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Experimental studies on strength performance of high strength geopolymer concrete using Egg shell powder, and rice husk ash with recycled coarse aggerate for sustainable environment

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Graphical abstract

Abstract

This research papers examines the strength aspects of High Strength Geopolymer Concrete (HSGPC) when waste materials such as Egg Shell powder (ES), Rice husk Ash (RA), are used in concrete. ES is used as a replacement for Fly ash (F). Trial percentages of ES are carried out from 0%, 10%, 20%, 30%. Two types of curing were used for the research work, ambient curing and heat curing. The mechanical, durability and micro structural properties of the samples are determined using the various tests available as per the ASTM standards. The suitability of ES and RHA as a replacement is studied as a main objective to determine the variation of strength aspects when tested for mechanical and durability studies. From the test results it was found that the use of ES 20% gave better results as it enhanced the mechanical properties and long-term characteristics. Samples under heat curing gave 20% better results when compared to ambient curing for compressive strength at 7 days, 12% improvement for flexural tests. Usage of ES in geopolymer concrete above 30% lead to decrease durability characteristic of concrete. From the microstructural analysis it was found that due to the usage of ES a dense bond arises in the concrete.

Keywords: geopolymer, mechanical, ambient, flexural, waste

1. Introduction

Large research works in the recent days show interest in using alkali activators in the preparation of concrete samples. Geopolymer concrete (GPC) is a type of concrete in which the cementitious materials are replaced, research is going on for the past three decades after the initial work carried out by Joseph *et al.*, Davidovits (1898), Karthiga *et al.* (2022). Activation of concrete by using primary components of alumino silica helps in attaining the geopolymerisation effect Shi *et al.* (2021), Jindal (2019), Argela *et al.* (2019), Karthiga *et al.* GPC concrete mainly uses waste materials from industries such as ground granulated blast furnace slag (GGBS), metakaolin (M), fly ash (F) as a substitution for cementitious materials Jindal (2023), Marvila *et al.* (2021), Karthiga *et al.* 2022(b). Replacement of waste materials instead of cement helps in the reduction of greenhouse gases and usage of nonrenewable energy resources Rivera *et al.* 2021, Youyuan *et al.* (2025), Tong *et al.* (2025). With the use of alkaline activation, the raw materials are transformed to binders which has minimal pollution impact on the eco system Falah *et al.* (2020). Material such as sodium hydroxide, sodium silicate, potassium hydroxide, potassium silicate, calcium hydroxide, sodium carbonate etc, Blesson and Rao (2023), Karthiga *et al.* (2022c). As per the recent research studies the waste of GGBFS is continuously increasing and it reached to 225 million tons in 2025 Yousuf *et al.* (2020), FA also is increasing in a massive manner which leads to huge pollution Yanhua *et al.* (2025), Danhong *et al.* (2025), Yunxia *et al.* (2025). Some studies have been carried out in the field of agricultural waste that are rich in few pozzolanic materials such as SiO_2, Al_2O_3, Fe_2O_3 as agricultural wastes are rich in aluminosilicates Elahi *et al.* (2020), Athira *et al.* (2021), Nassar and Kathirvel 2023, Tchakoute *et al.* 2017. Few agricultural wastes Wu *et al.* (2025), Huifang Liu *et al.* (2025), Ding Li *et al.* (2025) that are predominantly used in the recent researches are rice husk ash as it produces 70 million tons of waste Tong *et al.* (2018), Mahmad *et al.* (2022), sugarcane bagasse waste (BA) to about 45 million tons, corn stalk ash nearly 30-32 million tons waste Bahurudeen *et al.* (2015), Memon *et al.* (2020), Prusty *et al.* (2016), ASTMC618, Hemalatha and Ramaswamy (2017).

