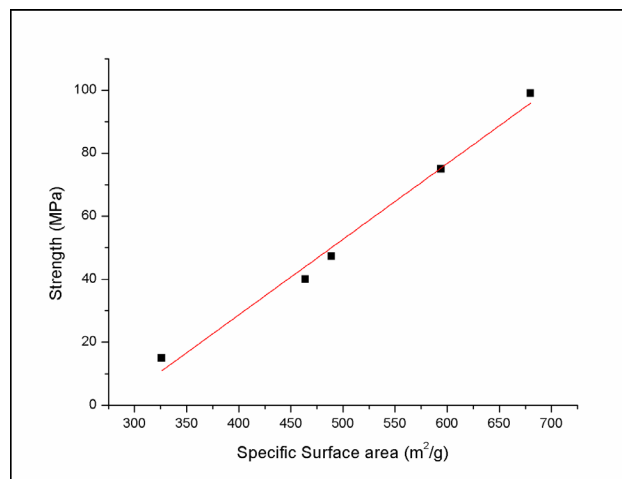


Fig. 8 - Relationship between ultimate compressive strength and Blaine’s specific surface area of Class-F fly ash activated with 1:2.5 mass ratio of 16M NaOH solution: liquid Na₂SiO₃ as cured in sealed ambient environment (R²=0.984, y = -67.25 + 0.24 x)

5. Discussions

5.1 Mix Proportioning

Mix proportion was optimised using typical Class-C and a Class-F FAs from NLC and RTPS respectively with significant differences in granulometry as seen in Figures 2, 3 & 4. In bi-component mix, highest water demand is exhibited by coarse NLC-II FA in FGNII with w/b=0.55 for 100 mm of slump but reduced to w/b=0.37 in FRG2 by changing the NLC-II FA to RTPS medium/2 for similar slump of 110 mm. Table 4 and 5 showed that NLC FAs required more water as compared to RTPS although particle size distribution in the finer side (< 100 μm) is almost same in both NLC-III and

RTPS medium/3 (Fig. 4). In this connection the tap density measurement can predict the feature; lowest tap density of 1000 kg/m³ exhibited by NLC-III FA (Table 2). Water demand reduced marginally in mono component systems from w/b=0.27 in FGR3 to 0.24 in FR3 eliminating GGBS in the mix design. However water demand is found to be higher in Pond ash from Koradi with w/b= 0.33 with a low tap density of 1040 kg/m³ while the lowest w/b=0.16 is exhibited by D-pass YTPS FA with the highest tap density of 1240 kg/m³ in mono component FGPC of mix design FY (Table 2 and 5). Hence the source of the original FA and it's overall granulometry influence the water demand in the mix design and in turn L/S ratio and strength therein.

5.1.1 Fineness vs. Strength of Mono Component FGPC

Considering all the experimental materials, D-pass YTPS produced highest 28-day strength of 99 MPa in FY (Table 5) with 487 kg of solid binder (FA) loading. D-pass FA has the finest size with SSA of 680 m²/kg considering all the FAs studied. Similar trend is observed in Mettur FA based FGPC producing higher strength of 75 MPa with finer variety (SSA of 594 m²/kg) in mix design FMF (457 kg of FA). A plot of strength vs. fineness shows the linear relationship presented in Fig. 8. The requirement of alkali activator as well as water demand in the mix proportions reduced as the FA becomes finer in size evolving a dense structure with density of concrete in the range of 2388-2439 kg/m³ (Table 5). Fig. 8 provides a guideline for selection of fly ash for desired strength of mono component FGPC up to M80 applying the same formula for target strength in IS 10269 : 2019. In M40 grade concrete target strength, $f'_{ck} = f_{ck} + 1.65.s = 48.25$ MPa is required as per the said guideline. Referring to the fineness-strength graph in Fig. 8, it is found that Blaine's SSA should be 481 m²/kg which is close to mix design, FR3 (Tables 2, 4 & 5). At the fineness of 500 m²/kg, the expected strength would be 53 MPa. Patankar et al. (2015) reported that a strength value of 48 MPa with 430 m²/kg SSA of fly ash using activator solution to fly ash ratio of 0.35, 13M NaOH solution as against 480 m²/kg SSA in Fig. 8. In the lower region of fineness, the strength value of about 16 MPa is reported in 28-day ambient cured FGPC with a coarse fly ash of 322 m²/kg SSA which is 11 MPa as per Fig. 8 (Jindal, Praveen, Singhal and Goyal 2017). Hence Fig. 8 provides a safer estimate of 28-day strength in mono component FGPC. Same authors reported that 28-day compressive strength improved from 13-15 MPa to 20-25 MPa by replacing 10% of FA with alcofines (D50 of 4.4 μm) in ambient cured low calcium FGPC. In the present study superior strength is achieved with modified mix design than the values reported so far.

