Mix Design of Fly Ash Based Geopolymer Concrete

Subhash V. Patankar, Yuwaraj M. Ghugal and Sanjay S. Jamkar

Abstract Geopolymer is a new development in the world of concrete in which cement is totally replaced by pozzolanic materials like fly ash and activated by highly alkaline solutions to act as a binder in the concrete mix. For the selection of suitable ingredients of geopolymer concrete to achieve desire strength at required workability, an experimental investigation has been carried out for the gradation of geopolymer concrete and a mix design procedure is proposed on the basis of quantity and fineness of fly ash, quantity of water, grading of fine aggregate, fine to total aggregate ratio. Sodium silicate solution with Na_2O = 16.37 %, SiO_2 = 34.35 % and H_2O = 49.28 % and sodium hydroxide solution having 13 M concentration were maintained constant throughout the experiment. Water-to-geopolymer binder ratio of 0.35, alkaline solution-to-fly ash ratio of 0.35 and sodium silicate-to-sodium hydroxide ratio of 1.0 by mass were fixed on the basis of workability and cube compressive strength. Workability of geopolymer concrete was measured by flow table apparatus and cubes of 150 mm side were cast and tested for compressive strength after specified period of oven heating. The temperature of oven heating was maintained at 60 °C for 24 h duration and tested 7 days after heating. It is observed that the results of workability and compressive strength are well match with the required degree of workability and compressive strength. So, proposed method is used to design normal and standard geopolymer concrete.

Keywords Geopolymer concrete · Mix design · Fly ash · Alkaline solution · Flow · Heat-cured · Compressive strength

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1 Introduction

Use of concrete is globally accepted due to ease in operation, mechanical properties and low cost of production as compared to other construction materials. An important ingredient in the conventional concrete is the Portland cement. Production of Portland cement is increasing due to the increasing demand of construction industries. Therefore the rate of production of carbon dioxide released to the atmosphere during the production of Portland cement is also increasing. Generally for each ton of Portland cement production, releases a ton of carbon dioxide in the atmosphere [1]. The green house gas emission from the production of Portland cement is about 1.35 billion tons annually, which is about 7 % of the total greenhouse gas emissions [2]. Moreover, cement production also consumes significant amount of natural resources. Therefore to reduce the pollution, it is necessary to reduce or replace the cement from concrete by other cementitious materials like fly ash, blast furnace slag, rice husk ash, etc.

Fly ash is a by-product of pulverized coal blown into a fire furnace of an electricity generating thermal power plant. According to the survey, the total fly ash production in the world is about 780 million tons per year but utilization is only about 17–20 % [2, 3]. In India more than 220 million tons of Fly ash is produced annually [4]. Out of this, only 35–50 % fly ash is utilized either in the production of Portland pozzolana cement, workability improving admixture in concrete or in stabilization of soil. Most of the fly ash is disposed off as a waste material that covers several hectares of valuable land. The importance of using fly ash as a cement replacing material is beyond doubt. Malhotra [5, 6] recommended replacing cement by fly ash up to 60 % known as high volume fly ash concrete. But it was observed that the pozzolanic action of fly ash with calcium hydroxide formed during the hydration of cement is very slow. The particles of size less than 45 μm are responsible for pozzolanic reaction. Higher size particles present in fly ash acts as filler.

Therefore for complete replacement of cement by fly ash and to achieve the higher strength within a short period of curing, Davodavits [7, 8] suggested the activation process of pozzolanic material that are rich in silica and alumina like fly ash with alkaline elements at certain elevated temperature. Fly ash when comes in contact with highly alkaline solutions forms inorganic alumino–silicate polymer product yielding polymeric Si–O–Al–O bonds known as Geopolymer [7–9].

To produce concrete of desired strength, various mix proportioning methods are used on the basis of type of work, types, availability and properties of material, field conditions and workability and durability requirements. Rangan [10] have proposed the mix design procedure for production of fly ash based geopolymer concrete whereas Anuradha et al. [11] have presented modified guidelines for mix design of geopolymer concrete using Indian standard code.