Pozzolanic materials such as fly ash C of F types are used in the preparation of geopolymer concrete that are mainly got from the thermal power station in India. They have aluminum silicate compounds which are pozzolanic in nature as per the recommendations of ASTM C618. F and C type FA is recognized when the percentage of silicate components is 70% and 50-70% respectively Hemalatha and Ramaswamy (2017), Kaniraj and Havanagi (1999). For this current research work the C type FA is used, it is collected from the thermal power plant from Mettur Hemalatha and Ramaswamy (2017), Kaniraj and Havanagi (1999). Agricultural waste is got as a residue by heating the waste to a temperature of 700-900°C. then it is ground to a fine powder in the ball grinding machine so that the waste product reaches an amorphous state as a result of which the required strength gets achieved when tested for fresh and hardened properties. Combination of FA and GGBFS for the production of geopolymer concrete results in a proper blend and activation of aluminosilicates Elgarahy *et al.* (2021), Senneca *et al.* (1998), Mostafa *et al.* (2022), Faried *et al.* (2021), Xu *et al.* (2016), Norhasri *et al.* (2017), Fadzil *et al.* (2014). Similarly, when Rice husk Ash (RA) is heated isothermally to 500°C-700°C, the required waste materials are obtained . Few researches use RHA by mass Caihua *et al.* (2025), Lei and Zhao (2024) as it has silica content ranging between 77-95% and found it to produce improving results in compressive strength as it accelerates the setting time Faried *et al.* (2021), Li *et al.* (2017), Demiss *et al.* (2018), Ozawa *et al.* (2019). Curing is the most important parameter that helps in achieving the desired strength, in case of the geopolymer concrete curing can be carried either by ambient or autoclave or steam curing. Out of the three-steam curing was mostly preferred as it gets the desired strength when the samples are heated at 48°C for an hour Shen *et al.* (2019), Zhang *et al.* (2019), Peng *et al.* (2018). Self-curing technology is also introduced and found to fill the voids in concrete automatically when the optimal dose percentage is accurately proportioned during the mix design process, the percentage provided by the researches if the use of polyethylene glycol is limited to 1% Vijayan *et al.* (2020), Kamal *et al.* (2018), ASTM (2013).

1.1. Discussion on Recent relevant research

RA with ES combination in high strength geopolymer concrete was found to be very rare in the recent years. Most of the research work uses Egg shell + Rice husk ash + Recycled aggregate or Egg shell +Fly ash + Metakaolin combinations Zhang *et al.* (2019), Kai duan etal (2025). Many researchers experimented the high strength concrete strength varies from 35-60MPa with respect to compressive strength. In very few cases when addition of waste materials and recycled aggregate the compressive strength reduces to 20-35MPa. When the recycled aggregate is used in concrete the strength of the concrete was found to reduce due to the accumulation of mortar, increase on porosity in the interfacial transition zone and was not found to be in a standardized state. Durability aspects of the use of this waste materials were found to be very less studied.

This research work aims in evaluating the properties of High Strength Geopolymer Concrete (HSGPC) as a replacement of ordinary conventional concrete due to its significant increase in durability and strength parameters. This research work is carried by using F, ES and RA as the key components in concrete, ES is used a s a replacement for F for reducing the emission of CO_2 into the atmosphere. Various testes were carried out and the results are outlined in this research paper.

2. Experimental work

2.1. Mix Proportions

The physical and chemical characteristics of the materials used in this research work are tabulated in **Tables 1 and 2** respectively. The mix design of the samples that are used for this research work were given in **Table 3**. The replacement of RA from varies 10% to 40% and ES varies from 0% -30% for abbreviations GPCRE0 meaning Geopolymer concrete with RA as 40% and ES 0% etc., The second set of samples has only ES varying from 0-30% and it was abbreviated as GPCBE10 meaning that it has 10 % of ES replaced in it as an example. The chemical solution added in the concrete proportion for mixing the waste materials was in the proportion of 1:3, that is one part of sodium hydroxide and 3 parts of sodium silicate with additional binder ratio of 0.4. As per the mix proportion the composition of Fine aggregate and Coarse aggregate is calculated as 780kg/m^3.

Table 1. Chemical composition of waste materials.

Elements	F	RA	GGBFS	ES
SiO_2	50.57	87.69	30.5	0.65
Al_2O_3	46.4	0.41	16.26	0.52
Fe_2O_3	0.81	0.42	0.74	0.24
CaO	0.34	3.38	34.28	97.8
MgO	0.29	0.45	16.75	0.61
SO_3	0.22	1.85	0.5	0.24
K_2O	0.04	5.09	-	0.13
P_2	0.81	0.33	-	-
Cl	-	0.04	-	-

Table 2. Physical properties of recycled aggregates.