5.1.2 Water:Binder Ratio (w/b) vs. Strength of Mono and Bi-Component FGPC

Figure 9(a) represents a plot of water:geopolymer solid binder (w/b) against the 28-day compressive strength of mono component FGPC prepared with RTPS medium/3 FA and 16M alkali activator (L/S=0.35 by weight) in the mix design FR3. Ultimate compressive strength increased linearly from 14.7 MPa to 47.3 MPa as w/b decreased from 0.40 to 0.24. The linear relationship is found to be significant with R² = 0.95 for a fixed source of FA with the lowest w/b=0.24 in the series of medium variety. As the fineness changes, the values will also change as seen in the case of fine MTPS FA where the strength value is 75 MPa with w/b=0.25 in the mix designs FMF.

Referring to the strength vs. w/b ratio curve in Fig.9(b) for bi-component FGPC with RTPS FA:GGBS in 65:35 proportion, it is revealed that strength increased rapidly from 53-56 MPa to 84 MPa when w/b ratio reduced from 0.37-0.40 in the mix designs FGR1 and FGR2 to 0.27 in FGR3. Likewise low strength of 15.5 MPa is exhibited by coarse NLC-II FA in FGNII mix design where w/b=0.55.

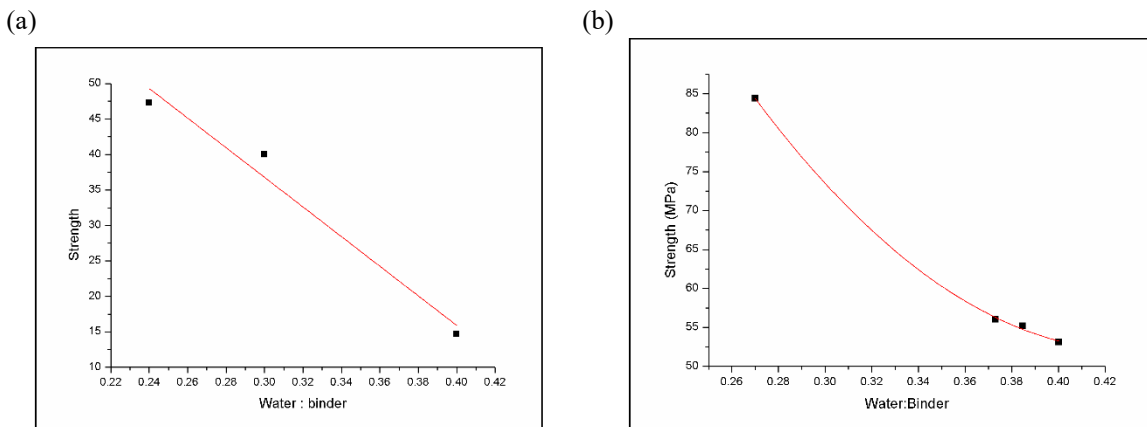


Fig. 9 - Effect of water:binder (w/b) ratio on compressive strength of (a) mono component medium sized fly ash (RTPS M3) geopolymer (FR3) concrete (R²=0.946, y = 99.41 – 208.78 x); (b) bi-component alkali-activated geopolymer concrete with fly ash and GGBS in 65:35 mass ratio (R² = 0.999) cured in sealed ambient condition

