International Journal of Concrete Technology
Vol. 1: Issue 2
www.journalspub.com

Influence of GGBFS on the Mechanical Properties of the Water Cured Fly Ash Aggregate-Based Geopolymer Concrete

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Abstract
Conventional concrete consists of cement, sand as fine aggregate and gravel, limestone or granite in various sizes and shapes as coarse aggregate including with water. In the present work, the feasibility of using industrial inorganic polymeric residues wastes as a total (100%) replacement to the traditionally used normal conventional concrete materials is examined in the preparation of the geopolymer concrete (GPC). In this GPC, the cement is totally replaced by the fly ash (class F) with ground granular blast furnace slag (GGBFS), bottom ash is used in place of fine aggregate, water cured fly ash aggregates (WCA) were (prepared using the class C fly ash by adopting palletisation technique) used in place of coarse aggregate and the alkaline solution is used in place of water for polymerization purpose with binding material. A new design mix (volume batch) procedure was formulated for geopolymer concrete. The GPC mixes were cast with WCA at 0, 10, 20 and 30%replacement of fly ash (class F) by GGBFS at 8 molar ratios of NaOH solution. The concrete was cured at normal room/ambient temperature only to minimise the water in the water curing. The physical and mechanical properties of the GPC were studied. It was observed that the GPC mixes with WCA at 30% GGBFS with 8 Molar ratio of NaOH concentration attained maximum compressive strengths of 33.93 MPa cured at room temperature.

Keywords: bottom ash, fly ash, ground granulated blast furnace slag, palletisation, sodium hydroxide solution

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INTRODUCTION

Coal/lignite-based thermal power generation has been the backbone of capacity addition in the country. Indian coal contains ash content as high as 45% compared to imported coals.

A large quantity of ash is, thus, being generated at coal/lignite-based thermal power stations in the country, which not only requires large area of land for its disposal, but is also a source of pollution (air and water). In India, 184.14 million tonnes of fly ash was produced in 2014 from the 143 thermal power stations.

The utilization of the fly ash for various purposes is shown in Figure 1 (Source from Central Electricity Authority, New Delhi, India). From this only 0.74% of the fly ash only is utilized for the preparation of concrete. Actually in any type of concrete, 65–75% of the volume is occupied as inert filler by the course aggregates only. To fill this volume natural crushed aggregates are generally used and the bulk usage of these aggregates leads to the depletion of natural resources. To maintain this resource, an alternative artificial aggregate is needed. Fly ash is used as raw material from the thermal power stations of waste by product for production of the fly ash aggregates artificially.

This quantity is estimated to reach about 225 million tons by the end 2017. From Figure 2 (Source from Central Electricity Authority, New Delhi, India) Out of this only 44.44% of fly ash was utilized for various purposes and the remaining 55.55% is not used and is simply disposed on land.

