EXPERIMENTAL INVESTIGATIONS ON STRENGTH, DURABILITY, SUSTAINABILITY & ECONOMIC CHARACTERISTICS OF GEO-POLYMER CONCRETE BLOCKS

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Abstract

With the growth in infrastructure development and boom in the housing sector, the demand for cement is bound to increase. Due to environmental concerns of cement industry, there arises a strong need to make use of alternate technology which is sustainable. Geopolymer, an inorganic alumina silicate polymer is synthesized predominantly from silicon and aluminum materials or from by- product materials like fly ash. In the present work, an attempt is made to develop geopolymer concrete blocks at ambient curing condition and to investigate strength and durability aspects. The geopolymer blocks prepared here in without the use of cement. The materials considered are Flyash (Class F), Ground granulated blast furnace slag (GGBS), Quarry dust and sand. Sodium hydroxide & sodium silicate were used as alkaline activators. The experimental program involves casting of geopolymer blocks and testing the same for compressive strength. The parameter considered in this study is alkaline solution to binder ratio at 8M molarity. The result revealed that geopolymer concrete block develops strength at ambient curing conditions. The study is further extended to understand the economic impact and sustainability of geopolymer concrete blocks.

Keywords: *Geopolymer concrete blocks, Flyash, GGBS, Embodied energy.*

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1. INTRODUCTION

In recent times the emission of carbon dioxide into the air is being increased day by day. Considerable amount of fossil fuel, coal and oil are burnt for different reasons. This weakens the heat–trapping blanket that surrounds the planet, causing global warming. Various alternatives can be considered to protect the planet. The rapid increase in the capacity of thermal power generation has resulted in the production of a huge quantity of fly ash. The prevailing disposal methods are not free from environmental pollution and ecological imbalance. The CO_2 emission from the concrete production is directly proportional to the cement content used in the concrete mix; 900 kg of CO_2 are emitted for the fabrication of every ton of cement[1]. The usage of cement can be reduced by using the other possible cementing materials without compromising the strength and durability. It is also anticipated, that there would be considerable short-fall in production of various building materials. According to (TIFAC 2000) study, there would be a large short-fall in the production of bricks – to the tune of 25 billion bricks on an estimated demand of 100 billion bricks per year in India by the turn of the century [2].

The most basic building material for construction of houses in the Asian countries is the usual burnt clay brick. A significant quantity of fuel is utilized in making these bricks. Also, continuous removal of top soil, in producing conventional bricks creates environmental problems. There is strong need to adopt cost effective sustainable technologies using local material and appropriate/intermediate technologies using materials with efficient and effective technology inputs. Different methods are adopted to produce the building blocks using cement, lime-fly ash, lime-slag bindings etc. The imperative need to produce more building materials for various elements of construction and the role of alternative options would be in sharp focus. This is in considering the short supply, increasing cost, energy and environment considerations for traditional and conventional materials. The possibility of using innovative building materials and technologies, using waste material like fly ash & GGBS have been considered.

It is found that 180 billion tones of common burnt clay bricks are consumed annually approximately 340 billion tones of clay- about 5000 acres of top layer of soil dug out for bricks manufacture, soil erosion, emission from coal burning or fire woods which causes deforestation are the serious problems posed by brick industry. The above problems can be reduced to certain extent by using GPC blocks in dwelling units. Demand for dwelling units likely to raise to 80 million units by year 2015 for lower middle and low income groups, involving an estimated investment of $670 billion, according to the Associated chamber of commerce and industry. Demand for dwelling units will further grow to 90 million by 2020,which would requires a minimum investment of $890billion. The Indian housing sector at present faces a shortage of 20million dwelling units for its lower middle and low income groups which will witness a spurt of about 22.5million dwelling units by the end of Tenth plan period. There is ample scope for fly ash GPC block units [3].

Past research data have shown that geopolymeric materials perform much better in acid resistance compared to Portland cement [4,5,6]. A study reported that heat-cured fly ash-based geopolymers have excellent resistance to sulphate attack and showed that there was no mechanism to form gypsum or ettringite from the main products of polymerization [7]. Some other studies reports that the geopolymer specimens exhibit good resistance when exposed to acid and sulphate solutions[8,9]. A study revealed that thermal cured low-calcium fly ash-based geopolymer concrete offers several economic benefits over Portland cement concrete[10]. The cement industry is responsible for about 6% of all CO_2 emissions, because the production of one ton of Portland cement emits approximately one ton of CO_2 into the atmosphere. The geopolymer technology could reduce the CO_2 emission to the atmosphere caused by cement industries by about 80% [11]. A study also made an effort in reproportioning of geopolymer blocks by phenomenological model[12]. Thus, the development and application of geopolymer cement and its composites is of great significance in terms of environmental protection.

