STRENGTH HARDENING OF FLYASH BASED GEOPOLYMER CONCRETE

Dr. B.G. Vishnuram[1], Ms.N.Kowsika[2], Ms. A. LakshmiPrabha[3], Ms. V. Murugaveni[4], Ms. K. Shalini[5]

[2,3,4,5] Final Year Students, Department of Civil Engineering, P.S.R. Engineering College, Sivakasi-626140,Virudhunagar District, Tamilnadu ,India.

[1]Professor, Department of Civil Engineering, P.S.R. Engineering College, Sivakasi-626140,Virudhunagar District, Tamilnadu ,India.

Abstract– The production of ordinary Portland cement (OPC) causes pollution to the environment, due to the emission of CO .Geo-polymer concrete an alternate material is introduced to replace OPC.. Hence it reacts with alkaline solution to produce alumina silicate gel that binds the aggregate to produce a good concrete. The mix designs with strengths of 40N/mm^2 were considered. This study was carried out using several tests, which includes material property test and workability of SCC. Workability was determined through slump flow, L-box and V-funnel flow test .It enhances the strength properties of fiber reinforced geo polymer concrete with suitable mineral admixtures and super plasticizers.

Keywords: *Geo-polymer concrete, Fly ash, GGBS, alkaline solution, Granite Powder, Compressive Strength, Split Tensile Strength.*

I. Introduction:

Concrete is the single most widely used construction material in the world today. The key to a strong and durable concrete are the mix proportions between the various components. Less cement paste can lead to more voids, thus less strength and durability while more cement paste can lead to more shrinkage and less durability. The gradation and the ratio of fine aggregates to coarse aggregates to coarse aggregates can affect strength and porosity. The mix design should also achieve the desired workability of concrete so as to prevent segregation and allow for ease of placement. Typically, a concrete mix is about 10% to 15% cement,25% to30% M Sand ,40% to 45%percent aggregate and 15% to 20% water. Concrete should have enough compressive strength and flexural strength to support applied loads. At the same time it should have good durability to increase its design life and reduce maintenance costs. In general, durable concrete will have good resistance to freeze and thaw, abrasion, sulfate reactions, UV radiation, sea water, alkali-silica reaction, and chlorides.

Inhalation of granite powder fine particles is a health hazard and is a cau5se of lung diseases especially for people living near granite quarry. In this present work, granite powder is used as partial replacement of M-Sand in concrete in different percentage and the associated compressive strength, Split tensile strength of concrete have been evaluated. By doing so, natural resources of m-sand can be preserved and the health hazards of these industrial wastes are minimized.

Recycling of granite dust will prevent these wastes from ending up in landfills and provides affordable, eco-friendly, solid stone for various used.

II. Geo-polymer:

In 1978, Davidovits proposed that a binder could be produced by a polymerization process involving a reaction between alkaline liquids and compounds containing aluminium and silicon .The binders created were termed ad “GEO-POYMER”. Unlike ordinary Portland/ Pozzolana cements, geo-polymers do not form calcium-silicate hydrates for matrix formation and strength, but silica and alumina reacting with an alkaline solution produce an alumina-silicates gel that binds the aggregates and provides the strength of concrete. Source materials and alkaline liquids are the two main constituents of geo-polymers, the strengths of which depend on nature of the materials and the types of liquids. Materials containing silicon(SI) and aluminium (AL) in amorphous form, which come from natural minerals or byproduct materials, could be used as source materials for geo-polymer.

Kaolinite, clays, etc., are included in the natural minerals group whereas fly-ash, silica fume, slag, rice husk ash, red md, etc by – product materials. For the man facture of geo-polymers, the choice of source materials depends mainly on their availability and cost, the type of application and the specific demand of the users. Fly-ash based geo-polymer concretes provide excellent engineering properties that make them suitable materials for structural applications.