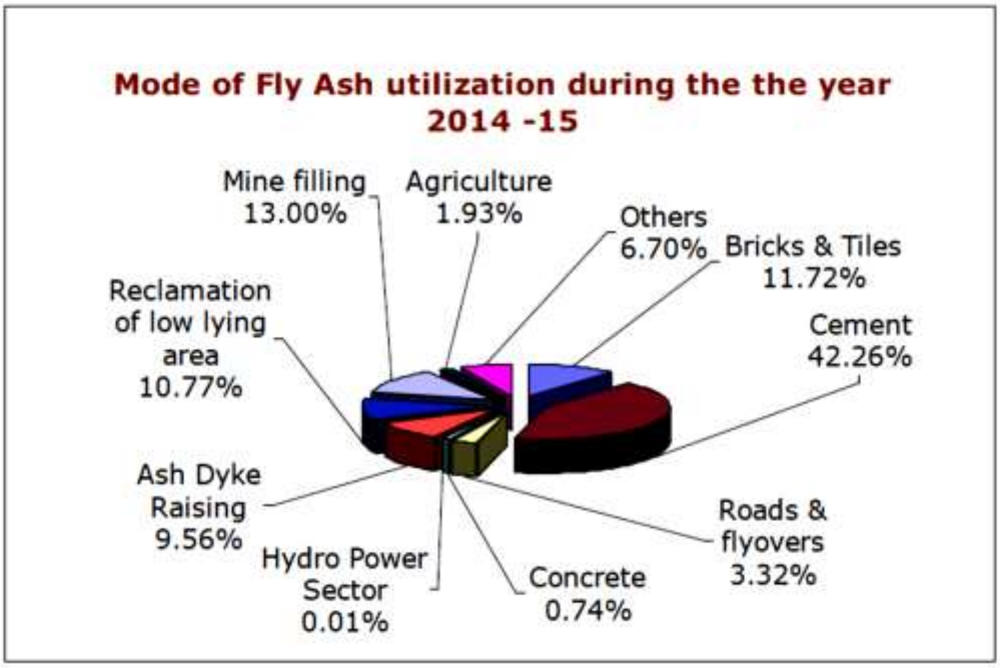

Fig. 1. *Percentage Utilization of Fly Ash.*

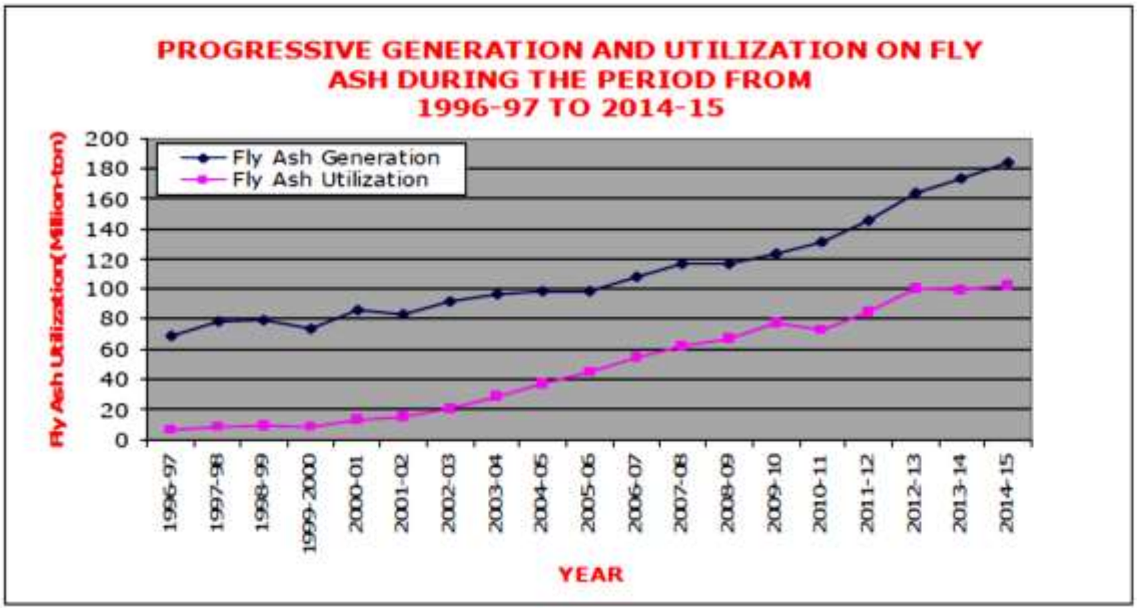

Fig. 2. *Utilization of the Fly Ash.*

As per previous studies, Wasserman et al.[1] have conducted the crushing tests for aggregates as well as concretes prepared with these aggregate and compared the results. The microstructure observation at low magnification shows that core and external shell could be distinct. Pores in the shell are smaller. The overall composition of the aggregates has been obtained by X-ray diffraction. Silica content was 63.1%. The tests for the properties like porosity, density and absorption has also been conducted. Verma et al.[2] This paper discusses about the method of production, pilot plant investigation, process of a demonstrative unit, equipment specifications, cost economics, etc. The raw materials used are fly ash, coal dust and clayey soil. It has been concluded that the demand for these aggregates is yet to be established in India. Due to the low modulus of elasticity, the resistance of lightweight concrete to impact forces and vibrations is greater than that of commercial concrete. Hardjito *et al.*[3]

This paper presents the information about fly ash-based geopolymer concrete. It covers the materials used, mix proportions, manufacturing process and influence of various parameters on the properties of fresh and hardened concrete. The base material used is two batches of low calcium (class F) dry fly ash obtained from local power station silos. Chang et al.[4] This paper discusses the engineering properties of lightweight aggregate concrete by adopting stress wave propagation methods. Two kinds of sintered light weight aggregates were used in this study to cast 100 × 200 mm cylindrical and 600 × 600 × 200 mm plate specimens. The method implemented was ultrasonic pulse velocity method in ASTM C597-02, impact-echo method in ASTM C1383-04 and one-sided wave velocity method ASTM C1383-04 were used. Jo et al.[5] In this paper, investigation has been done on the properties of the hardened paste of fly ash by alkali activation and to determine the possible use of the paste in the production of lightweight aggregates.

The highest compressive strength was 33.9 MPa, for paste with 10% NaOH, 15% sodium silicate and 5% MnO_2, cured at room temperature after 24 h of moisture curing at 50 °C. Biernacki et al.[6] This paper discusses about the sinterability of a class F fly ash. An experiment has been conducted to correlate density, shrinkage, splitting tensile strength, water absorption can evaluated as measure of sintering efficiency. Cylindrical specimens of size 2.54 × 1.4 cm size with composition of fly ash 95%, water 2% and corn syrup 3% was used. SEM and X-ray microanalysis were conducted. The effect of sintering time was observed by sintering the samples for a period of 0, 30, 60, 90 min at each temperature 1050–1200 ℃. A maximum density of 1703 kg/m^3 was observed in the case of 1200 ℃ and 90 min of sintering time.