Property	FA	RCA
Specific gravity	2.67	2.65
Unit weight (kg/m^3)	1694	1662
Fineness modulus	2.615	6.458
Water absorption (%)	0.91	1.04
Clay and fine materials (%)	0.76	0.54
Elongation index (%)	-	11.51
Flakiness index (%)	-	16.92
Impact value (%)	-	13.13
Crushing value (%)	-	12.61
Los angles abrasion value (%)	-	14.24

2.2. Mixing procedure

The waste powder materials (F, RA, ES) in definite proportions are initially taken in the blender and mixed for about 3 mins. Next the fine aggregate and the recycled coarse aggregate is added to the blender and mixed again for 3 mins. Then, the alkaline solutions were cautiously added in the dry mixer and mixed for 5 mins, so that it results into a new mixture in a paste consistency. The samples are placed in the prepared moulds. 9 samples are placed for ambient curing at a temperature of 35°C for 7 days, 28 days and 180 days respectively. 6 samples for heat curing for a temperature of 70°C for a duration of 24hrs. the mechanical and durability properties of the samples are tested in the laboratories at the specified age.

Table 3. Mix proportions of specimens

Mix	Mineral Additives (kg/m³)				Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Sodium Hydroxide ratio	Sodium Silicate ratio	Alkaline binder ratio
	F	GGBFS	RA	ES					
GPCRE0	200	200	40	0	780	780	1	3	0.4
GPCRE10	160	240	30	10	780	780	1	3	0.4
GPCRE20	240	160	20	20	780	780	1	3	0.4
GPCRE30	280	120	10	30	780	780	1	3	0.4
GPCBE0	200	200	-	0	780	780	1	3	0.4
GPCBE10	160	240	-	10	780	780	1	3	0.4
GPCBE20	240	160	-	20	780	780	1	3	0.4
GPCBE30	280	120	-	30	780	780	1	3	0.4

Alkaline solution preparation for the geopolymer concrete.

The study used 10 Molarity for the experimental work for concrete mix proportions. The molar mass of sodium hydroxide is 40 g.mol-1, when we need to prepare for 1 Molarity 400 grams pellets of sodium hydroxide is taken in a borosilicate container and mixed with 1 liter of water, the temperature if maintained at 50-60 degree Celsius. It is kept in the laboratory for 24 hours without any disturbance and the it is used in mixing the concrete ingredients. 1 part of sodium hydroxide with 3 parts of sodium silicate is used for this research work. The concrete is cast and then after 24 hours of casting the mould is removed and then half samples are cured at room temperature and the remaining half are hot oven cured.

2.3. Test Procedure

The fresh properties were tested for the prepared samples as per the ASTM-C-143-15a [53] standards. The compressive strength for the prepared samples with size 100mm x100mm x 100mm at 7days, 28 days and 180 days were tested as per the IS and BS-1881 codal provisions [54]. The spilt tensile strength was performed in accordance to ASTM-C496-11 standards [55]. The flexural testing prisms of size 100mm x 100mm x 500mm were tested at 28 days in accordance with ASTM-C78-16 and IS 516 codal provisions. The durability tests such as Sorptivity [57], sulphate attack [58-59] was conducted for the prepared samples at different ages to determine the formation and width of cracks.

3. Results and Discussions

3.1. Slump test

The flowability of concrete for different proportions of ES are represented in the figure below. From the results it can be found that there was a significant decrease in flowability due to the presence of very fine particles in ES (0-30%). Addition of ES with RA and BA decreases the slump flow to drastically. The gradual decrease in slump was due to the absence of water usage in concrete, as the geopolymerzation effect was formed due to the addition of only alkaline solutions. The increase in ES powder shows a decrease in flowability for about 5% as in **Figure 1.**

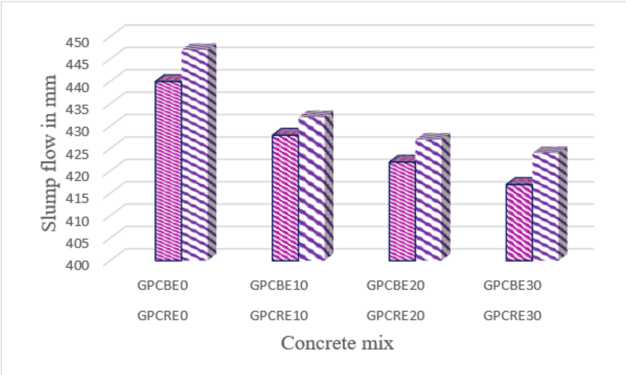

Figure 1. Slump Flow for different mixes of GPC

3.2. Compressive strength by ambient curing

The compressive strength of the different mixes when replaced by ES instead of FA in four proportions from 0 to 30% were studied in detail. From the test results it was found that the compressive strength increased significantly under ambient curing conditions from 10-20% replacement of ES. The increase in strength is mainly due to the micro filler content as the packing density is very closely packed. Due to ambient curing technique the compressive strength was increased to about 9 % in case of 7 days, 5% in case of 28 days and 9.5% in case of 180 days respectively. When the ES percentage was increased further above 20% there was decrease in compressive strength due to the dilution effect of the ES that leads to weaker intermolecular bonding in the geopolymerzation process as shown in **Figure 2**.