5.2 Mix Design for Reinforced Beam

RC beam (FM40M) prepared from mono component FGPC shows a similar load bearing capacity to that of the two RC beams prepared with PPC and bi-component FGPC. FA used is medium sized in either cases of RC beams and had a Blaine's SSA in the range of 464-489 m²/kg commonly available. Prisms prepared from the same mix, FM40M, however showed compressive strength of 40 MPa although the PPC strength was higher at 50 MPa (Table 4). Cube strength can be met if the finer FA is selected e.g., Mettur fine with SSA of 594 m²/kg as in FM40F. Strength is also increased from 50 MPa to 75 MPa when quantity of finer fly ash is increased from 385 kg/m³ (FM40F) to 457 kg/m³ as in FMF. Interestingly the strength gain is same i.e., increased by 50 % in the case of bi-component mix design also for the similar increase in weight of solid binders from 375 kg/m³ in FGR2 to 457 kg/m³ in FGR3 (Table 5). In a previous study with Australian fly ash as much as 550 kg/m³ was recommended for M30 grade of concrete cured at elevated temperature of 60-70°C [15]. Interestingly increased proportion of FA resulted in the density in the region of 2400 kg/m³ similar to that of the normal CC (Table 5). It is to be noted here FGPC releases water in the curing period and strength is not affected by marginal reduction in density of hardened mono component FGPC in the region of 2300 kg/m³ unlike CC. Hence, FA proportion can be increased up to 30% over the minimum cement requirement specified in Table 5 of IS 456:2000 and instead of 10% specified in the mix design guidelines of IS 10262:2019 [17]. Reduction in FA from 457 kg/m³ in FMF to 385 kg/m³ in FM40F and simultaneous increase in coarse aggregate from 947 kg/m³ to 1042 kg/m³ could possibly have triggered drop in strength from 75 MPa to 50 MPa. As mentioned earlier in section 3.1 that reducing coarse aggregate by 15-20%, increasing fine aggregate compensating by the same quantity as well as increasing FA are the parameters that can lead to better strength gain in FGPC (Table 5). Based on the experience gained in the series of experimental batch, an illustrative example of mono component M40 FGPC is presented in Appendix A.

5.3 Fly Ash Selection by XRD and SEM

All the FAs studied are found to have quartz in various proportions as seen in Fig. 1 typically. Quartz peak is the shortest in D-pass YTPS FA powder that yielded highest strength (Figure 1b). In contrast strength is seen to be as low as 19 MPa (FNIII) with a medium NLC-III FA (Table 4 & 5). Experimentss were made to dissolve finer silica, both microfined and amorphous silica powders, in the strong alkaline activator of 16M NaOH solution. After 28 days of sealed ambient curing the said geopolymers gained compressive strength of 9-13 MPa. High water demand associated with NLC FA (Table 4 and 5) is possibly due to sharp contours of quartz sand (Fig. 2). If the FA is predominantly spherical sized, unlike in NLC FA, higher fluidity can be expected with same level of w/b ratio.

Table 6 - Grading of original fly ash based on strength in mono component ambient cured concrete

Grade of fly ash	Premium	Medium	Low
Compressive strength, MPa	50-99	40-47	10-20
Source of fly ash	YTPS, Mettur fine	RTPS, Mettur, Koradi medium	NLCIL medium and coarse, Sipat, Vindhyachal, Koradi pond
Type based on fineness and quartz content	Finer sized fly ash with low quartz	Medium sized fly ash with low quartz	Coarse sized fly ash with high quartz or pond ash

Preceding discussion suggests that the quality of FA from original source vary widely even within a generation unit and affect the fresh and hardened properties of in-situ placed concrete. Based on the fineness and quartz content, the experimental FA sources have been classified into three categories viz. Low, Medium and Premium as shown in Table 6. FA glass dissolves in the alkaline solution and is responsible for gelation. In the experimental batch of FA, however role of glass content is not reflected significantly in strength gain under ambient curing condition as similarly reported in literature for similar FA sources even in heat curing [11]. Cost of monocomponent FGPC is lower in comparison to both the bi-component FGPC and CC although monocomponent FGPC with relatively coarse size may need a higher proportion of alkali activator than that of the GGBS due to its ease of activation.

