Developments in the Built Environment 13 (2023) 100115

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Physical characteristics and mechanical properties of a sustainable lightweight geopolymer based self-compacting concrete with expanded clay aggregates

Balamurali Kanagaraj [a], N. Anand [a,*], B. Praveen [a], Sivakumar Kandasami [b], Eva Lubloy [c,**], M.Z. Naser [d]

[a] *Department of Civil Engineering, Karunya Institute of Technology and Sciences, Coimbatore; India*
[b] *Buildings & Factories IC, L&T Constructions, Chennai, India*
[c] *Department of Construction Materials and Technologies, Faculty of Civil Engineering, Budapest University of Technology and Economics, Budapest, 1521, Hungary*
[d] *AI Research Institute for Science and Engineering (AIRISE), Clemson University, Clemson, SC, 29634, USA*

ARTICLE INFO

Keywords:
Geopolymer
Expanded clay
Self-compacting concrete
Lightweight concrete
Hardened properties
Environmental impact assessment

ABSTRACT

Geopolymer Concrete (GPC) is a unique and sustainable building material that has the potential to be transformed into a self-compacted lightweight composite for industrial applications. This paper investigates the sustainability of self-compactable lightweight geopolymer concrete (SCLGC) made from Expanded Clay Aggregate (ECA) to further explore this front. In this study, the physical properties of SCLGC, such as slump flow test, T_{500} test, V-funnel, and J-ring tests, are examined. Furthermore, the density, Ultrasonic Pulse Velocity (UPV), compressive strength, splitting tensile strength, and impact resistance are also tested to evaluate the mechanical properties of SCLGC mix with various concentrations of Sodium Hydroxide (SH) cured under different curing regimes. The aforenoted properties are examined following the American, Indian and European guidelines. In addition, microstructural analysis is conducted to assess the compactness and internal structure of SCLGC blends with varying SH concentrations cured under different curing regimes. Finally, the sustainability aspects of GPC and SCLGC mixes are analyzed through the Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) to evaluate the energy requirement and CO_2 emission and cost. The Sustainability analysis was performed to evaluate the energy requirement and CO_2 emission of SCLGC in the production of 1 m^3 concrete based on the previous literatures. The significance of the proposed research work emphasizes the utilization of ECA as an aggregate material for the development of SCLGC. The cost, carbon and energy efficiency of the SCLGC's mixes were estimated. Mix with ECA requires higher energy demand and emits high CO_2 in the open atmosphere. Based on the present analysis it can be concluded that an increase in the concentration of activator solution increases the energy demand and emits more amount of CO_2. The inference from the present study reveals ECA can be employed for the production of SCLGC with the replacement percentage not exceeding 50%.

1. Introduction

In recent years, sustainable construction practices have emerged as the primary key area for the new movement toward modern construction. Utilization of industrial by-products such as Fly Ash (FA), Rice Husk Ash (RHA), Palm Oil Fuel Shell Ash (POFA), etc., are now being favored as alternate binder materials. Supplementary cementitious materials (SCM) and an alkaline activator solution for concrete production have the potential to completely replace conventional Ordinary Portland Cement (OPC), thus paving the way toward sustainability and circular economy (Lee and Van Deventer, 2002).

The production of concrete with SCM and alkaline activators is called geopolymer concrete, coined by the French scientist and researcher Joseph Davidovits (1991). GPC made using industrial by-products resembles its cement-based concrete counterpart in terms of strength and durability performances. Recent development shows that GPC has a

* Corresponding author.
** Corresponding author.
E-mail addresses: balakmurali31@gmail.com (B. Kanagaraj), nanand@karunya.edu (N. Anand), praveenboopathy007@gmail.com (B. Praveen), drks@lntecc.com (S. Kandasami), lubloy.eva@epito.bme.hu (E. Lubloy), mznaser@clemson.edu (M.Z. Naser).

https://doi.org/10.1016/j.dibe.2022.100115
Received 18 September 2022; Received in revised form 4 December 2022; Accepted 21 December 2022
Available online 28 December 2022

higher potential for strength development than conventional cement concrete (Alanazi et al., 2017; Kanagaraj et al., 2022d; Provis, 2018; Provis and van Deventer, 2014).

The hardened density of GPC is similar to that of cement concrete. Therefore, investigations are required to develop Lightweight Geopolymer Concrete (LGC) by replacing conventional natural coarse aggregate with lightweight material (Youssf et al., 2022). .There is some work that aimed to fabricate light weight geopolymer concrete with consideration for sustainability and the use of recycled lightweight concrete aggregate. For example, results from the study of (Junaid et al., 2022) reveal that the density and strength of the mix decreased simultaneously and the observed density is found to be in the range of 1200–1500 kg/m^3.

Further, the recycled aggregate can be employed to reduce the density from 1400 to 800 kg/m^3 with adequate strength and elastic properties of GPC (Liguori et al., 2014). Similarly, expanded vermiculite offers an excellent reduction in weight and a density range of 700–900 kg/m^3, resulting in lower strength development and reduced thermal conductivity (Koksal et al., 2020). Some researchers reported the development of GPC with lightweight palm oil shells as aggregates (Hamada et al., 2020a, 2020b; Oyejobi et al., 2020; Salami et al., 2017; Ting et al., 2020). The recent literature (Murali et al., 2021; Nahhab and Ketab, 2020) shows that the initial strength of the concrete is enhanced by utilizing steel fibers and lightweight aggregates (LA) to maintain reasonable strength and lightweight. Up to 2000 kg/m^3 reduction in density was achieved while attaining a remarkable strength of 32 N/mm^2 (Alqahtani and Zafar, 2021).