A complex interaction between sintering time and temperature was found which was revealed in densification and binder volatilization. Mishra et al.[7] This paper present results of an experimental study on the water absorption characteristics of GPC. The experiments were conducted on fly ash-based GPC by varying the concentration of NaOH and curing time. Total nine mixes were prepared with NaOH concentration as 8, 12, 16M and curing time as 24, 48 and 72 h. Compressive strength, water absorption and tensile strength tests were conducted on each of nine mixes. Lloyd and Rangan[8] This paper discusses about the progress of development and opportunities of geopolymer concrete.

This paper presents the results on mix design development which will improve workability and strength of the specimen. The influence factors such as curing temperature, aggregate shape, strength, moisture content, preparation grading are also presented. It was concluded that the aggregate particle size and grading on properties of geopolymer concrete is similar to that of OPC. The economic benefits and contributions of GPC to sustainable development are also outlined in this paper, Anuradha et al.[9] A new design procedure was formulated for Geopolymer Concrete which was relevant to Indian standard (IS 10262-2009) and find out the mechanical properties based on the new design. Gomathi et al.[10] investigated the strength characterization of fly ash aggregates using alkali activator as a binder in the Pelletisation process and followed controlled humidity curing, hot air oven curing for the preparation of fly ash aggregates. The production efficiency is also found to be dependent on the percentage of binders, and concentration of alkali activator added to the fly ash.

The objectives of the present study are

1. To prepare fly ash aggregates without using any binding material.
2. To cast the GeoPolymer Concrete (GPC) mixes with WCA at 0%, 10%, 20% and 30% replacement of fly ash (class F) by Ground Granulated Blast Furnace Slag (GGBFS) at 8 molar ratio of NaOH solution (8 M) and to cure the concrete at normal room/ambient temperature.
3. To compare the mechanical properties and workability of the GPC mixes of the above.

EXPERIMENTAL METHODS

Materials Used

The materials used for this study consist of

1. Fly ash (class F) which is obtained from Mettur thermal power plant, Tamil Nadu, India was used as a binding material for the preparation of GPC.
2. Granulated Ground Blast Furnace Slag (GGBFS) used as admixtures for partial replacement of Fly ash (class F) up to 30%.
3. Lignite fly ash (class C) which is obtained from Neyveli Lignite Corporation, Tamil Nadu, India was used for the preparation of fly ash aggregates (using disc type pelletizer) in place of normal conventional granite aggregates.
4. Bottom ash is used as fine aggregate in place of normal conventional fine aggregate (sand) from the Neyveli Lignite Corporation, Tamil Nadu, India.
5. Sodium silicate (Na_2SiO_3) which has 15.9 % Na_2O, 31.4% SiO_2 and 52.7% water and Sodium hydroxide (NaOH) flakes with 97 to 98 % purity is used for the preparation of the alkaline solution with 8 molar ratios (8 M).
6. Fosroc conplast SP 430 superplasticizer were used for the preparation of GPC to maintain workability.

Physical Properties of the Fly Ash

The physical property of the industrial waste materials is shown in Tables 1 and 2 used for the preparation of fly ash aggregates.

From Table 1, it is clearly indicated that the majority of the particles are above a range of 75 µm.

Table 1. *Sieve Analysis of Industrial Waste Materials*.

Sieve size (µm)		300	150	75	63	45	38
100% Finer	Class C: fly ash	100	65.12	8.42	6.66	3.26	0.96
	GGBFS	100	89.4	13	3.2	1	0.4
	Class F: fly ash	100	96.6	32.8	25.8	9.4	4.6