6. Conclusions

Fly ash exhibited wide variation in granulometry from source altering the water:binder (w/b) ratio in mix proportioning. Ultimate compressive strength of mono component geopolymer concrete in sealed ambient curing is influenced by fineness as well as w/b ratio. A Class-F fly ash containing low quartz sand, finer in size with Blaine's SSA of 680 m²/kg and median (D50) particle size of 4.5 µm produced highest strength suitable for M80 grade concrete with w/b ratio as low as 0.16. Based on the experimental results, fly ash powders can be classified as 'medium' with SSA of 400-500 m²/kg, 'fine' above 550 m²/kg and 'coarse' less than 350 m²/kg for corresponding 28-day strength of 40-47 MPa, 50-99 MPa and 15-19 MPa respectively. Load-deflection behaviour of M40 grade of reinforced concrete with mono component

medium sized fly ash was comparable to Portland pozzolana cement based M40 concrete prepared as per IS 10262:2019 and bi-component medium sized fly ash with GGBS. Results indicated that finer variety of fly ash is most suitable for better strength gain in ambient cured mono component fly ash based geopolymer concrete. Furthermore 20-30 wt.% higher quantity of fly ash can be used over minimum cement content specified in Table 5 of IS 456:2000 simultaneously increasing fine aggregate proportion by 15-20% from coarse aggregate ratio specified in IS 10262:2019, Guidelines for mix design. The optimised mix designs are 10-15% cheaper than Portland cement-based concrete.

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References

1. Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes, a cement for the future. *Cement and Concrete Research*, 29, 1323-1329.
2. Provis, J. L. (2018). Alkali-activated materials. *Cement and Concrete Research*, 114, 40-48. <https://doi.org/10.1016/j.cemconres.2017.02.009>
3. Goswami, A. P., & Reddy, C. P. (2017). Co-generation of cementitious material in thermal power plant, Annual Technical Volume, Mechanical Engineering Division Board, IEI, 2, 37-41.
4. Goswami, A. P., Determining Physico-Chemical Parameters in Stronger Ambient Cured Geopolymer from Fly Ash, *Advances in Cement Research*, Submitted in.
5. Shi, C., & Day, R.I. (1999). Early strength development and hydration of alkali-activated blast furnace slag/fly ash blends. *Advanced Cement Research*, 11, 189-196.
6. Huynh, T.P., Hwang, C. L., & Lin, K.L. (2017). Performance and microstructure characteristics of the fly ash and residual rice husk ash-based geopolymers prepared at various solid-to-liquid ratios and curing temperatures, *Environmental Progress & Sustainable Progress*, 36, 83-92.
7. Bakharev, T., (2005). Geopolymer materials prepared using Class-F fly ash and elevated temperature curing. *Cement and Concrete Research*, 35, 1224-1232.
8. Xu, H., & Deventer, J. S. J. (2000). The geopolymerisation of aluminosilicate minerals. *International Journal of Mineral Processing*, 59, 247-266.
9. Barbosa, V. F. F., MacKenzie, J. D., & Thaumaturgo, C. (2000). Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. *International Journal of Inorganic Materials* 2, 309- 317.
10. Chindaprasirt, P., Chareerat, T., Hatanaka, S., & Cao, T. (2011). High-strength geopolymer using fine high-calcium fly ash, *Journal of Materials in Civil Engineering*, ASCE, 23, 264-270.
11. Kumar, S., Kumar, R., Alex, T. C., Bandopadhyay, A., & Mehotra, S. P. (2007). Influence of reactivity of fly ash on geopolymerisation, *Advances in Applied Ceramics*, 106, 120-127.
12. Khan, M. Z. N., Shaikh, F. U. A., Hao, Y. i., & Hao, H. (2016). Synthesis of high strength ambient cured geopolymer composite by using low calcium fly ash, *Construction and Building Materials*, 125, 809-820.
13. Pieterse, H. S., & Bijen, M. J. (1991). Reactivity of low-Ca fly ash in cement, *Studies in Environmental Science*, 48, 651-65.
14. Fernández-Jime'nez, A., Palomo, A., & Criado, M. (2005). Microstructure development of alkali-activated fly ash cement: a descriptive model, *Cement and Concrete Research*, 35, 1204-1209.
15. Anuradha, R., Sreevidya, V., Venkatasubramani, R., & Rangan, B.V. (2012). Modified guidelines for geopolymer concrete mix design using Indian Standard, *Asian Journal of Civil Engineering*, 13, 353-364.
16. Fernández-Jimenez, A., de la Torre, A. G., Palomo, A., López-Olmob, G., Alonso, M. M., & Aranda, M. A. G. (2006). Quantitative determination of phases in the alkali activation of fly ash. Part I. Potential ash reactivity, *Fuel*, 85, 625-634.
17. IS 10262:2009. (2019). Concrete Mix Proportioning – Guidelines, BIS, New Delhi – 110002.
18. Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2015). Mix design of fly ash based geopolymer concrete, In V. Matsagar (Ed.), *Advances in Structural Engineering*, (pp. 1619-1634). New Delhi: Springer,