3.3. Compressive strength by heat curing

Investigations were carried out to determine the influence of using ES as a replacement of FA in four proportions from 0% to 30% on the compressive strength of HSGPC. Compressive strength for the two types of samples using RA and BA varying from 10% to 40% were determined. Heat curing was adopted for samples, the samples are placed in an oven for 24 hours at 70°C. Initially after the addition it results in significate increase in compressive strength when RA and ES are used when compared to BA and ES. The reason for increase in compressive strength due to the addition of ES acts as a micro filler, strengthening the packing density of the matrix in geopolymer concrete. When the ES is increased above 20% the compressive strength decreases due to the dilution effect of geopolymerzation reactions. This same effect was found at higher curing ages of 28, 60 and 90 days. It was also found that the compressive strength was found to reduce after 90 days due to the interaction of ES with RA with the reduction in micro filler content as in **Figure 3**.

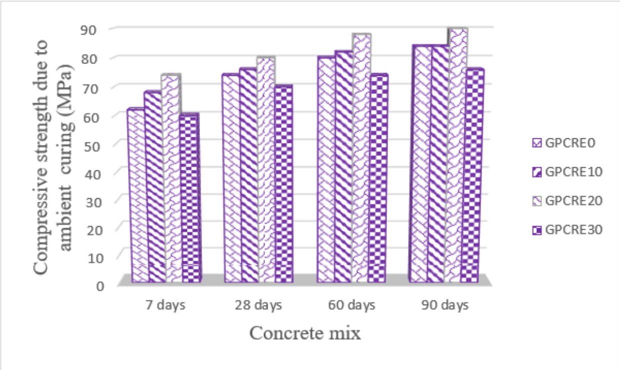

Figure 2. Compressive strength due to ambient curing for different mixes of GPC

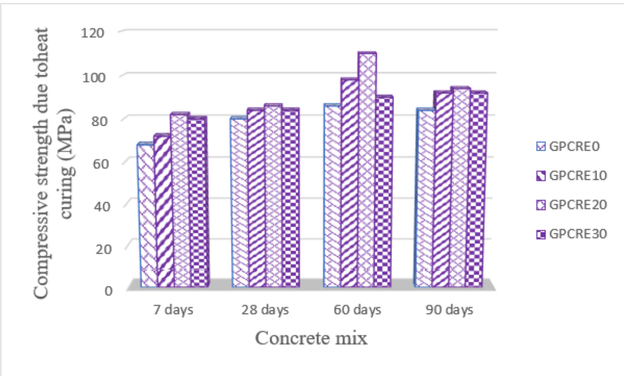

Figure 3. Compressive strength due to heat curing for different mixes of GPC

3.4. Split tensile strength

The proportions of ES and RA were replaced for FA in proportions from 10 to 40%. **Figure 4** shows the results of the split tensile strength under the two curing conditions. The split tensile strength was found to increase from 10-20% due to the arrangement of the dense packing and micro filling capability of ES and RA usage. From the test results it was found that the strength increased between 6.3 to 7.1 MPa. When the waste composition was increased to 40% further the strength was found to decrease and it reached 6.1 MPa due to the increase in the calcium content in ES and RA. Test results from self-curing for split tensile reported that the strength was increased by 24% due to the micro filling capacity and moisture filling capabilities. When the proportion was increased above 20% the strength was found to decrease by 8% when compared to the controlled concrete. Without the use of ES the result was found to be higher that the controlled concrete. When the samples were tested using heat curing at a temperature of 80 degree Celsius for 24 hours there was an increase in strength 6.4 to 8.5MPa due to the effect of geopolymerzation when RA and ES were replaced from 10-20%. Further on increase above 20% there was decrease in the split tensile strength from 8.5MPa to 7.5MPa as the inter molecular effects reduces the strength of geopolymerzation as in **Figure 4**.