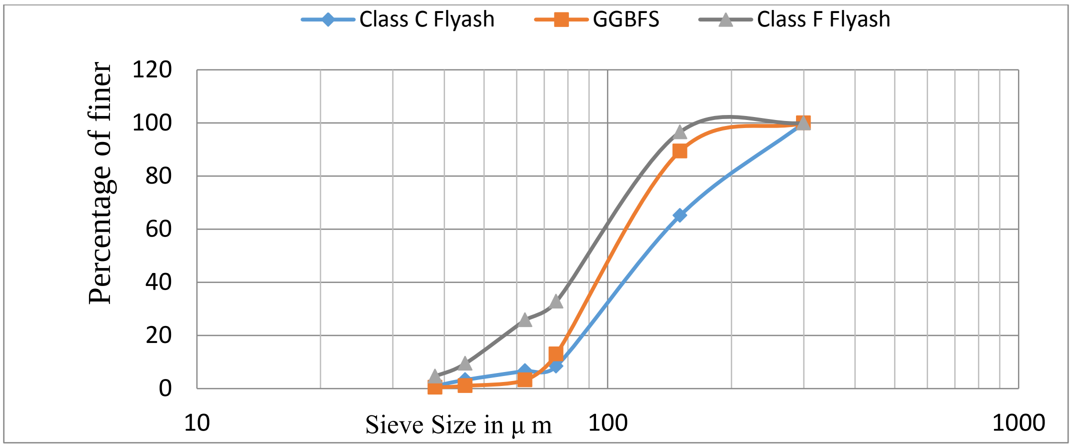

Fig. 3. *Particle Size Distribution (Semi-Log Graph).*

Table 2. *Physical Properties of Materials.*

Materials	**Fly ash**		**GGBFS**	**Fine aggregate(bottom ash)**	**Coarse aggregate (WCA)**
	Class C	**Class F**			
Specific gravity	2.62	2.64	2.63	2.64	1.87
Particle size	Slightly less than 38–300 µm			0.15–2.36 mm	4.75–16.0 mm

Figure 3 shows that the particles present in class C fly ash are more coarse compared with GGBFS, followed by class F fly ash. From Table 2, it is observed the physical properties of the industrial waste material, i.e., fly ash with class C, class F, GGBFS, bottom ash and the fly ash aggregates, i.e., WCA and CCA.

The SEM images of fly ash are shown in Figure 4 with various shapes like sphere, agglomerate and angular.

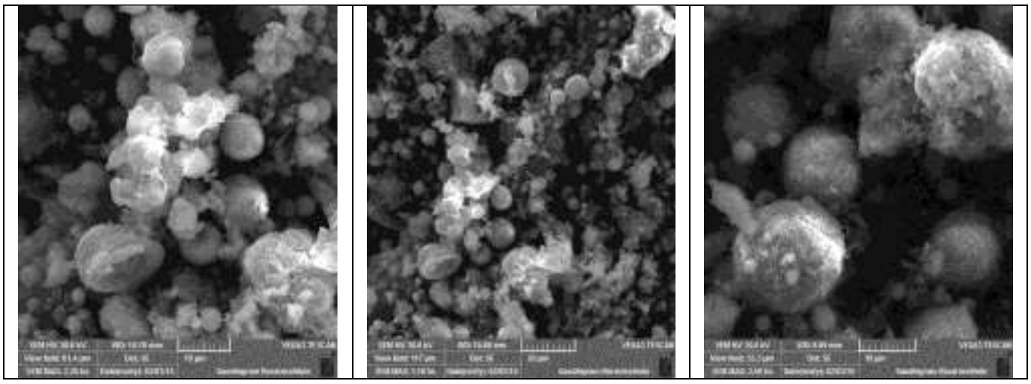

Fig. 4. *SEM Micrograph of Class C Fly Ash.*

From the Figure 5, the phase analysis of the catalyst was investigated by X-ray diffraction (XRD) (Model: Rigaku, D/MAX, Ultima III, Japan) at a scan speed of 10°/minute and step size of 0.02 for a scan range of 10°–80°. The peaks obtained were compared with the data from the Joint Committee on Powder Diffraction Standards (JCPDS).

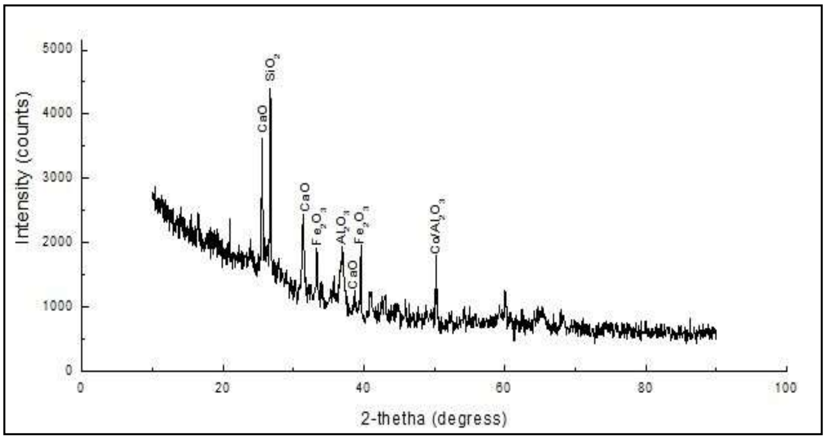

Fig. 5. *XRD of Fly Ash (Class C).*

Table 3. *Chemical Compositions of the Industrial Waste Materials*.

Chemical compositions (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl
Class C fly ash	25.3	24.54	12.91	20.21	4.85	7.95	1.25	0.13	0.020
Class F fly ash	60.86	24.35	3.936	1.73	0.00	0.57	4.56	1.33	0.025
Bottom ash	77.91	2.97	6.16	3.68	1.04	7.32	0.53	0.05	0.05
GGBFS	32.84	11.01	0.89	45.67	4.28	2.69	0.00	0.26	0.004

Chemical Composition of the Industrial Waste Materials

The chemical composition of fly ash is obtained from X-ray fluorescence (XRF) and shown in Table 3.