It is in this context an effort is made to produce GPC block (400 mm X 200 mm X 150 mm) using fly ash and GGBS as binders with compressive strength of 4 MPa using locally available materials i.e Quarry dust & sand at ambient temperature. The prime factor or parameter considered in this work is alkaline solution to binder ratio for which the optimum ratio is found out at 8M molarity. The water absorption test is carried out for the specimens. The durability test of GPC blocks is carried out by immersing them into sulphuric acid and hydrochloric acid. The economic & sustainability analysis of GPC block was done by calculating the cost of raw materials as well as Embodied energy required in preparing a GPC Block. This attempt will result in two benefits. i.e. reduced CO_2 release due to OPC and effective utilization of industrial waste by products such as flyash, GGBS.

2 MATERIALS

Fly ash which is obtained from Raichur Thermal Power Station, India and GGBS obtained from JSW steel, Bellary, India are having specific gravity of 2.4 & 2.9 respectively. The chemical composition of Flyash & GGBS as obtained by X-ray fluorescence (XRF) is shown in Table-1 & Table-3 respectively. The IS code requirements & composition of Flyash is shown in Table-2. The class F fly ash used here confirms to requirement as per 3812-2003 IS code & shown in Table 2. Locally available sand of specific gravity 2.63 & Quarry dust (6 mm) retained on 2.36 mm of specific gravity 2.73 is used in this experimental work.

A combination of 8M sodium hydroxide and sodium silicate in the ratio of 2.5 was used as solution for activation. Sodium hydroxide flakes of laboratory grade with purity of 99% were used in this work. Sodium silicate also known as water glass is of industrial grade with SiO_2 as 34.8% by mass and Na_2O as 16.51% & water as 48.69%. Water used for the mix is of potable quality.

Table-1: Chemical composition of Fly ash as determined by XRF analysis in (mass %)

Binder	Fly Ash
S.Gr	2.4
*LOI	0.90
Al_2O_3	31.23
Fe_2O_3	1.50
SiO_2	61.12
MgO	0.75
SO_3	0.53
Na_2O	1.35
Chlorides	0.05
CaO	3.2

***LOI - Loss on Ignition**

Table -2: Constitution of Flyash and code requirements

Constituents	Composition in %	Requirements as per IS 3812- 2003
LOI	0.90	Max 5
$(Al_2O_3+Fe_2O_3+SiO_2)$	93.85	Min 70
SiO_2	61.12	Min 35
MgO	0.75	Max 5
SO_3	0.53	Max 3
Na_2O	1.35	Max 1.5
Chlorides	0.05	Max 0.05

Table -3: Chemical composition of GGBS as determined by XRF analysis in (mass %)

Binder	GGBS
S.Gr	2.9
LOI	0.19
Al_2O_3	13.24
Fe_2O_3	0.65
SiO_2	37.21
MgO	8.46
SO_3	2.23
Na_2O	- - -
Chlorides	0.003
CaO	37.2

2.1 Microstructure Analysis of Flyash & GGBS

The microstructure of flyash is analyzed using Scanning Electron Microscope (SEM). From figure 1, the microstructure of flyash appears to be a glassy, hollow, spherical particle which is cenospheres (thin walled hollow spheres). Furthermore, surface texture appears to be smooth and dense to highly porous.