The type of alkaline liquid used plays an important role in the polymerization process. Sodium hydroxide (NaOH) with sodium silicate (Na_2SiO_3) and potassium hydroxide (KOH) with potassium silicate (K_2SiO_3) are the most common alkaline liquids used in geo-polymerisation. Both sodium hydroxides and potassium hydroxide have a strong based and, at room temperature, exhibit almost identical solubilities in water. From literature study it is found to be the mechanical strength of mortar increases when water glass (Na_2SiO_3) is added to NaOH, compared with using only NaOH. The addition of water glass increases the Si/Al and Na/Al ratios, resulting in increased formation of N-A-S-H (sodium alumina- silicates gel) which indicates greater strength . The compressive strength of fly ash based geopolymer concrete can be improved by either increasing the concentration (in molar terms) of the sodium hydroxide solution or increasing the mass ratio of the sodium silicate to sodium hydroxide solutions. Currently fly ash based geo-polymer concrete has proven to be a suitable replacement for cement concrete due to their excellent engineering properties.

2.1Geo Polymer Concrete:

Geo polymer concrete is a type of inorganic polymer composite, which has recently emerged as a prospective binding material based on novel utilization of engineering materials. It has the potential to form a substantial element an environmentally sustainable construction industry by replacing/supplementing the conventional concretes. GPC can be designed as high strength concrete with god resistance to chloride penetration, acid attack, sulphate attack, etc. The geo-polymeric concretes are commonly formed by alkali activation of industrial alumina silicate waste materials such as fly ash (FA) and ground granulated blast furnace slag (GGBS), and have very small footprints of greenhouse gases when compared to traditional concretes. Because of possible realization of even superior chemical and mechanical properties compared to ordinary Portland cement (OPC) based concrete mixes and higher cost effectiveness.

2.2. Need of Geo polymer Concrete:

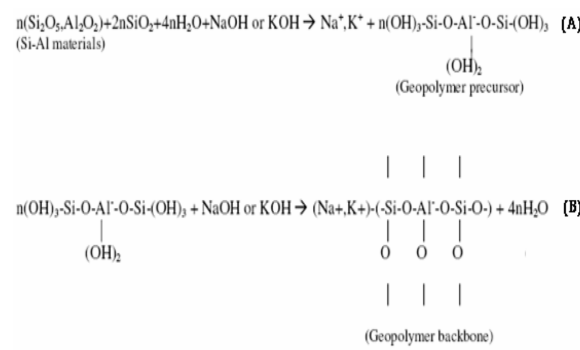
To produces environmental friendly concrete, we have to replace the cement with some other binders which should not create any bad effect on environment. The se of industrial by products as binders can reduce the problem. In this respect, the new technology geo-polymer concrete is a promising technique. In terms of reducing the global warming, the geo-polymer technology cold reduce the CO_2 emission to the atmosphere caused by cement and aggregate industries by about 80% and also the proper usage of industrial wastes can reduce the problem of disposing the waste products into the atmosphere

2.3. The Schematic Formation of Geopolymer Concrete

The reaction of fly-ash with an aqueous solution containing sodium hydroxide and sodium silicate in their mass ratio, results in a material with three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds, as follows:

Mn [-(SiO_2) z-AlO_2] N. WH_2O

Where M is a mono valentcation such as potassium or sodium, the symbol – indicates the presence of a bond, n is the degree of poly-condensation or polymerisation and z is 1, 2, 3 or high.



Results from this study and from studies by others referenced in this introduction showed that there are advantage to concrete when granite powder is used to partially replace m-sand in the concrete mix. The benefits of using granite powder as partial replacement of m-sand not only can enhance strength but also preserve the natural resources of m-sand and also keeps these powder particles from being airborne into the atmosphere causing health hazard to humans, in particular children

III. Research Significance:

Granite powder by-products resulting from the granite stone crushing and polishing respectively .These by-products can be used as partial replacement of m-sand in concrete. When used in certain proportions, granite powder have shown to increase the compressive strength, splitting tensile strength of concrete. The experimental research conducted in this study showed the mechanical properties of concrete have improved when granite powder were used as partial replacement of m-sand in specified percentages. In addition, the use of these powders as a partial replacement of m-sand will reduce the consumption of m-sand in the construction industry thus preserving more of these natural resources. Recycling of these by-products and using them in concrete will reduce their health hazards and their impact on the environment.

IV. Experimental Investigation:

The experimental program comprised of preparing concrete cubes and cylinders with and without granite replacement .The concrete mix included Fly-ash, M-sand, Granite powder, Coarse aggregates, super plasticizer, and water. The cylinders was used to test the split tensile strength respectively.