As geopolymer concrete is a new material in which cement is totally replaced by fly ash and activated by alkaline solutions. Chemical composition, fineness and density of fly ashes are different from cement. Similarly, in cement concrete, water plays main role during hydration process while water come out during polymerisation process as in case of geopolymer concrete. Therefore it is necessary to develop a new mix design procedure for geopolymer concrete to achieve desired strength at required workability.

So, in the present investigation, geopolymer concrete mix design procedure is proposed on the basis of quantity and fineness of fly ash to achieve desired strength [12], quantity of water to achieve required degree of workability [13], grading of fine aggregate [14] and fine-to-total aggregate ratio by maintaining solution-to-fly ash ratio by mass of 0.35 [15], water-to-geopolymer binder ratio of 0.35 [16], sodium silicate-to-sodium hydroxide ratio by mass of 1 [17] and tested after oven heating at a temperature 60 °C for duration of 24 h and tested after test period of 7 days [13].

2 Experimental Work

2.1 Materials

In the proposed mix proportioning method, low calcium processed fly ash of thermal power plant was used as source material. The laboratory grade sodium hydroxide in flake form (97.8 % purity) and sodium silicate (50.72 % solids) solutions are used as alkaline activators. Locally available river sand is used as fine aggregate and locally available 20 and 12.5 mm sizes crushed basalt stones are used as coarse aggregates.

2.2 Parameters Considered for Mix Proportioning of Geopolymer Concrete

For the development of fly ash based geopolymer concrete mix design method, detailed investigations have been carried out and following parameters were selected on the basis of workability and compressive strength.

A. **Fly ash**
   Quantity and fineness of fly ash plays an important role in the activation process of geopolymer. It was already pointed out that the strength of geopolymer concrete increases with increase in quantity and fineness of fly ash [12]. Similarly higher fineness shows higher workability and strength with early duration of heating. So, the main emphasis is given on quantity and fineness of fly ash in the development of mix proportioning procedure of geopolymer concrete. So, in the proposed mix design procedure, quantity of fly ash is selected from Fig. 1 on the basis of fineness of fly ash and target strength [12].

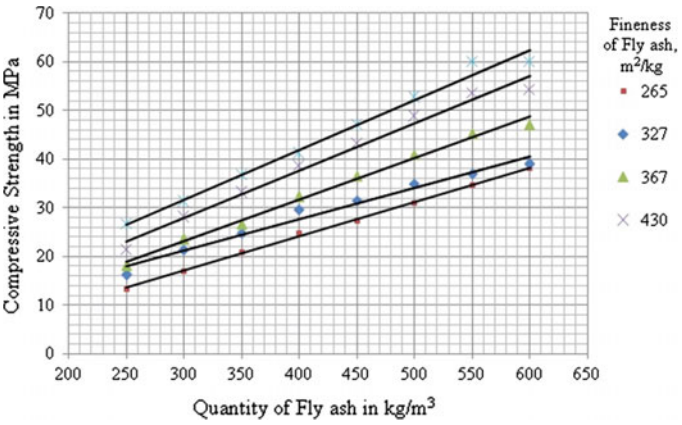

Fig. 1 Effect of quantity of fly ash on compressive strength for different fineness at solution-to-fly ash ratio of 0.35 [12]