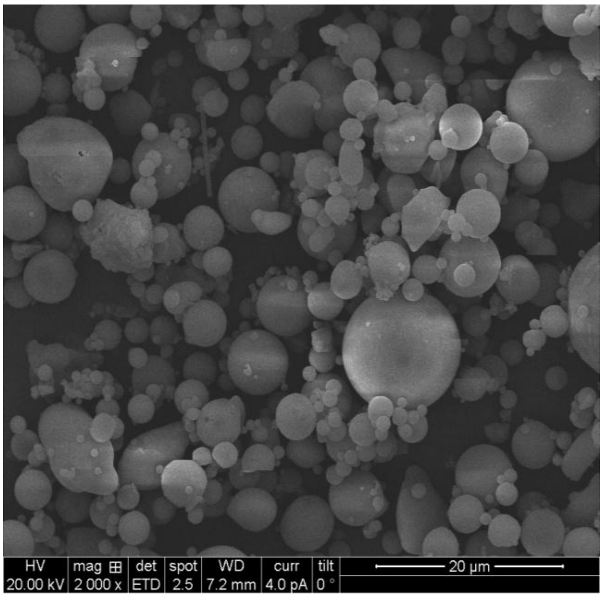

Fig - 1: SEM images of Fly ash

It is clear from figure 2 that the shape of GGBS is not really spherical; it varies according to different grinding techniques. It is predominantly in anomalous shape with clear edges and angles. The reason for this shape is inter-impacting & inter-rubbing between steel balls in Ball mill.

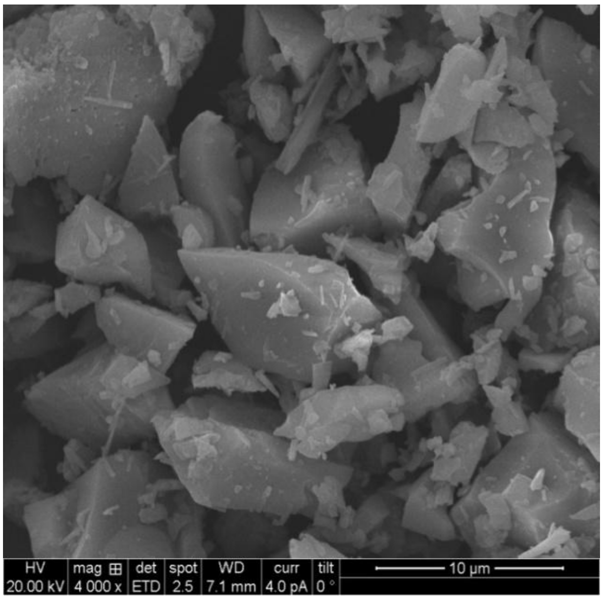

Fig - 2: SEM images of GGBS

3. EXPERIMENTAL WORK

3.1 Mix Design for Optimum Alkaline Solution to Binder Ratio

From earlier studies GPC is produced with many combinations of materials viz GGBS, flyash & binders. Here an attempt is made initially to produce GPC of strength 4MPa [13] using locally available materials. Based on observations made on initial trials, further trials are modified. Initially the density of Geopolymer concrete is assumed as 2350 kg/m^3. The total quantity of aggregates considered is 75% to 80% but can be taken from 72% to 80% of the entire mass in kg/m^3. The remaining mass is combination of Alkaline solution and Binder (Geopolymer paste). Assuming the Alkaline solution to Binder ratio from 0.17 to 0.24, masses of Alkaline solution and Binder in kg/m^3 are obtained. Assuming Sodium silicate solution to Sodium Hydroxide Solution ratio as 2.5, mass Sodium silicate solution and sodium hydroxide solution are obtained (kg/m^3). Assuming the molarity of sodium hydroxide solution 8M, the geopolymer mix is designed.

The Mix designs for various combinations of alkaline solution to binder ratio for 150X150X150mm cubes were prepared as listed in Table - 4.

3.2 Preparation of Geopolymer Concrete

The preparation of GPC mix involves the following process i.e preparation of alkaline solution, mixing, casting, curing & testing of samples.

To prepare sodium hydroxide solution of 8 molarity, 480 g (8 x 40) that is, molarity x molecular weight) of sodium hydroxide flakes (99% purity) are dissolved in one litre of water. The mass of sodium hydroxide solids in a solution will vary depending on the concentration of the solution expressed in terms of molar M. The prepared NaOH solution is added with sodium silicate solution proportionately according to the mix 24 hours before casting.

The alkaline solution prepared 24 hours before is thoroughly stirred, addition of solution has to be done in small quantities so that there shouldn't be any wastage of solution, wet mixing time should be about 10 to 15 minutes or greater. The mixing of total mass will continued till the mixture become homogeneous and uniform in color. After this the mix is left for 10 to 15 minutes then the extra water is added to the mix, again mix it homogenously.