V. Materials

The material used in this study included the following: Fly-ash, coarse aggregates, fine aggregates(m-sand), granite powder, GGBS, water and super plasticizers. The Fly-ash was. The coarse aggregates were crushed angular coarse aggregate to 20mm (3/8in to 3/4in) in size. The specific gravity of the aggregates was 2.72 and fineness modulus was 4.2. The M-sand was approximately 4.75mm in diameter and has a specific gravity of 2.74 and a fineness modulus equal to 2.3. The specific gravity of granite powder was 2.53 and the fineness modulus was approximately 2.4 with a particle size less than 90 μm. Typical chemical analysis of the granite powder and fly ash is shown in Table 1and 2.

VI. General Materials:

1) Fly ash
2) Coarse aggregate with size 20mm
3) Fine aggregate(M-sand)
4) Mineral additive
5) Alkaline liquids
6) Granite powder
7) Super plasticizer

1. **Granite Powder:**

Granite powder is a partially replacement of fine aggregate for concrete. It is a waste material from the granite polishing industry, is a promising material for use in concrete similar to those of pozzolanic materials such as silica fume, fly ash, slag, and others it is shown in fig 1. These products can be used as a filler material (substituting sand) to reduce the void content in concrete.

Fig-1 granite powder

2. **Fly ash:**

Any country's economic and industrial growth depends on the availability of power. In INDIA also, coal is a major source of fuel power generation. About 60% power is produced using coal is fuel. Indian coal is having low calorific value (3000-3500 K. Cal) and very high ash content (30-45%) resulting in huge quantity of ash generated in the coal based thermal power stations. During 2005-06 about 112 million tonne of ash has been generated in 125 such power stations. With the present growth in power sector, it is expected that ash generation will reach to 175 million tonne per annum by 2012.

Any coal based thermal power station may have the following four kinds of ash:

2.1Fly-ash:

This kind of ash is extracted from the gases through electrostatic precipitator in dry form. The ash is fine material and possesses good pozzolanic property.

2.2Bottom Ash:

This kind of ash is collected in the bottom of boiler furnace. It is comparatively coarse material and contains higher un-burnt carbon. It possesses zero or little pozzolanic property. Fly-ash produced in modern power stations of India is of good quality as it contains low sulphur and very low un-burnt carbon. In order to make fly-ash available for various applications, most of the new thermal power stations have set up dry fly-ash evacuation and storage system. In this system fly-ash from Electrostatic precipitators (ESP) is evacuated through pneumatic system and stored in silos. From silos, it can be loaded in open truck/closed tankers or can be bagged through suitable bagging machine. In the ESP, there are 6 to 8 fields (rows) depending on the design of ESP. The field at the boiler end is called as first field and counted subsequently 2, 3 onwards. The field at chimney end is called as last field. The coarse particles of fly-ash are collected in first fields of ESP. The fineness of fly-ash particles increases in subsequent fields of ESP.

2.3 Types of Fly-ash:

Currently, more than 50 percent of the concrete placed in the U.S. contains fly-ash. Dosage rates vary depending on the type of fly-ash and its reactivity level.

Typically, Class F fly-ash is used at dosages of 15 to 25 percent by mass of cementious material, and Class C fly-ash at 15 to 40 percent.

- Class F fly-ash, with particles covered in a kind of melted glass, greatly reduces the risk of expansion due to sulphate attack as may occur in fertilized soils or near coastal areas. Class F are generally low-calcium fly-ashes with carbon contents less than 5 percent but sometimes as high as 10 percent.
- Class C fly-ash is also resistant to expansion from chemical attack, has a higher percentage of calcium oxide, and is more commonly used for structural concrete. Class C fly-ash is typically composed of high-calcium fly-ashes with carbon content less than 2 percent.

Use of fly-ash in concrete imparts several environmental benefits and thus it is eco-friendly. It saves the cement requirement for the same strength thus saving of raw materials such as limestone, coal etc required for manufacture of cement. Manufacture of cement is high-energy intensive industry. In the manufacturing of one tonne of cement, about 1 tonne of CO_2 is emitted and goes to atmosphere. Less requirement of cement means less emission of result in reduction in green house gas emission. Due to low calorific value and high ash content in Indian coal, thermal power plants in India, are producing huge quantity of fly-ash. This huge quantity is being stored/disposed off in ash pond areas. The ash bonds acquire large areas of agricultural land. Use of fly-ash reduces area requirement for pond, thus saving of good agricultural land.