B. **Alkaline Activators**

In the present investigation, sodium based alkaline activators are used. Single activator either sodium hydroxide or sodium silicate alone is not much effective as clearly seen from past investigation [17]. So, the combination of sodium hydroxide and sodium silicate solutions are used for the activation of fly ash based geopolymer concrete. It is observed that the compressive strength of geopolymer concrete increases with increase in concentration of sodium hydroxide solution and or sodium silicate solution with increased viscosity of fresh mix. Due to increase in concentration of sodium hydroxide solution in terms of molarity (M) makes the concrete more brittle with increased compressive strength. Secondly, the cost of sodium hydroxide solid is high and preparation is very caustic. Similarly to achieve desired degree of workability, extra water is required which ultimately reduce the concentration of sodium hydroxide solution. So, the concentration of sodium hydroxide was maintained at 13 M while concentration of sodium silicate solution contains Na_2O of 16.37 %, SiO_2 of 34.35 % and H_2O of 49.72 % is used as alkaline solutions. Similarly, sodium silicate-to-sodium hydroxide ratio by mass was maintained at 1 which set cubes within 24 h after casting and gives fairly good results of compressive strength [17].

C. **Water**

From the chemical reaction, it was observe that the water comes out from the mix during the polymerization process. The role of water in the geopolymer mix is to make workable concrete in plastic state and do not contribute towards the strength in hardened state. Similarly the demand of water increases with increase in fineness of source material for same degree of workability. So, the minimum quantity of water required to achieve desired workability is selected on the basis of degree of workability, fineness of fly ash and grading of fine aggregate [13].

D. **Aggregates**

Aggregates are inert mineral material used as filler in concrete which occupies 70–85 % volume. So, in the preparation of geopolymer concrete, fine and coarse aggregates are mixed in such a way that it gives least voids in the concrete mass. This was done by grading of fine aggregate and selecting suitable fine-to-total aggregate ratio. Workability of geopolymer concrete is also affected by grading of fine aggregate similar to cement concrete. So, on the basis of grading of fine aggregate, fine-to-total aggregate ratio is selected in the proposed mix proportioning method which is given in Fig. 2 [14].

E. **Degree of Heating**

For the development of geopolymer concrete, temperature and duration of heating plays an important role in the activation process. In the present investigation, cubes were demoulded after 24 h of casting and then place in an oven for heating at 60 °C for a period of 24 h. After specified degree of heating, oven is switched off and cubes are allowed to cool down to room temperature in an oven itself. Then compression test is carried out on geopolymer concrete cubes after a test period of 7 days. Test period is the period considered in between testing cubes for compressive strength and placing it in normal room temperature after heating. Table 1 shows the effect of duration of heating and test period on compressive strength of geopolymer concrete. It is observed that the compressive strength of geopolymer concrete increases with increase in duration and test period. From the design point of view, 24 h of oven curing at 60 °C and tested after a period of 7 days was fixed as per past research [13].

F. **Water-to-geopolymer binder ratio**

The ratio of total water (i.e. water present in solution and extra water if required) to material involve in polymerization process (i.e. fly ash and sodium silicate and sodium hydroxide solutions) plays an important role in the activation

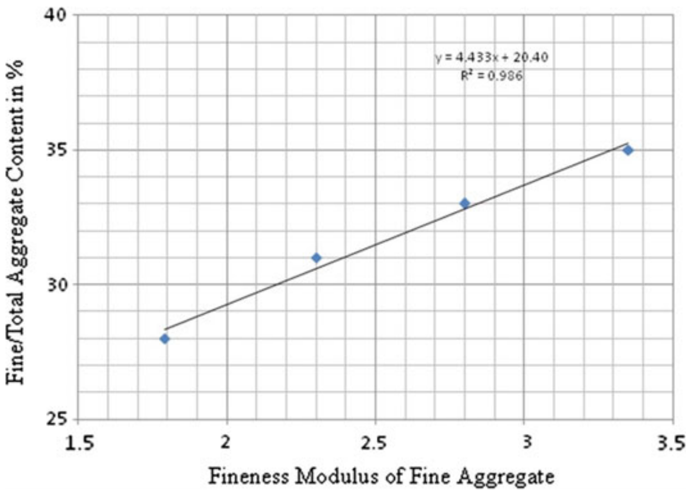

Fig. 2 Relation between fineness modulus of fine aggregate and fine-to-total aggregate content [14]