To test the compressive strength of initial trials, the fresh geopolymer concrete is casted in cubes of size 150 X150 X 150 mm in three layers and is compacted by using the standard compaction rod so that each layer receives 25 strokes followed by further compaction on the vibrating table. Compressive strength of cubes were determined until it was reached to 4MPa. Later after determining the optimum ratio (alkaline solution to binder ratio) corresponding to 4MPa, the concrete is casted in blocks of size 400 X 200 X 150 mm dimension.

The casted specimens after one day rest period are demoulded and specimens are kept in lab at ambient temperature for the curing hours of 72 hours. After required curing period the specimens are tested as per IS 516 : 1979.

Table -4: Mix design trials with different alkaline solution to binder ratio for geopolymer

Materials	GPC 1	GPC 2	GPC 3	GPC 4	GPC 5	GPC 6
Coarse Aggregate kg/m^3	1099.8	1099.8	1099.8	1099.8	1099.8	1099.8
Fine Aggregate kg/m^3	592.2	592.2	592.2	592.2	592.2	592.2
Fly ash kg/m^3	281.19	276.47	274.16	269.67	267.47	265.32
GGBS kg/m^3	281.19	276.47	274.16	269.67	267.47	265.32
NaOH Solution kg/m^3	27.31	30.01	31.33	33.90	35.15	36.38
Molarity of NaOH	8M	8M	8M	8M	8M	8M
Na_2SiO_3 Solution kg/m^3	68.30	75.04	78.33	84.76	87.90	90.96
Temperature in C	27	27	27	27	27	27
Curing Period (hours)	72	72	72	72	72	72
Water to geopolymer solids ratio	0.40	0.40	0.40	0.40	0.40	0.40
Alkaline solution to Binder ratio	0.17	0.19	0.20	0.22	0.23	0.24
Rest period (hours)	24	24	24	24	24	24
Days of testing	3	3	3	3	**3**	3
Extra Water kg/m^3	187.67	180.21	176.57	169.47	**165.99**	162.59
Average load (kN)	33.52	46.05	47.55	58.20	**91.97**	186.90
Area (mm^2)	22500	22500	22500	22500	**22500**	22500
Three day compressive strength (N/mm^2)	1.49	2.04	2.11	2.58	**4.08**	8.30

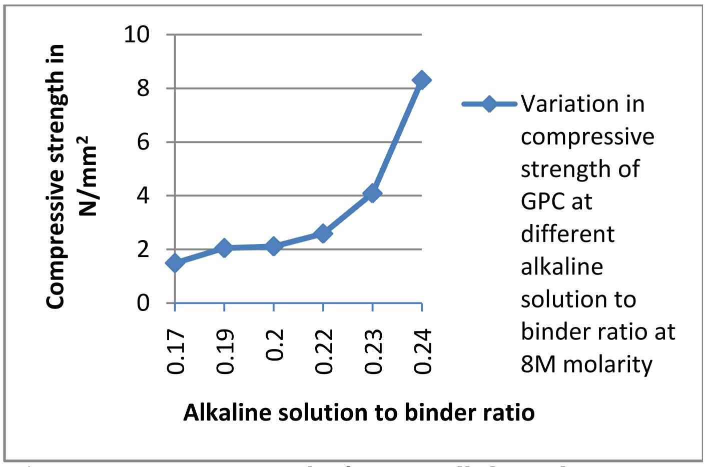

Fig -3: Compressive strength of GPC vs alkaline solution to binder ratio

Here figure-3 shows the compressive strength of geopolymer concrete specimen at ambient temperature at 3rd day of curing. The casting of blocks was carried out from 0.17 to 0.24 with increase in solution to binder ratio to achieve the desired strength. At the alkaline solution to binder ratio of 0.23 the strength of GPCB is around 4MPa which is adequate for a concrete block as per IS : 2185 Part1 1979. Beyond this ratio the strength of the blocks will be high and not required and moreover this higher ratio will be uneconomical. Hence the geopolymer blocks can be casted with this optimum ratio i.e as per trial No 5.

Three days compressive strength of GPC is compared with 28 days compressive strength of cement concrete. The added advantage is that the GPC blocks are not cured with water and moreover the time required for preparation of GPC is relatively less. Figure 4 shows the prepared sample of GPC block.

Here Table - 5 shows the results after casting it in blocks (400mm X 200mm X 150mm) for optimum alkaline solution to binder ratio i.e 0.23. Prepared GPCB5$_{1\text{-}3}$ blocks are tested for compression (figure 5). Quantity of materials required to prepare the Geopolymer block (for 1cum) for optimum ratio are shown in Table-6, similar to traditional concrete blocks.