Fig.2 FLYASH

3. M-sand:

Manufactured Sand (M – Sand) is a substitute of River sand for concrete construction. It is produced from hard granite stone by crushing. It is of cubical shape with grounded edges, washed and graded to as a construction material. It confirming to zone II of IS 383-1970.Sand is used in the work which has the particle was less than 4.75mm. Shown in fig.3

Fig .3 M-sand

4. Alkaline Liquids:

Generally alkaline liquids are prepared by mixing of the sodium hydroxide solution and sodium silicate at the room temperature. When the solution mixed together the both solution start to react i.e. (polymerisation takes place) it liberates large amount of heat so it is recommended to leave it for about 24 hours thus the alkaline liquid is get ready as binding agent. The activators required to complete the polymerisation process are typically sodium silicate (SiO_2/Na_2O) and sodium hydroxide (NaOH) solutions. The higher the NaOH content the higher the resultant compressive strength. Potassium based hydroxide solutions are able to be used instead of the NaOH solutions but are generally ignored due to the higher associated costs.

Table 1

Chemical composition of granite powder used in this study.

Chemical compound	Water (%)
SiO_2	64.5
TiO_2	0.67
Al_2O_3	12.01
Fe_2O_3	5.77
MgO	0.57
MnO	0.39
CaO	4.80
Na_2O	5.92
K_2O	5.26
P_2O_5	0.07

Table 2

Chemical composition of fly ash used in this study.

Chemical Properties % by mass	Fly-ash MTPP
$SiO_2 + Al_2O_3 + Fe_2O_3$	90.5% Max
SiO_2	58% Max
CaO	3.6% Min
SO_3	1.8% Min
Na_2O	2% Max
LOI	2% Min
MgO	1.91% Min

VII. Preparation of granite powder test specimens:

The granite powder was collected from granite crushing and polishing quarry and was dried before use. The Fly-ash and granite powder were first mixed thoroughly. Further m-sandand coarse aggregate were added to the mix. The materials were mixed in dry conditions for few minutes. Once all the materials were mixed well, the super plasticizer was added to the dry mix in a standard concrete mixer. The resulting concrete mix was used to prepare 150×150×150mm (6in×6in×6in) cubes and 150mm×300mm (6 in×12 in) cylinders. The concrete was poured into the molds and was compacted 15 blows by a compaction rod. After that the molds were left to dry for 24h. The specimen were then removed from the molds and cured in normal room temperature for curing for 7,14 and 28days. The curing time was not a parameter in this study and hence no comparisons were made for the effect of granite powder (GP) on curing time. Several mixes were prepared with different percentages of granite powder as partial replacement of m-sand. The percentages of granite powder used were 10%, 15% and 20% of m-sand. The mix proportions for the mixes tested by Molarity this study are shown in Table 3 and fig 4 . A total of three mixes were tested: MG10, MG15 and MG20 containing 10%, 15% and 20% of GP by weight respectively. Super Plasticizing admixtures are added to a concrete mixture to make the mix workable without additional water especially for use in ready mixed concrete

Table 3

Mix design proportions for various granite powder (GP)

MATER IALS	10%	15%	20%
FA	3. 539kg (90%)	3.343kg (85%)	3.146kg (80%)
GRANIT E POW DER	393gms	590gms	790gms
CA	3.664kg(20mm) 5.497kg(10mm)	3.664kg(20mm) 5.497kg(10mm)	3.664kg(20mm) 5.497kg(10mm)
Na_2SiO_3	610ml(1cube)	610ml(1cube)	610ml(1cube)
Fly ash	2.515kg	2.515kg	2.515kg
GGBS	280gms	280gms	280gms
Extra water	0. 597ml	0. 597ml	0. 597ml
SP	13ml	13ml	13ml