Table 1 Effect of heating temperature, duration and test period on compressive strength of geopolymer concrete [13]

S.No.	Temperature (°C)	Duration of heating (h)	Compressive strength in MPa				
			Tested after heating @				
			1 day	2 days	3 days	7 days	28 days
1	2	3	4	5	6	7	8
4	60	8	–	–	11.56	17.76	38.78
5		12	5.67	9.11	15.67	22.56	40.22
6		24	13.11	19.67	26.78	36.00	42.33

process. Rangan [10] suggested the water-to-geopolymer solid ratio in which only solid content in solution and fly ash is considered. But the calculation is tedious and water present in solution indicates the concentration of solution itself. So, in the present investigation, water-to-geopolymer binder ratio is considered. From the investigation, it is observed that the compressive strength reduces with increase in water-to-geopolymer binder ratio similar to water-to-cement ratio in cement concrete. At water-to-geopolymer binder ratio of 0.25, the mix was very stiff and at 0.40, the mix was segregated. Similarly water come out during polymerisation process and does not contribute anything to the strength. So, water-to-geopolymer binder ratio is maintained at 0.35 which gives better results of workability and compressive strength [16].

G. **Solution to fly ash ratio**
As solution (i.e. sodium silicate + sodium hydroxide) to fly ash ratio increases, strength is also increases. But the rate of gain of strength is not much significant beyond solution to fly ash ratio of 0.35. Similarly the mix was more and more viscous with higher ratios and unit cost is also increases. So, in the present mix design method, solution-to-fly ash ratio was maintained at 0.35 [15].

2.3 Preparation of Geopolymer Concrete Mixes

Preparation of geopolymer concrete is similar to that of cement concrete. Two types of coarse aggregates, sand and fly ash were mixed in dry state. Then add prepared mixture solution of sodium hydroxide and sodium silicate along with extra water based on water-to-geopolymer binder ratio and mix thoroughly for 3–4 min so as to give homogeneous mix.

It was found that the fresh fly ash based geopolymer concrete was viscous, cohesive and dark in color. After making the homogeneous mix, workability of fresh geopolymer concrete was measured by flow table apparatus as per IS 5512-1983 and IS 1727-1967. Concrete cubes of side 150 mm are casted in three layers. Each layer is well compacted by tamping rod of diameter 16 mm. All cubes were place on table vibrator and vibrated for 2 min for proper compaction of concrete. After compaction of concrete, the top surface was leveled by using trowel.

After 24 h of casting, all cubes were demoulded and then placed in an oven for thermal curing (heating). To avoid the sudden variation in temperature, the concrete cubes were allowed to cool down up to room temperature in an oven. Three cubes were cast and tested for compressive strength for each curing period.

3 Method Proposed for Mix Proportioning

Based on the experimental investigation carried out in the present study the following mix proportioning method is proposed.

3.1 Data Required for Mix Design

1. Characteristic compressive strength of Geopolymer Concrete (f_{ck})
2. Fineness of fly ash in terms of specific surface in m^2/kg
3. Workability in terms of flow
4. Oven curing (heating) 60 °C for 24 h and tested after 7 days
5. Fineness modulus of fine aggregate
6. Water absorption and water content in fine and coarse aggregate

Following design steps are used to select the suitable mix proportion of fly ash based geopolymer concrete.

3.2 Design Steps

1. **Target Mean Strength (F_{ck}) for Mix Design**

$$F_{ck} = f_{ck} + 1.65 \times S \tag{1}$$

   The standard deviation, S for each grade of geopolymer concrete shall be calculated, separately on the basis of minimum 30 test samples. With reference to IS 456-2000, the value of S is assumed as per Table 1 in the first instant as mentioned in clause 9. 2. 4. 2. [18].
2. **Selection of Quantity of Fly ash (F)**
   Quantity of fly ash selected based on target mean strength and fineness of fly ash at solution-to-fly ash ratio of 0.35 from Fig. 1.
3. **Calculation of the Quantity of Alkaline Activators**
   Based on the quantity of fly ash (F) determined in the previous step, the amount of total solution is obtained using solution-to-fly ash ratio of 0.35 by mass. After that, quantity of sodium silicate and sodium hydroxide is decided using sodium silicate-to-sodium hydroxide ratio of 1 by mass.