Table -5: Strength of geo-polymer concrete blocks with optimum ratio

Sl. No	Specimen name	Load in tons	Area in mm^2	Three day compressive strength (N/mm^2)
1	GPCB5$_1$	26	400X150	4.25
2	GPCB5$_2$	25	400X150	4.08
3	GPCB5$_3$	25.5	400X150	4.17

Table -6: Quantities of materials for GPC block in kg for one m^3

Flyash	GGBS	Quarry Dust	Fine aggregate	NaOH solution	Na_2SiO_3 solution	Extra water
267.47	267.47	1099.80	592.20	35.15	87.90	165.99

Fig -4: View of GPC block

Fig -5 : Testing of Geo-polymer block

4. WATER ABSORPTION TEST

To study the water absorption characteristics of geopolymer blocks, the cast specimens $GPCB5_{4-6}$ blocks are subjected to water absorption test. After the curing period is completed, the specimen are immersed in the water tank and kept for 24 hours in water. The weight of the specimen is noted. The specimen is placed in a oven at 105°C temperature, then the weight of the specimen is recorded. From these two values, the water absorbed by the entire specimen is calculated and tabulated.

$$\text{Percentage of Water absorption} = [(W_1-W_2) / W_1] \times 100$$

Where,
W_1 = Weight of the wet specimen
W_2 = Weight of the dry specimen

Table -7: Water absorption test results

Sl. No	Specimen name	Water absorption %
1	$GPCB5_4$	1.58
2	$GPCB5_5$	1.21
3	$GPCB5_6$	1.42

Table-7 shows the results of Water Absorption test. The average water absorption value is determined as 1.40 % which is less than 10% by mass of block as per code IS:2185 Part1 1979.

5. DURABILITY TESTS

Acid resistance test is conducted on geopolymer concrete blocks. Because no universal or widely accepted standard procedures for acid resistance test exist, the type and concentration of the acid solution to which the specimens are exposed varied. However the test procedure is carried out using 3% of solution[14].The test specimens for acid resistance test on geopolymer concrete are 400 X 200 X 150 mm blocks for the change in mass test.

5.1 Sulphuric Acid Resistance

To study the effects of exposure to acidic environment, specimens are immersed in 3% solution of sulphuric acid of 98% purity. Test is carried out at regular intervals after 7 days for a period of 84 days. The solution is replaced at regular intervals to maintain concentration of solution throughout the test period. The evaluations are conducted after 7, 14, 28, 56 & 84 days from the date of immersion. After removing the specimens from the solution, the surfaces are cleaned under the running tap water to remove weak products and loose material from the surface. Later the specimens are allowed to dry and measurements are taken. From the initial measurement and measurements at particular intervals, the loss or gain of the weight are studied. Table - 8 shows the results of sulphuric acid resistance test.

Table -8: Sulphuric acid resistance test by reduction of weight

	Average reduction by weight in %				
Block	7 days	14 days	28 days	56 days	84 days
GPCB	0.76	0.91	1.03	1.23	1.31

5.2 Hydrochloric Acid Resistance

For the study on chloride attack, solution is prepared by mixing 3% hydrochloric acid (HCl) in a plastic container. The solution is stirred on alternate days to avoid deposits of chloride in the container. The solution is replaced with fresh one after 28 days. The evaluations are conducted after 7, 14, 28, 56 & 84 days from the date of immersion. After removing the specimens from the solution, the surfaces are cleaned under the running tap water to remove weak products and loose material from the surface. Then the specimens are allowed to dry and measurements are taken. From the initial measurement and measurements at particular intervals, the loss or gain of the weight are studied. Table - 9 shows the results of Hydrochloric acid resistance test.

Table -9: Hydrochloric acid resistance test by reduction of weight

	Average reduction by weight in %				
Block	7 days	14 days	28 days	56 days	84 days
GPCB	0.21	0.46	0.59	0.65	0.72

6. SUSTAINABILITY CHARACTERISTICS OF GPC BLOCKS

This study considers only the embodied energy consumed in the production of GPC block. Fly ash and GGBS are waste products from industry. The embodied energy of fly ash is zero as collection of fly ash from flue gas is mandatory in India. GGBS will have to be grinded after quenching. The embodied energy of cement manufactured by dry process is 4.2MJ/kg [15]. Therefore an embodied energy of 0.31MJ/kg (6-7% that of cement) has been considered. The embodied energy of sodium hydroxide is 20.5MJ/kg as per SPLINE LCI datasheet. The embodied energy of sodium silicate shall be taken as 5.37 MJ/kg [16]. The transportation energy is not considered here in the analysis. Table - 10 shows the calculation of Embodied energy for one GPC block.