Fig .4 mix of granite powder

VIII. Testing of Geo-polymer concrete cubes and cylinders:

Compression tests and Split tensile tests were conducted on concrete cubes and concrete cylinders respectively. The compressive strength tests were according to ASTM C39 while the flexural strength tests and the splitting tensile strength tests were done according to ASTM C78 and ASTM C496 respectively. Tests were performed at 7 days, 14days and 28 days . The compressive tests were conducted using 2000kN compressive testing machine. Nine cubes were prepared and 3 were tested at 7 days,3 were tested at 14 days and the remaining 3 were tested at 28 days. Splitting tensile test specimens were tested using 1000KN testing machine. Fig 3showed photos of the compression testing machine .Similarly for the cylinders, Nine cylinders were prepared and 3 were tested at 7days, 3 were tested at 14days and the remaining 3 were tested at 28days. The test results of the cubes and cylinders of concrete made with GP were compared to test results of the normal concrete (control) specimens.

IX. Test results of granite powder (GP) concrete mixes:

9.1Compressive strength:

The compressive strength of the cubes was determined for control specimens and for specimens with various percentages of granite powder. The average compressive strength of control cubes (Mix MG0) was 35.8N/mm^2. The cubes with granite powder showed higher compressive strength. The compressive strength of mix designs MG10 (10% GP), MG15 (15% GP) and MG20 (20% GP) were shown in table respectively. The test showed that the optimum percentage of granite powder to achieve the maximum increase in compressive strength was 10%. For 20% partial replacement of m-sand with granite powder the increase in the compressive strength was relatively small. The values of compressive strengths of cubes made with different percentages of granite powder replacement of sand are given in Table 4and also graphically presented in Fig. 5.

Fig 5. Testing of cube specimens in compression

Table 4

Compressive strengths of cubes with different proportion and molarity (GP).

DAYS	7th DAY	14th DAY	28th DAY
10 MOLARITY	31.3N/mm^2	39.2N/mm^2	43N/mm^2
12 MOLARITY	34.2N/mm^2	41.66N/mm^2	48N/mm^2
14 MOLARITY	30N/mm^2	36.9N/mm^2	42.9N/mm^2
16 MOLARITY	28.6N/mm^2	32.4N/mm^2	40N/mm^2

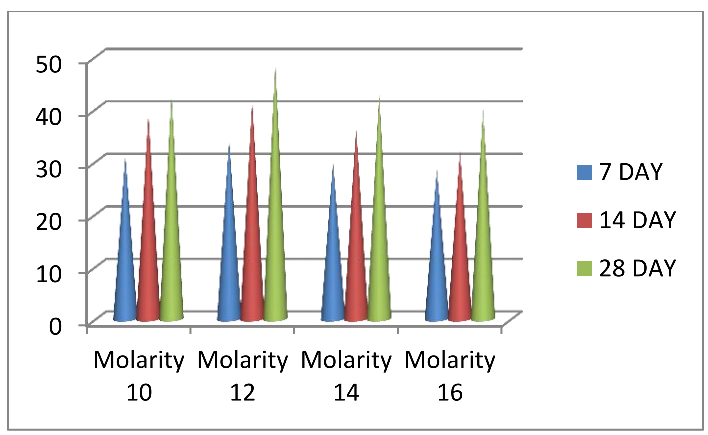


Fig.6 Compressive strengths of cubes with different proportions and molarity (GP)

9.2 Split tensile strength:

The Spilt tensile strength of concrete was determined indirectly using the split-cylinder strength test. The indirect test is widely accepted test method to determine the tensile strength of concrete given the difficulty and variability associated with the direct tensile tests. The split-cylinder tensile strength was determined by testing 150 mm × 300 mm (6 in × 12 in) cylinders. Three cylinders were tested at 7 days, Three cylinders were tested at 14 days and Three cylinders were tested at 28 days. The split tensile strength of the cylinders was determined for the control cylinders as well as the cylinders with various percentages of granite powder. The split tensile strength of the control cylinders at 28 days (Mix MG0) .The cylinders with granite powder showed higher flexural strength compared to control mixes. The split tensile strength of mix designs MG10 (10% GP), MG15 (15% GP) and MG20 (20% GP) were shown in table respectively. The tests showed that the optimum percentage of granite powder to achieve the maximum increase in split tensile strength was 15% compared to an optimum value of 10% for compression. For 20% partial replacement of m-sand with granite powder, the split tensile strength was lower than the control cylinders. This observation was different than those of compression . For compression , the 20% replacement of granite powder showed a modest increase rather than a decrease in strength. The values of split tensile strength of cylinders made with different percentages of granite powder of sand are shown in Table 4and also presented graphically in Fig. 7,8&9.