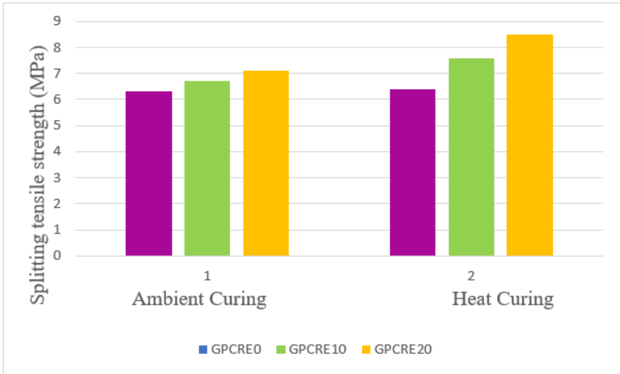

Figure 4. Split tensile strength due to ambient and heat curing for different mixes at 28 days strength.

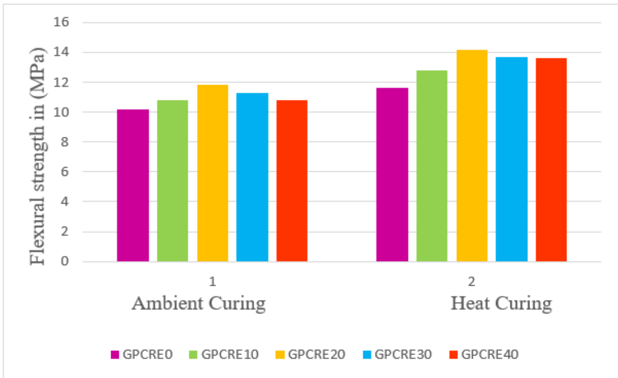

Figure 5. Flexural strength due to ambient and heat curing for different mixes at 28 days strength.

3.5. Flexural strength

The ratios of GPCRE are varied from 0 to 40%. From the test results it was concluded that the replacement ratios were increasing from 0 to 20% and after that there was decrease in flexural strength. The increase in flexural strength was due to the filling ability in the micro structure characteristics due to intermolecular packing as a result of which the density of concrete matrix increases. It was concluded that when the replacement waste materials RA and ES were reduced and the heat curing is maintained at a lower temperature there was increase in flexural strength. When the temperature was increased above 70°C for a period of 24 hours the flexural strength was increased from 11.2 MPa to 14.2MPa for a percentage of 27%. On further increase of RA and ES, the flexural strength was found to decrease till 12.3%. Decrease percentage of 13.4% due to the dilution effect and weak intermolecular bonding of geopolymerzation effect is as represented in **Figure 5**. Samples when cured using ambient condition there was increase in flexural strength when the proportion was from 10-20% due to geopolymerzation and compact density filling the micro filling effects.

3.6. Physical Properties-Sorptivity Tests

For different percentage replacements of ES for FA using ambient and heat curing, the water Sorptivity tests exhibited improved results especially when heat cured which results in the improved microstructure and geopolymerisation effect. Use of ES in the concrete sample exhibits a positive effect in sorptivity hence increasing the pore morphology reducing the sorptivity effect by 14%. In case of ambient curing there was strength improvement to 12% due to water penetration effect. The sorptivity was found to decrease to 50% when ES percentage was increased after 20% as in **Figure 6**.

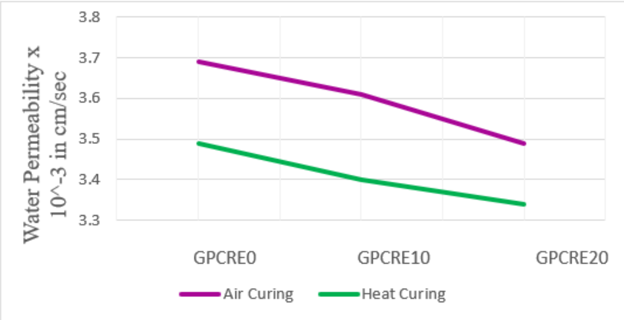

Figure 6. Water Sorptivity coefficient of HSGPC mixes.

3.7. Sulphate attack

Concentration of sodium sulphate 5% and 10% was used for the sulphate attack test. The sulphate attack was found to show a linear increase in strength to 9.6% when cured using ambient condition. When percentage of ES was increased above 20%, the concentration of sodium sulphate is 10% there was decrease in strength to 29%. When samples are subjected to heat curing the strength was found to increase to 13.7% at 20% ES as in **Figure 7**.