Table -10: Embodied energy in one GPC block

Material	Embodied energy (MJ/kg)	Material required for one GPCB (kg)	Total embodied energy in one GPCB (MJ)
Quarry dust	0.10	13.19	1.31
Fine aggregate	0.02	7.10	0.14
Flyash	0.00	3.20	0.00
GGBS	0.31	3.20	0.99
NaOH solution	4.98	0.42	2.09
Na_2SiO_3 solution	5.37	1.05	5.63
			10.17MJ

Hence, the Embodied energy of fly- ash GGBS based geopolymer concrete BLOCK is found to be 10.17MJ

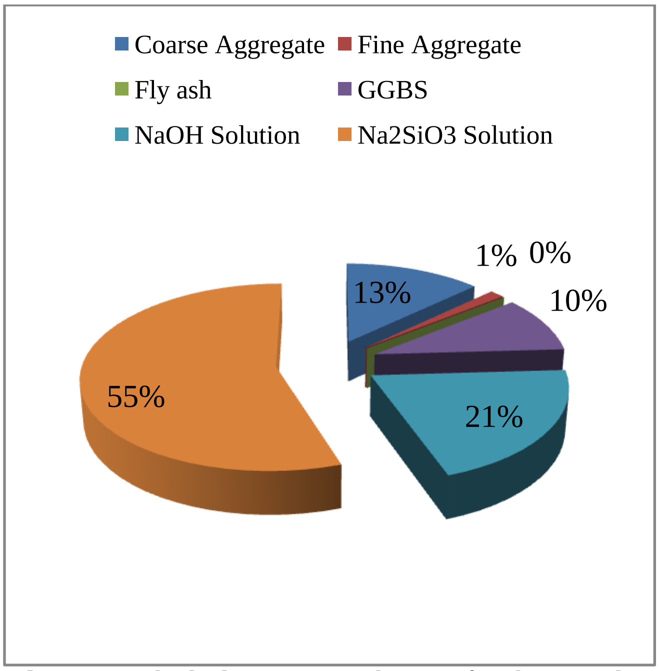

Chart -1: Embodied energy contribution of each material in Flyash-GGBS based GPC Block

Table -21: Comparative analysis of Embodied Energy

Sl No	Blocks	Total Embodied Energy
1	Concrete block (10N/mm^2) Density 1450kg/m^3	11.65 MJ
2	Steam cured block (230x190x100)	18.09 MJ
3	Burnt brick (230x105x70)	30.13 MJ
4	Stabilized Mud block (230x190x100)	7.13 MJ
5	Geo-polymer Concrete block (400x200x150)	10.17 MJ

Based on the different technologies used, the Table-11 shows the calculation of embodied energy of various building blocks as mentioned in Jagadish et al(2007)[17]. The total embodied energy is calculated by multiplying the size factor of different blocks for comparative analysis. Here it is observed that embodied energy of GPC blocks is 14.5% less than traditional concrete block, 77.87% less than steam cured block, 196.26% less than Burnt brick. Another study by G.P.Hamond and C.I.Jones(2006)[18] clearly indicates that Concrete blocks(medium density), limestone blocks and aerated blocks have an embodied energy of 0.67MJ/kg, 0.85MJ/kg and 3.5MJ/kg respectively. But GPC blocks as prepared above has an Embodied energy of 0.36MJ/kg which is very low to the order of 86.11%, 136.11% 872.22% less as compared to concrete blocks, limestone blocks and aerated blocks respectively. Embodied energy of Mud block is lower than GPC block but strengths are not comparable and GPC block is much superior in all other aspects.

7. ECONOMIC CHARACTERISTICS OF GPC BLOCKS

Calculation of Single Unit of GPC Block:

Local market price for Sodium Hydroxide flakes, Sodium Silicate, Flyash, GGBS and aggregates are considered to evaluate the cost of GPC block. The cost for each material and total cost is mentioned in the Table - 12.