Table 5

Split tensile strength of cylinders with different proportion and molarity of (GP).

DAYS	7th DAY	14th DAY	28th DAY
10 MOLARITY	2.7 N/mm²	2.8 N/mm²	2.22N/mm²
12 MOLARITY	2.10 N/mm²	3 N/mm²	2.6 N/mm²
14 MOLARITY	3 N/mm²	3.3 N/mm²	3.14N/mm²
16 MOLARITY	2.7 N/mm²	2.8 N/mm²	2.22N/mm²

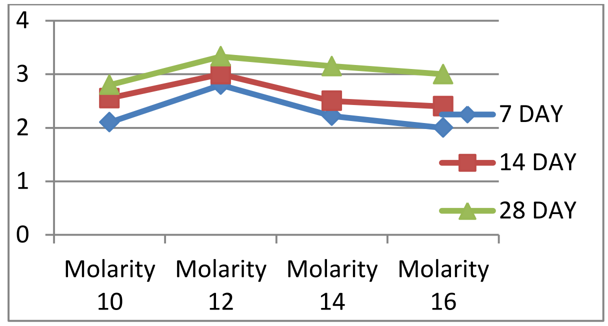


Fig.7 Split tensile strength of cylinders with different proportions and molarity (GP).

Fig.8 Testing of cylinder specimen using spilt tensile in compression.

Fig.9 Testing of cylinder specimens using compression meter.

X. Summary of test results of granite powder (GP) specimens:

The concrete mix with granite powder (GP) in concrete showed good workability and had slump values similar to those of normal concrete mixes. The ingredients were easy to mix, pour, transport, finish and demold. The compressive strength of concrete increased with the addition of granite powder (GP) as partial replacement of sand. This results in more surface area that allows more Using 10% granite powder (GP) in concrete gave the best result (highest increase in compressive strength) compared to other ratios. For the split-cylinder tensile strength, the optimum value of the percentage of (GP) in concrete was 15% compared to 10% for compressive strength. The increase in tensile strength for 15% and 10% of (GP) was approximately 30% and 15% respectively. For 20% (GP) in concrete the split tensile strength was lower than that of the control mix.

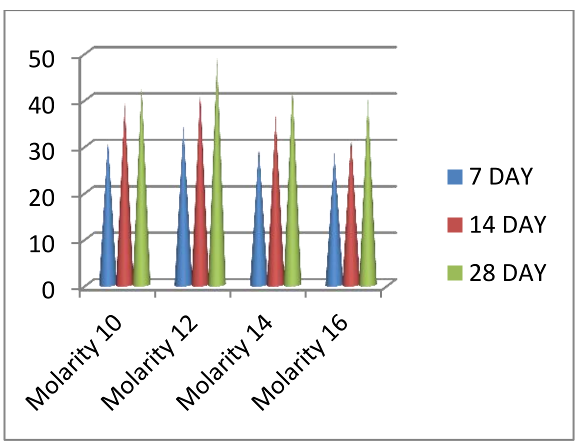
XI. Conclusions:

Based on the results:

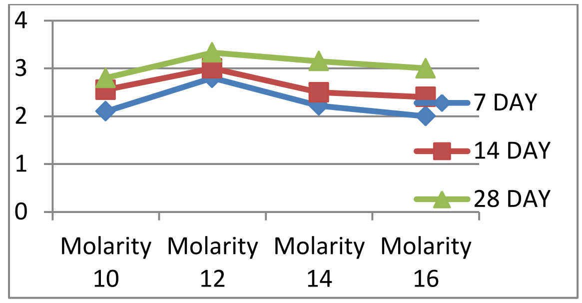
1. The concrete mix made using granite powder (GP) as partial replacement of M-Sand showed good workability and fluidity similar to normal concrete mixes.