The sum of the chemical composition concentration of the $SiO_{2,}$ $Al_2O_{3,}$ Fe_2O_3 more than 50% it is classified as class C the sum of the chemical composition concentration of the $SiO_{2,}$ $Al_2O_{3,}$ Fe_2O_3 more than 70% it is classified as class F and as per ASTM C 618-91.

Pelletisation

It is the process of consolidating finer moisturized particles into larger solid material due to the thumbing force without application of external force using Disc type pelletizer. The pellets formed, attain sufficient strength by the force generated by itself, inside the mixer.

Preparation of Fly Ash Aggregates

A 6 kg of dry fly ash (class C) is fed into the pelletizer disc after fixing the angle of the drum and constant speed of the motor to assure the homogeneity of the mixer shown in Figure 6a.

(a) (b)

Fig. 6. *Fly Ash Aggregates, (a) Pelletizer Machine, (b) Palletised Aggregates.*

Then pour a certain percentage of water into the fly ash as the coagulant and add it to the fly ash in the disc by sprinkling it, to form spherical pellets by consolidating finer moisturized particles into the larger solid material without application of external force, with the motion of the rolling disc of the agglomeration process. Proper care should be taken to avoid water film on the surface of the pellets during the preparation of the pellets. Note the time taken for complete agglomeration process of fly ash and formation of the pellets inside the disc. After completing the formation of the pellets, the fly ash aggregates are allowed to air dry to get the initial handling purposes. The procedure is repeated by changing the angle, speed and the percentage of the water until the maximum efficiency of the agglomeration or pelletisation is reached flowed by curing the fly ash aggregates in the water for 7 and 28-days, i.e. water curing (WCA).

Mix Proportions

A new design mix (volume batch) procedure was formulated for preparing the geopolymer concrete (Tables 4 and 5).

Table 4. *Design Mix of Light Weight GPC for 1 m^3.*

Input parameters					
Sp. gravity of fly ash	2.64	Vol of aggregates (assumed)			0.67
Sp. gravity of coarse aggregate	1.87	Air entraint (%)		1	0.01
Sp. gravity of fine aggregate (bottom ash)	2.65	Total volume			**0.68**
Sp. gravity of NaOH	1.2	Extra water (%) of FA		10	0.044
Sp. gravity of Na_2Sio_3	1.6	Vol of SP (%) of FA		1.5	0.005
Sp. gravity of S.P	1.2	Vol. FA = (440.66/2640)			0.167
$NaOH/Na_2SiO_3$	2.5	Vol of sol = (154.2/1490)			0.104
Sp. gravity of solution = (Sp.gr of NaOH*1 + Sp.gr of Na_2Sio_3*2.5)/(1 + 2.5)	1.48		Total volume (checked)		1.000
Alkaline sol/FA ratio	0.35				
Output values					
Assumed vol of CA = 68% and fine aggregate = 32%					
Weight of coarse aggregate (kg) = vol of CA*Vol of total Aggregate* Sp. gravity of CA*1000	0.68	0.67	1.87	1000	851.97
Weight of fine aggregate (kg) = vol of FA*vol of total aggregate* Sp. gravity of FA*1000	0.32	0.67	2.65	1000	568.16
Vol of (Fly Ash + alkaline solution + water+S.P) = (1–total vol of aggregates – vol of assumed air entrainment)	0.32				
(Wt. of FA/Sp.gr. of FA) + (Wt. of Alkaline solution/Sp.gr of combined sol.) + Assumed% of FA/Sp.gr. of water) + (Assumed % of FA/Sp.gr. of SP)				0.32	
Assume Wt of FA = Z, then (X/2.64) + (0.35X/1.49) + (0.1X/1.0) + (0.015X/1.2)) = 0.32					
Wt of Fly Ash(Z) in (kg)=					439.7
Alkaline solution = Wt of Fly Ash(Z)*0.35	153.9	kg			
Wt of NaOH (kg) = (wt. of Alkaline solution)/(1 + 2.5)					43.97
Wt of Na_2SiO_3 (kg) = wt of Alkaline solution – wt of NaOH					109.93
wt of water (kg) = 10% of wt of FA = 0.1*440.66					43.97
wt of S.P (kg) = 1.5% of wt of FA = 0.015*440.66					6.60
	Total wt of concrete (kg)=				2064.30

Aggregate Gradation

To study the effect of these lightweight aggregates on compressive strength and workability of concrete, the aggregate with sizes 12–16 mm and 4.75—12 mm are taken as 70 and 30% by weight of total coarse aggregate, respectively. The coarse aggregate and fine aggregate proportions are taken as 68 and 32% by volume of total aggregate, respectively.