19. Jindal, B. B., Praveen, Singhal, D., Goyal, A. (2017). Predicting relationship between mechanical properties of low calcium fly ash-based geopolymer concrete. *Transactions of the Indian Ceramics Society*, 76(4), 258-265.

Appendix

Salient Features of Mix Proportioning with Mono Component Fly Ash-Based Alkali activated Geopolymer using Guidelines of IS 10262 : 2019 and IS 456 : 2000

A1: Stipulations for Proportioning

- | | |
|---|--|
| a) Grade designation | : M40 |
| b) Type of fly ash | : Class-F fine (Refer Fig.8 for fineness) |
| c) Minimum fly ash content and maximum water-binder (w/b) ratio | : Severe (for reinforced concrete), 385 kg/m ³ minimum and w/b=0.28 |
| d) Workability | : Harsh mix without superplasticizer |
| e) Degree of supervision | : Good |
| f) Type of aggregate | : Crushed angular aggregate |
| g) Minimum liquid activator / solid binder | : 0.42 |
| h) Concentration of NaOH solution | : 16 M |
| i) Maximum allowable water in liquid Na ₂ SiO ₃ | : 40% by mass |

A-2: Test Data for Materials

- | | |
|--|--------------------------------|
| a) Specific gravity of fly ash to be used | : 2.209 |
| b) Specific gravity of Coarse aggregate (at dry condition) | : 2.62 |
| c) Maximum nominal size of Coarse aggregate | : 20 mm |
| c) Specific gravity of Fine aggregate (at dry condition) | : 2.59 |
| d) Grading of Fine aggregate | : Zone II of Table 9 in IS 383 |
| e) Purity of NaOH pallet | : 97% |
| f) Moisture content in Na ₂ SiO ₃ | : 39.42 % |

A-3 Target Strength for Mix Proportioning

Target strength using a) $f'_{ck} = f_{ck} + 1.65 S = 40 + 1.65 \times 5 = 48.25$ MPa, b) $f'_{ck} = f_{ck} + 6.5 = 40 + 6.5 = 46.5$ MPa. The higher value is adopted. Therefore, target strength will be 48.25 MPa as $48.25 \text{ MPa} > 46.5 \text{ MPa}$.