4. **Calculation of Total Solid Content in Alkaline Solution**
   Calculate solid content in sodium silicate and sodium hydroxide solution on the basis of percentage solid present in each solution.
5. **Selection of Quantity of Water**
   Workability of geopolymer concrete is depending on total quantity of water including water present in both alkaline solutions and the degree of workability. Select the total quantity of water required to achieve desired workability based on fineness of fly ash as per Table 2.
6. **Correction in Water Content**
   In concrete, volume occupied by fine and coarse aggregate is about 70–85 % of total volume. Similarly, finer particles have large surface area as compared to coarser one and hence required more water to produce workable mix. IS 10262 [19] suggested some correction in water content for the mix proportioning of cement concrete on the basis of grading of fine aggregate. In geopolymer concrete, the role of water is to make workable concrete. So, it is recommended to apply same correction to geopolymer concrete in the proposed mix design on the basis of grading zones of fine aggregate [15]. Table 3 shows the correction in water content per cubic meter of concrete on the basis of grading zones of fine aggregate.
7. **Calculation of Additional Quantity of Water**
   In geopolymer concrete, alkaline solutions are used which contains certain quantity of water on the basis of their concentration. But to meet workability requirements, additional water may be added in the mix externally which is calculated as:

$$\text{Additional quantity of water, if required} = [\text{Total quantity of water}] - [\text{Water present in alkaline solutions}]$$

Table 2 Water content per cubic meter of concrete [14]

Degree of workability	Flow in percentage	Quantity of water required in kg/m^3			
		Fineness of fly ash in m^2/kg			
		<300	300–400	400–500	>500
Low	0–25	80	85	100	110
Medium	25–50	90	95	110	120
High	50–100	100	110	120	135
Very high	100–150	120	130	140	160

Table 3 Correction in water content per cubic meter of concrete

Grading zone of fine aggregate as per IS 383 [20]	Correction in water content (%)
Zone-I	−1.5
Zone-II	–
Zone-III	+1.5
Zone-IV	+3

8. **Selection of Wet Density of Geopolymer Concrete**
   Select wet density of geopolymer concrete based on fineness of fly ash as per Fig. 3.
9. **Selection of Fine-to-Total Aggregate Content**
   Fine-to-total aggregate content is taken from Fig. 2 on the basis of grading (fineness modulus) of fine aggregate [15].
10. **Calculation of Fine and Coarse Aggregate Content**
    Fine and Coarse Aggregate Contents is obtained using following relations:

$$\begin{aligned}\text{Total quantity of aggregate} &= [\text{Wet Density of Geopolymer concrete}] \\ &\quad - [\text{Quantity of Geopolymer Binder} + \text{Additional water, if any}] \\ \text{Sand content} &= [\text{Fine-to-total aggregate content in \%}] \\ &\quad \times [\text{Total quantity of aggregate}] \\ \text{Coarse aggregate content} &= [\text{Total quantity of aggregate}] - [\text{Sand content}]\end{aligned}$$

11. **Actual Quantity of Materials Required on the Basis of Field Condition**
    The above mix proportion has been arrived on the assumption that aggregates are saturated and surface dry. For any deviation from this condition i.e. when aggregates are moist or air dry or bone dry, correction has to be applied on quantity of mixing water as well to the aggregates.