Mix Design

Table 5. *Mix Proportions of GPC Mixes With Different Fly Ash Aggregates.*

Description (Weight)	Water cured aggregate (WCA) GPC			
	0% GGBFS	**10% GGBFS**	**20% GGBFS**	**30% GGBFS**
Fly ash (class F)	440.36	396.32	352.29	308.25
GGBFS	-	44.036	88.072	132.11
Sodium hydroxide (for 8, 10, 12 M)	44	44	44	44
Sodium silicate	110	110	110	110
Coarse aggregate (FAA) (class C fly ash)	852	852	852	852
Fine aggregate (class C- bottom ash)	568	568	568	568
Extra water (10% weight of binding material i.e. FA)	44.04	44.04	44.04	44.04
Super plasticizer – fosroc conplast SP 430 (1.5% weight of fly ash)	6.61	6.61	6.61	6.61

Details of Mixing

The NaOH solution is prepared 24 h before the concrete mixing and then is mixed with the sodium silicate solution according to their ratio just 30 min before concrete mixing. First fly ash (class F), GGBFS and bottom ash are added to the pan mixer and mixed thoroughly. Then alkaline solution followed by extra water and superplasticizer are added, and mixing is continuous for 3 min until the mortar paste is uniform. The coarse aggregate is added next and allowed to mix for 2 min. Then the fresh GPC is placed into 100 mm × 100 mm × 100 mm cube moulds in accordance with IS 516: 1959.

RESULTS AND DISCUSSIONS

Tests on Fly Ash Aggregates

The crushing strength tests was conducted for different diameters of fly ash aggregate pellets from 6 to 16 mm by using Digital Display California Bearing ration (CBR) testing machine shown in Figure 7, the specific gravity and water absorption were determined as per ASTM C127.

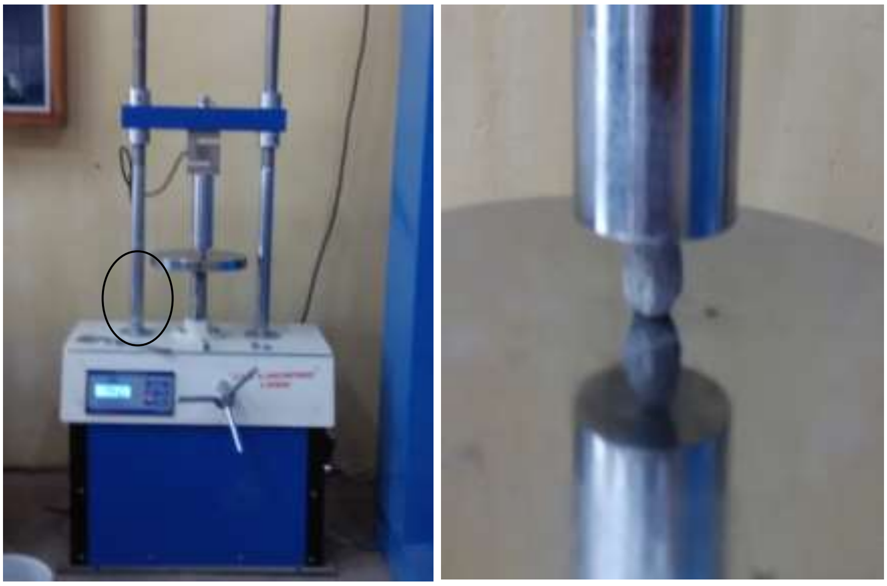

Fig. 7. *Crushing Strength (Digital Display) of the Pellets Tested Using CBR Testing Machine.*

Individual crushing strength of the pellets σ (MPa) = $\frac{2.8*P}{\pi*X^2}$

here P is the failure load (kN) and X is the distance between the two plates (mm).

A total of 25 numbers of pellets was taken for calculating the mean crushing strength of the aggregates from each method of curing.

Table 6. *Properties of the Water Cured Fly Ash Aggregates*.

Description	Specific gravity	Rodded bulk density (kN/m^3)	Percentage of water absorption in		Mean crushing strength (MPa)	
			7 days	28 days	7 days	28 days
WCA	1.86	1235	12.25	12.25	2.93	3.63

Fresh Properties Slump Cone Test

The slump cone test was performed for all the GPC mixes to check the workability. The maximum slump values of 80 mm were obtained for the GPC mixes with 8 M NaOH solution at 0% GGBFS replacement having WCA.