A-4 Preparation of Alkali Activator

- a) For 16 M NaOH solution preparation with 97% purity pallet, molecular weight of NaOH, $40 \times 16 \div 0.97 = 660$ gm is weighed and dissolved in water to make up 1000 ml volume and used after cooling.
- b) Mix 1 part 16 M NaOH solution with 2.5 times Na₂SiO₃ liquid by mass and use as alkali activator in 0.42 part of fly ash by mass.

A-5 Selection of Fly Ash

Minimum fineness required for the target strength of 48.25 MPa from Fig. 8 is 481 m²/kg. Selecting 10% higher fineness, $481 + 48 = 529$ m²/kg is required fineness of fly ash suitable.

A-6 Quantity of Fly Ash and Alkali Activator

Take 30 % higher quantity than the minimum cement (OPC) content for exposure condition of 'severe' under reinforced concrete from Table 5 of IS 456 2000 i.e., $320 \text{ kg/m}^3 \div 0.7 = 457 \text{ kg/m}^3$. 457 kg/m^3 is more than 385 kg/m^3 (FM40F) so 457 kg/m^3 is ok.

Alkali activator @ L/S of 0.42 = 192 kg/m^3

Weight of NaOH solution = 54.9 kg/m^3

Weight of Na₂SiO₃ liquid = 137.1 kg/m^3

Volume of alkali activator = $192 \div 1.497 = 128 \text{ m}^3$

A-7 Calculation of Water

Fraction of water in 16 M NaOH is known from the weight of NaOH pallet dissolved and net weight of solution = 0.5429.

So, weight of water in 16 M NaOH solution of $54.9 \text{ kg/m}^3 = 54.9 \times 0.5429 = 29.805 \text{ kg}$

Fraction of water in Na₂SiO₃ liquid = 0.3942, so in 137.1 kg/m^3 of Na₂SiO₃ liquid, water = 54.062 kg

Total weight of water from alkali activator using L/S = 0.42 is $29.805 + 54.062 = 83.867 \text{ kg}$

Maximum water : binder allowed is 0.28. So water = $457 \times 0.28 = 128 \text{ kg/m}^3$

Option to add extra water = $128 - 83.867 = 44.133 \text{ kg}$ is available, hence ok.

A-8 Proportion of Volume of Coarse Aggregate and Fine Aggregate Content

From Table 5, volume of coarse aggregate (CA) corresponding to 20 mm size aggregate and fine aggregate (Zone II) for water-cement ratio of 0.50 = 0.62. In the present case water : binder ratio is 0.28. As the water : binder ratio is lower by 0.22, the proportion of volume of CA is increased by 0.044 (at the rate of 0.01 for every ± 0.05 change in water:cement ratio). Therefore, corrected proportion of volume of coarse aggregate for the water : binder ratio of 0.28 = $0.62 + 0.044 = 0.664$. Reducing 15%, proportion of CA is 0.5644.

Proportion of fine aggregate (FA) = $1 - 0.5644 = 0.4356$

A-9 Mix Calculations for Trial

- a) Total volume = 1 m^3 and target density = 2400 kg/m^3

- b) Volume of Fine aggregates = Mass of FA \div (Specific gravity of FA \times 1 000) = $457 \div 2.209 \times 1\ 000 = 0.207\ m^3$
- c) Volume of alkali activator = $128\ m^3$
- d) Volume of extra water = $44.133\ 1000 = 0.044\ m^3$
- d) Volume of aggregates = $1 - (0.207 + 0.128 + 0.044) = 0.621$
- e) Coarse aggregates = $0.621 \times 0.5644 \times 1000 \times 2.62 = 918\ kg/m^3$
- f) Provisional Fine aggregates = $0.621 \times 0.4356 \times 1000 \times 2.59 = 701\ kg/m^3$
- g) Wet density = $457 + 192 + 44 + 918 + 701 = 2311\ kg/m^3$. Extra FA in trial mix = $2400 - 2311 = 89\ kg/m^3$
- h) Final Fine aggregates = $701 + 89 = 790\ kg/m^3$.