The contribution of sodium silicate and sodium hydroxide to the embodied energy and cost of geopolymer concrete is very high (Chart-1, Chart-2) Manufacturing processes of these materials for large scale production must be redesigned so as to reduce the embodied energy. High energy in sodium silicate is due to melting and drying process involved during its manufacturing. Hence research for alternative materials in place of sodium hydroxide and sodium silicate is very much essential.

Table 12: Cost calculation of one GPC block

Material	Cost per kg in Rs.	Material required for one GPCB (kg)	Total cost for one GPCB in Rs.
Quarry dust	0.40	13.19	5.27
Fine aggregate	1.42	7.10	10.08
Flyash	1.20	3.20	3.84
GGBS	1.20	3.20	3.84
NaOH solution	19.36	0.42	8.17
Na_2SiO_3 solution	18.5	1.05	19.42
Cost of each GPC block			50.62 ₹

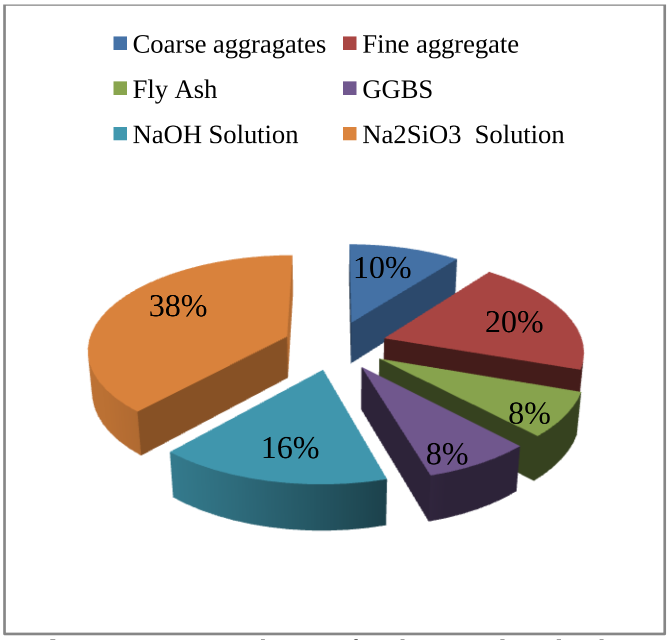

Chart -2: Cost contribution of each material to Flyash - GGBS based GPC Block

In the analysis of cost from Table-12, we see that the cost of single unit of GPC block is estimated to be around 50.62₹. In this estimation the cost of NaOH solution & Na_2SiO_3 solution contributes to 54.5% of the cost of GPC blocks (figure 7). Presently extensive research is been carried out to produce sodium silicate by cost effective methods which will reduce the price & also the embodied energy in due course.

8. CONCLUSIONS

The following are the conclusions obtained after this study :

- The optimum alkaline solution to binder ratio for the preparation of geopolymer concrete blocks is found to be 0.23 for 8M Molarity of NaOH at ambient curing.
- The strength achieved by Geopolymer blocks is 4MPa which is equivalent to the strength of cement concrete block & the average density of the block (400x200x150) is 23kN/m^3.
- The average water absorption percentage of GPC block is found to be 1.40 %.
- The mass reduction of GPC block due to sulphuric acid resistance at the end of 84 days is found to be 1.31%.
- The mass reduction of GPC block due to hydrochloric acid resistance at the end of 84 days is found to be 0.72%.
- The Embodied energy of GPC block is calculated as 10.17MJ. It is found that Sodium hydroxide & sodium silicate together contribute to 76% of total embodied energy.
- The cost of one GPCB block is estimated to be 50.62 ₹.

Even though the cost of GPC blocks seems to be higher as compared to traditional cement concrete block, it is recommended to use in place of cement concrete blocks and burnt brick, since GPC blocks are ecofriendly, sustainable and have lower embodied energy. Hence geopolymer blocks can be recommended to as masonry units for non-structural purposes. However more research is necessary to further optimize the proportions and study the economical aspects of such blocks.

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Dr Manojkumar. V. Chitawadagi obtained his M. E. in Structural Engg. He completed his Ph.D. under Quality Improvement Programme, at NITK Surathkal. He is working as Professor at Civil Engg. Dept. BVBCET, Hubli. He has guided students for their M.Tech. dissertation in the field of Fibre reinforced concrete, aerated concrete, high strength concrete and concrete filled steel tubes used as columns and beams. In his 25 years of service he has several publications in the areas of his research interest in National and International Journals.