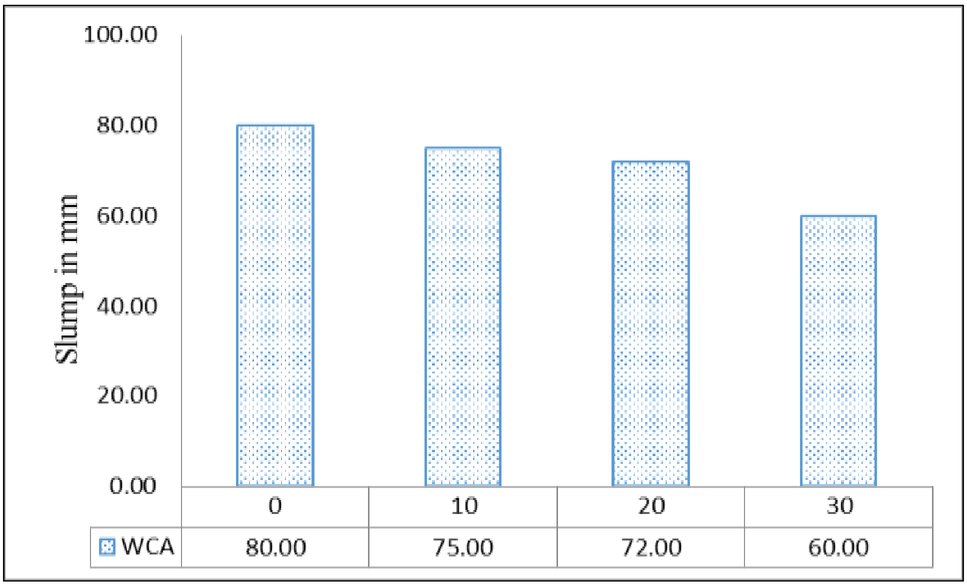

Fig. 8. *Workability (Slump) of GPC Mixes with WCA at 8 Molar Ratio With Different % of GGBFS.*

It is observed from the Figure 8**,** the workability is decreased with increase the percentages of GGBFS to the fly ash replacements.

Density and Compressive Strength

The density of 100 mm × 100 mm × 100 mm mould specimens was determined after 28 days. After the density determination, the cube specimens were tested in the compression testing machine to determine the compressive strength in accordance with IS 516:1959. The reported density and compressive strengths are the average of three samples. The densities of GPC mix with WCA at 8 Molar Ratios with different % of GGBFS shown in Figure 9. The densities of concrete are observed after 28 days cured at ambient curing.

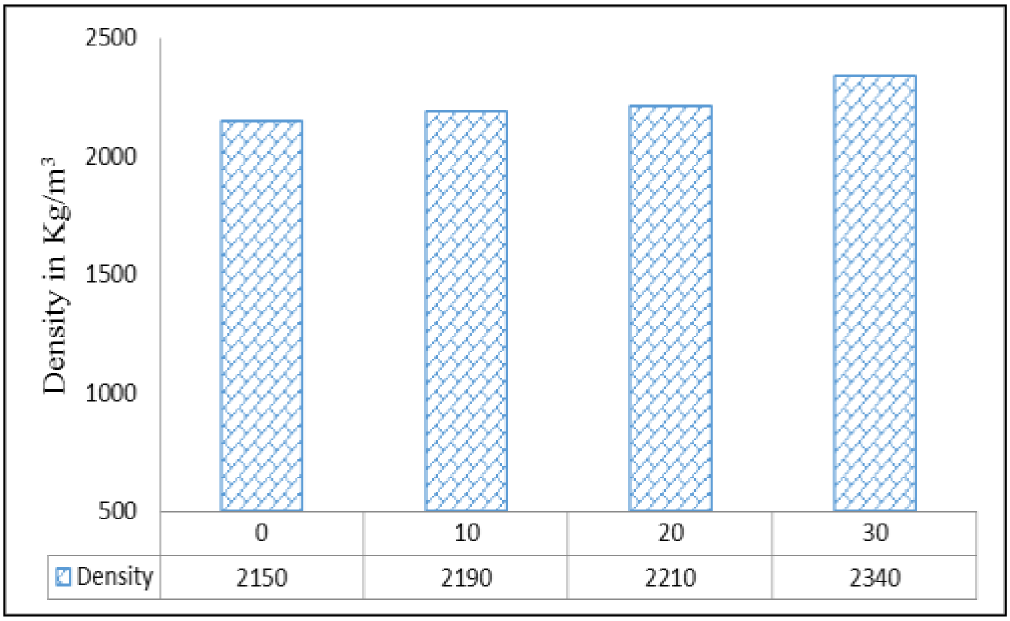

Fig. 9. *Densities of GPC Mix With WCA at 8 Molar Ratios With Different % of GGBFS.*

The densities of GPC mixes also did not change with the replacement of GGBFS. As both fly ash and GGBFS have similar specific gravity, there is no variation in the density of the GPC specimens is only up to 10%.