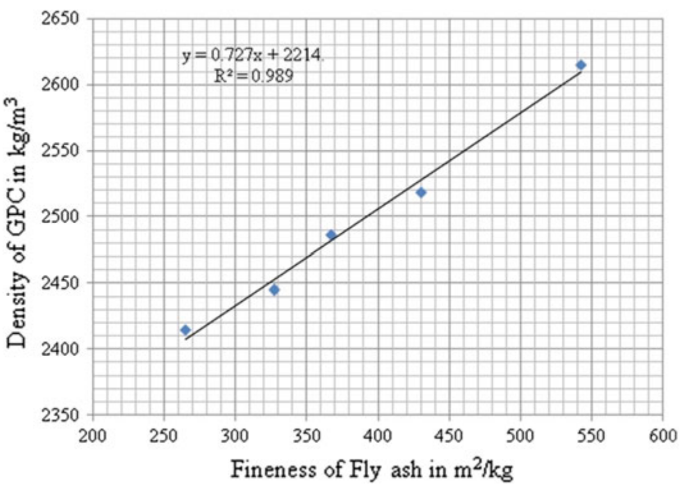

Fig. 3 Relation between fineness of fly ash and density of geopolymer concrete [15]

4 Mix Design for M30 Grade of Geopolymer Concrete Using Proposed Method

Based on the mix design steps discussed in preceding section, a sample mix proportioning for M30 grade of geopolymer concrete is carried out using proposed method. Following preliminary data is considered for the mix design:

1. Characteristic compressive strength of Geopolymer Concrete (f_{ck}) = 30 MPa.
2. Type of curing: Oven curing at 60 °C for 24 h and tested after 7 days
3. Workability in terms of flow: 25–50 % (Degree of workability—Medium)
4. Fly ash: Fineness in terms of specific surface: 430 m^2/kg
5. Alkaline activators (Na_2SiO_3 and NaOH)
   (a) Concentration of Sodium hydroxide in terms of molarity: 13 M
   (b) Concentration of Sodium silicate solution: 50.32 % solid content
6. Solution-to-fly ash ratio by mass: 0.35
7. Sodium silicate-to-sodium hydroxide ratio by mass: 1.0
8. Fine aggregate
   (a) Type: Natural river sand confirming to grading zone-I as per IS 383 [20], F.M. = 3.35
   (b) Water absorption: 3.67 %
   (c) Water content: Nil
9. Coarse aggregate
   (a) Type: Crushed/angular
   (b) Maximum size: 20 mm
   (c) Water absorption: 0.89 %
   (d) Moisture content: Nil.

5 Design Steps

1. Target mean strength
   Fck = 38.25 MPa
2. Selection of quantity of fly ash
   From Fig. 1, the quantity of fly ash required is 405 kg/m^3 for the target mean strength of 38.25 MPa at solution-to-fly ash ratio of 0.35 and for 430 m^2/kg fineness of fly ash
3. Calculation of the quantity of alkaline activators

Calculate the quantity of alkaline activators considering:

$$\begin{aligned} \text{Solution/Fly ash ratio by mass} &= 0.35 \\ \text{i.e. Mass of } (Na_2SiO_3 + NaOH)/\text{Fly ash} &= 0.35 \\ \text{Mass of } (Na_2SiO_3 + NaOH)/405 &= 0.35 \\ \text{Mass of } (Na_2SiO_3 + NaOH) &= 141.75\,\text{kg/m}^3 \end{aligned}$$

Take the sodium silicate-to-sodium hydroxide ratio by mass of 1
Mass of sodium hydroxide solution (NaOH) = 70.88 kg/m^3
Mass of sodium silicate solution (Na_2SiO_3) = 70.88 kg/m^3

4. Calculation of total solid content in alkaline solution

$$\begin{aligned} \text{Solid content in sodium silicate solution} &= (50.32/100) \times 70.88 \\ &= 35.67\ \text{kg/m}^3 \\ \text{Solid content in sodium hydroxide solution} &= (38.50/100) \times 70.88 \\ &= 27.29\ \text{kg/m}^3 \\ \text{Total Solid content in both alkaline solutions} &= 62.96\ \text{kg/m}^3 \end{aligned}$$