2. Graph for compressive strength and spilt tensile strength for cube and cylinder using geo-polymer concrete replacement of granite powder.

1. Compressive Strength



2. Spilt tensile strength



3. The compressive strength of concrete increased with the addition of granite powder (GP) as partial replacement of M- Sand. Using 10% granite powder in concrete gave the best result compared to other ratios.

4. The following conclusions are drawn for feasibility study conducted on geopolymer concrete with flyash as partial replacement of fine aggregate includes, the conclusion based on the limited observations. The work represents the summary of literatures, parametric study of materials and collection of materials, mix design of geopolymer concrete as per references guidelines.

5. Thus the material properties are well studied for producing geopolymer concrete.

XII. References:

1) Ghannam, S., Najm, H., & Vasconez, R. (2016). Experimental study of concrete made with granite and iron powders as partial replacement of sand. Sustainable Materials and Technologies, 9, 1-9.

2) Gunasekera, C., Lokuge, W., Keskic, M., Raj, N., Law, D. W., & Setunge, S. (2020). Design of Alkali-Activated Slag-Fly Ash Concrete Mixtures Using Machine Learning. ACI Materials Journal, 117(5).

3) Alok, G., Ravali, K., Prasad, M. G., Pravalika, C., & Priya, P. S. (2020, December). Strength studies on Geopolymer Concrete produced by Recycled Coarse Aggregate and Quarry Stone Dust as Fine Aggregate. In IOP Conference Series: Materials Science and Engineering (Vol. 981, No. 3, p. 032057). IOP Publishing.

4) USMAN, S. (2017). STRENGTH STUDIES ON GEO-POLYMER CONCRETE BY USING FLY ASH AND QUARRY DUST (Doctoral dissertation, JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY KAKINADA).

5) Rao, S. M., & Acharya, I. P. (2014). Synthesis and characterization of fly ash geopolymer sand. Journal of materials in civil engineering, 26(5), 912-917.

6) Kumar, P., Pankar, C., Manish, D., & Santhi, A. S. (2018). Study of mechanical and microstructural properties of geopolymer concrete with GGBS and Metakaolin. Materials Today: Proceedings, 5(14), 28127-28135.

7) Saranya, P., Nagarajan, P., & Shashikala, A. P. (2020, June). Behaviour of GGBS-dolomite geopolymer concrete beam-column joints under monotonic loading. In Structures (Vol. 25, pp. 47-55). Elsevier.

8) Danda, U. K. (2020). Experimental study on reinforced geopolymer concrete columns using GGBS. Materials Today: Proceedings, 33, 632-636.

9) Wang, J., Xie, J., Wang, C., Zhao, J., Liu, F., & Fang, C. (2020). Study on the optimum initial curing condition for fly ash and GGBS based geopolymer recycled aggregate concrete. Construction and Building Materials, 247, 118540.

10) Prusty, J. K., & Pradhan, B. (2020). Effect of GGBS and chloride on compressive strength and corrosion performance of steel in fly ash-GGBS based geopolymer concrete. Materials Today: Proceedings, 32, 850-855.

11) Shahmansouri, A. A., Bengar, H. A., & Ghanbari, S. (2020). Compressive strength prediction of eco-efficient GGBS-based geopolymer concrete using GEP method. Journal of Building Engineering, 31, 101326.

12) Saini, G., & Vattipalli, U. (2020). Assessing properties of alkali activated GGBS based self-compacting geopolymer concrete using nano-silica. Case Studies in Construction Materials, 12, e00352.

13) Zhou, W., Shi, X., Lu, X., Qi, C., Luan, B., & Liu, F. (2020). The mechanical and microstructural properties of refuse mudstone-GGBS-red mud based geopolymer composites made with sand. Construction and Building Materials, 253, 119193.

14) Tiwari, P. K., Sharma, P., Sharma, N., & Verma, M. (2020). An experimental investigation on metakaoline GGBS based concrete with recycled coarse aggregate. Materials Today: Proceedings.

15) Lee, W. H., Wang, J. H., Ding, Y. C., & Cheng, T. W. (2019). A study on the characteristics and microstructures of GGBS/FA based geopolymer paste and concrete. Construction and Building Materials, 211, 807-813.