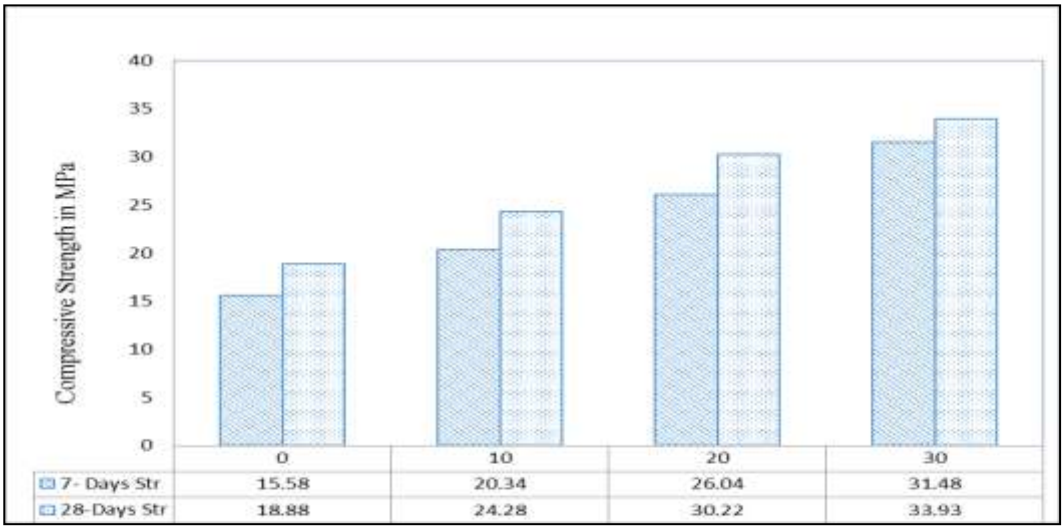

Fig. 10. *Compressive Strength of GPC by Using WCA With 8 molar Ratios and Different Percentages of GGBFS Content After 7 and 28 days Curing.*

From the Figure 10 shown the minimum and maximum compressive strength of all GPC mixes by using WCA at 8 molar ratios and different percentages of GGBFS content after 7 days ambient curing is 15.58 MPa at 0% GGBFS and 18.88 MPa at 30% GGBFS replacement level and after 28 days ambient curing is 31.48 MPa at 0% GGBFS and 33.93 MPa at 30% GGBFS replacement level.

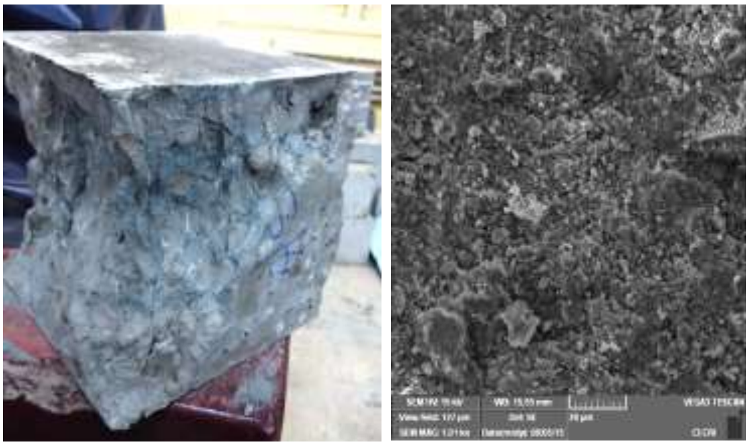

Fig. 11. *Fractured GPC Specimens and SEM Images.*

From the Figure 11 shows the GPC matrix appears to be uniform in colour, homogeneous and dense microstructure in the WCA GPC specimens. It is also observed that the interface transition zone had a tight and interlocking between the aggregates.

From Figure 10, it is observed that

1. The compressive strength of GPC mixes increased with the increase in GGBFS replacement from 0 to 30%. Due to further increased percentage of GGBFS the GPC mixes became flash set, so GGBFS replacement is restricted to 30% by weight of fly ash.
2. In this type of high strength concretes, the aggregate was considered weaker when compared to the matrix. So the mix design concepts were usually based on preparing high strength matrix with low alkaline solution to fly ash ratio to compensate for the aggregate's weakness.

CONCLUSIONS

Based on the test results and discussions the following are the conclusions drawn:

1. It is 100% successfully proved that the replacement of conventional concrete material in the concrete by industrial inorganic polymeric incineration residue.
2. The concrete can be done even in remote areas where the water is not available for mixing and curing purposes.
3. The compressive strength of concrete increases with partial replacement of fly ash by GGBFS content. As the percentage of GGBFS replacement increased from 0 to 30% the compressive strength of GPC mixes also increased by 50 to 65%.
4. The presence of GGBFS improves the setting and hardening properties of GPC.
5. The workability of GPC mix is reduced with increased percentage of GGBFS replacement.
6. The maximum slump values of 80 mm were obtained for the GPC mixes with 8 M NaOH solution at 0% GGBFS replacement having WCA.

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