5. Selection of water content
   For medium degree of workability and fineness of fly ash of 430 m^2/kg, water content per cubic meter of geopolymer concrete is selected from Table 2
   Water content = 110 kg/m^3
6. Adjustment in water content
   For sand conforming to grading-I, correction in water content is taken from Table 3

$$\begin{aligned} \text{Adjustment in water content} &= -1.5\,\% \\ \text{Total quantity of water required} &= 110 - (1.5/100) \times 110 \\ &= 108.35\,\text{kg/m}^3 \end{aligned}$$

$$\begin{aligned} \text{Water content in alkaline solutions} &= 141.75 - 62.96 \\ &= 78.79\,\text{kg/m}^3 \end{aligned}$$

7. Calculation of additional quantity of water
   = [Total quantity of water] − [Water present in alkaline solutions]
   = 108.35 − 78.79 = 29.46 kg/m^3
8. Selection of wet density of geopolymer concrete
   From Fig. 3, wet density of geopolymer concrete is 2,528 kg/m^3 for the fineness of fly ash of 430 m^2/kg
9. Selection of fine-to-total aggregate content

Table 4 Materials required for M30 grade geopolymer concrete

Ingredients of geopolymer concrete	Fly ash	NaOH	Na_2SiO_3	Sand	Coarse aggregate	Total water (W/GPB)	Extra water
Quantity (kg/m^3)	405	70.88	70.88	683.13	1,268.66	108.35	29.46
Proportion	1	0.35		1.82	3.37	0.211	0.07

From Fig. 2, Fine-to-total aggregate content is 35% for fineness modulus of sand of 3.35

10. Calculation of fine and coarse aggregate content

$$\begin{aligned}\text{Total aggregate content} &= [\text{Wet density of GPC}] - [\text{Quantity of fly ash} \\ &\quad + \text{Quantity of both solutions} + \text{extra water, if any}] \\ &= 2{,}528 - [405 + 141.75 + 29.46] \\ &= 1{,}951.79\ \text{kg/m}^3\end{aligned}$$

$$\begin{aligned}\text{Sand content} &= [\text{Fine} - \text{to} - \text{total aggregate content in }\%] \\ &\quad \times [\text{Total quantity of all-in-aggregate}] \\ &= (35/100) \times 1{,}951.79 \\ &= 683.13\ \text{kg/m}^3\end{aligned}$$

$$\begin{aligned}\text{Coarse aggregate content} &= [\text{Total quantity of all-in-aggregate}] - [\text{Sand content}] \\ &= 1{,}951.79 - 683.13 \\ &= 1{,}268.66\ \text{kg/m}^3\end{aligned}$$

Quantity of materials required per cubic meter for M30 grade of geopolymer concrete is shown in Table 4.

6 Results and Discussions

Geopolymer concrete mix is prepared using mix proportion calculated in preceding section and shown in Table 4. It was found that the fresh fly ash-based geopolymer concrete was viscous, cohesive and dark in colour and glassy appearance. After making the homogeneous mix, workability of fresh geopolymer concrete was measured by flow table apparatus as per IS 5512-1983 and IS 1727-1967. Freshly mixed geopolymer concrete is viscous in nature and water comes out during polymerization process, methods like slump cone test is not suitable to measure workability as concrete subside for long time while in compaction factor test, concrete cannot flow freely. So, flow table test is recommended for workability measurement of

Table 5 Results of M30 grade geopolymer concrete

Observation	Data considered in mix design	Results obtained
Workability (flow)	25–50 %	44.15 %
Degree of workability	Medium	Medium
Temperature/duration	60 °C/24 h	60 °C/24 h
Mass density	2,528 kg/m^3	2,601.48 kg/m^3
Compressive strength @ 7 days after heating	38.25 MPa (target strength)	37.22 MPa

geopolymer concrete. From Table 5, it is observed that the result of workability in terms of flow is 44.15 % which is in between 25 and 50 % which was considered for the design mix. That means the degree of workability is lies within considerable limit.