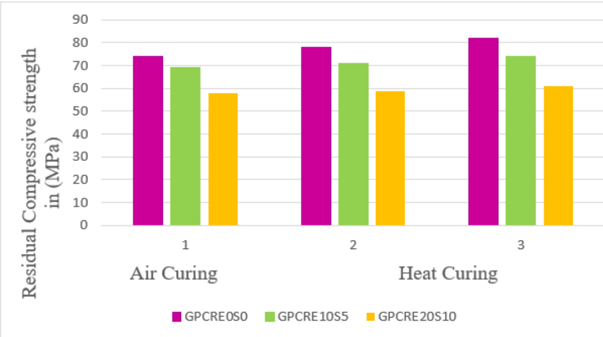

Figure 7. Residual Compressive strength of HSGPC mixes with 0,5 and 10% sulphate concentrations.

3.8. Micro structure analysis

The samples when exposed to scanning electron microscope containing GPCRE20 by replacement of FA. From micro structure analysis it was found that the packing density of the concrete was found to be dense increasing the bond and filling ability of the sample. It was also found to provide a far better interfacial transition zone when compared to other concrete types with high durability and mechanical properties. When samples are processed during heat curing the microstructure analysis was found to have uniform refining properties when ES and RA were used. When 20% usage of ES is used in HSGPC the internal microstructure of the concrete was found to increase as a result of which no cracks or voids were found due to which the strength of the concrete increases. The microstructural analysis of the samples are as shown in **Figure 7a and 7b** respectively.

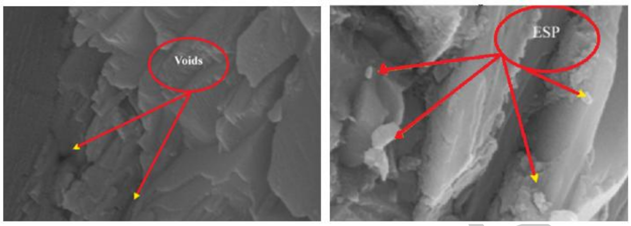

Figure 7. Microstructural analysis using a) Heat curing b) ambient curing

3.9. Limitations of the research study:

During the study of the research work there were few limitations that are listed below.

a) Use of chemical composition of ES may not be similar when studing the future durability of higher studies, as the processing methods, calcination conditions influence of repeatability may vary.

b) RCA when generally used in concrete generally reduces the workability and higher water demand.

c) Durability studies generally focus on permeability, acid sulphate attacks, carbonation, corrosion resistance are not comprehensively evaluated as it will be studied in detail.

d) The results tabulated are only based on laboratory scale experiments, filed or economic feasibility may be studied further in the future for practical applications.

4. Conclusions

In this research paper the egg shell powder is used as a replacement material for fly ash in HSGPC was studied. Two techniques for curing namely Ambient curing and heat curing (70 degree Celsius) were compared. The mechanical strength of concrete such as Slump test, Compressive strength by ambient and heat curing, split tensile strength and flexural strength. Finally, the durability properties such as sulphate attack and water sorptivity are studied and finally completed with microstructural analysis. The results were summarized as follows:

a) The ES composition when used as 20% was found to give satisfactory results for both ambient and heat curing.

b) Heat curing for 70 degree Celsius was found to give better results for mechanical and durability studies carried out in this research work.

c) At 28 days there was decrease in the split tensile strength from 8.5MPa to 7.5MPa as the inter molecular effects reduces the strength of geopolymerzation.

d) At 28 days the flexural strength was found to increase from 11.2 MPa to 14.2MPa for a percentage of 27% when subjected to heat curing then followed by ambient curing.

e) The sorptivity durability test it was concluded that decrease in strength reached till 50% when the ES was replaced above 20%.
f) The water permeability test was concluded that when the percentage of ES and sulphate was increased above 20% and 10% there was decrease in strength to 29%. When samples are subjected to heat curing the strength was found to increase to 13.7% at 20% ES

From the research paper findings, it can be used as an insight for material optimization for replacement of waste materials instead of Flyash for a sustainable environment.

Authors Contributions

Karthiga @ Shenbagam Natarajan, have equally contributed for this work. Revathi Kangaraj, have equally contributed for this work.

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Ethical Approval

This is the work done by me and the PG students; it is not published anywhere else by us.

Consent to Participate

All the authors of this paper have given their consent to participate and act as one of the authors.

Consent to Publish

I, the author, give my consent for the publication of identifiable details, which can include photograph(s) or case history and details within the text

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Competing Interests

There is no financial aid available

Availability of data and materials

All the necessary data are given in the paper in detail.

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