After measuring workability, concrete cubes of side 150 mm were cast in three layers and each is properly compacted similar to cement concrete. Then after 24 h of casting, all cubes were demoulded and weight was taken for the calculation of mass density. Average weight of three cubes was considered for calculation of mass density. It is observed that the average mass density obtained by proposed method is 2,601.48 kg/m^3 which is 3.33 % higher than that considered in design method.

Then cubes were placed in an oven for thermal curing at 60 °C for 24 h. To avoid sudden variation in temperature, the concrete cubes were allowed to cool down up to room temperature in an oven itself. Three cubes were cast and tested for compressive strength after 7 days of test period. Here, test period is the period considered after removing the cubes from oven till the time of testing for compressive strength. It is observed that the compressive strength of M30 grade geopolymer concrete is 37.22 MPa tested after 7 days of test period which is 2.69 % less than the target strength (38.25 MPa) considered in proposed mix design method which is within the limit of +/−15 % as per IS 456-2000.

In the previous design mixes provided by Rangan [10] and Anuradha [11], the major parameters such as fineness and quantity of fly ash, quantity of water, grading of aggregates and fine-to-total aggregate ratio were not considered. These parameters are also considered in the proposed method. The results of workability and compressive strength as per the proposed method match well with the targeted values. Present method also provides, comparatively, economical mix.

7 Mix Proportions for Various Grades of Geopolymer Concrete

Table 6 shows the quantities of all ingredients of fly ash based geopolymer concrete calculated using proposed method of mix proportioning. Also Table 7 shows the comparison between the theoretical result expected for M20–M40 grade geopolymer concrete and the experimental results of the workability and compressive strength obtained in the laboratory.

Table 6 Geopolymer concrete mixes for different grades

Grade	Quantity of water (kg/m^3) (W/GPB)[a]	GPB (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
M20	118.20	378	727.40	1350.88
	0.313	1	1.92	3.57
M25	118.20	445.50	707.53	1313.97
	0.265	1	1.59	2.95
M30	108.35	513	690.54	1282.43
	0.211	1	1.35	2.5
M35	108.35	594	667.19	1239.07
	0.182	1	1.12	2.08
M40	98.50	661.50	649.37	1205.97
	0.149	1	0.98	1.82

[a] *W* Quantity of water including extra water if any. *GPB* Geopolymer binder i.e. Fly ash + (NaOH + Na_2SiO_3) solution

Table 7 Test results of present mix proportioning method for different grades of geopolymer concrete

Grade of concrete	M20	M25	M30	M35	M40
Workability in terms of flow, (%)	77.86	61.61	44.15	29.17	21.20
Degree of workability	High	High	Medium	Medium	Low
Wet density, kg/m^3	2558.52	2582.22	2601.48	2610.37	2597.04
Compressive strength, MPa	28.67	33.33	37.22	43.56	44.78

8 Conclusions

This paper proposed the guidelines for the design of fly ash based geopolymer concrete of ordinary and standard grade on the basis of quantity and fineness of fly ash, quantity of water and grading of fine aggregate by maintaining water-to-geopolymer binder ratio of 0.35, solution-to-fly ash ratio of 0.35, and sodium silicate-to-sodium hydroxide ratio of 1 with concentration of sodium hydroxide as 13 M. Heat curing was done at 60 °C for duration of 24 h and tested after 7 days after oven heating. Experimental results of M20, M25, M30, M35 and M40 grades of geopolymer concrete mixes using proposed method of mix design shows promising results of workability and compressive strength. So, these guidelines help in design of fly ash based geopolymer concrete of Ordinary and Standard Grades as mentioned in IS 456: 2000.

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