In another investigation (Qu et al., 2016), were able to reduce the dead weight of the concrete using hollow ceramic spheres and expanded recycled glass. The result shows that the mix possesses an excellent strength of 43.4 N/mm^2 with a density of 1883 kg/m^3; a 49% reduction in weight is noticed compared to the reference conventional cement-based composites (Salleh et al., 2021). Some innovative technologies have been used, such as gas-forming, aerated, and blowing agents are employed to develop the LGC. Results from the investigation (Hajimohammadi et al., 2018; Jiang et al., 2016; Li et al., 2020) reveal that the weight reduction was significant and improved the thermal resistance of the mix since the employment of a gas-forming agent increases the viscosity of the mix, which results in enhancing the workability (Li et al., 2020). Other works that echo the above include (Alqarni, 2022; Badogiannis et al., 2019; Top et al., 2020; Tran and Ghosh, 2020; Wongsa et al., 2018). The work done on ECA has many benefits in terms of workability, durability, and fire resistance (Bicer, 2021a; Peys et al., 2022; Roces et al., 2021).

Lightweight aggregate concrete (LWAC) mainly improves the thermal and sound insulation properties of buildings beside its structural applications. Lightweight aggregate used in the LWAC should conforms to (ASTM C330-04, 2009) and 28 days compressive strength of LWAC should be at least 17 MPa with the density in the range of 1120–1920 kg/m^3 (Maghfouri et al., 2022). LWAC concrete can be prepared either by using naturally available lightweight aggregate or artificially made lightweight aggregate (LWA). Artificial LWA are normally produced by using the natural raw materials or byproducts (Güneyisi et al., 2015). Expanded clay aggregate (ECA) is a type of artificially produced LWA that is formed by expanding the natural clay at a high temperature of around 1200 °C in a rotary kiln (Burbano-Garcia et al., 2021; Ozguven and Gunduz, 2012; Pioro and Pioro, 2004). The particles shape of ECA is spherical with they have a closed and barely porous outer surface as compared to inner structure that is black in the color and highly porous. Previously ECA has been used to prepare lightweight masonry plaster and mortar (Koňáková et al., 2017; Muñoz-Ruiperez et al., 2016), self-healing concrete (Pan and Gencturk, 2021), structural lightweight and self-compacting concrete (Andressa F. Angelin et al., 2020; Nahhab and Ketab, 2020), as a filler in aluminum tubes (Kemény et al., 2020), and for the thermal insulation purposes (Füchsl et al., 2022). In the traditional concrete, strength of normal weight aggregate is generally higher as compared to interfacial transition zone (ITZ) and matrix. However, LWA acts as a weakest source of strength in the LWAC and it can significantly affect the elastic and mechanical properties of lightweight concrete (Güneyisi et al., 2015). Past studies investigated the aggregates properties and their effects on the properties of concrete. It was reported that weakest component of the concrete determines its strength. If aggregate is strongest component of concrete mixture, forces are transferred through the aggregate and matrix. However, stress is transmitted through the cement matrix and cracks are spread through the aggregate if LWA is weakest constituent in comparison with matrix. Hence, it was concluded that LWA is a weakest link as compared to ITZ in the LWAC (Andressa F. Angelin et al., 2020; Nahhab and Ketab, 2020).

In the case of ECA blenced concrete, low density and strength of the aggregate affect the internal load distribution of the material as in light weight concrete loads are mainly carried by the cement paste and not by the aggregate skeleton (Ahmad and Chen, 2019; Bicer, 2021b). Due to this, the mechanical properties of light weight concrete are different at normal temperature from the properties of normal concrete. The strength of the aggregate particles greatly influences the compressive strength of light weight concrete, higher aggregate strength causes higher concrete compressive strength (Cobo-Ceacero et al., 2022; Rickard et al., 2016). Light weight concrete are more sensitive to tension, and the ratio of tensile and compressive strength is different from that of normal concrete (Shafigh et al., 2014). Their fracture mechanical properties are also different, the fracture energy of concrete with normal aggregate can be twice the fracture energy of concrete with ECA, which has the same compressive strength (Rashad, 2018).

Based on past studies (Kurda et al., 2018; Pavlović et al., 2022; Tinoco et al., 2022; Wittocx et al., 2022; Xing et al., 2022), the experimental work on the environmental impact analysis and life cycle assessment shows that the production of GPC requires significantly less energy than its counterpart cement-based composites. As conventional GPC is known for its sustainable nature, which eliminates the use of conventional Portland cement, then this study aims to develop self-compactable GPC with appropriate strength to achieve a balanced mix proportion for traditional GPC and ECA. In addition to testing the mechanical properties of SCLGC, the sustainability index of SCLGC is evaluated qualitatively by comparing SCLGC with GPC. A comprehensive Environmental Impact Assessment (EIA) that includes emissions, energy demand, waste recycling, hazardous impacts of the material production process, and integrated sustainability aspects in the development and implementation of SCLGCs was carried out.

1.1. Research significance

The novelty of the current work is to create a lightweight GPC by utilizing lightweight aggregates to replace naturally occurring aggregates and then partially replacing FA with GGBS. The presence of GGBS in the mix enhances the geo-polymerization reaction without the aid of external heat; thereby, the preparation process of SCLGC becomes less energy intensive and hence, sustainable and economical. Further, the variation in the molar concentration of the activator solution and selection of different curing regimes, viz. ambient and sunlight curing, was adopted to study the behavior of SCLGC. SCC and GPC are green construction materials and in needs for further development. Therefore, the authors aimed to develop a light weight geopolymer concrete derivate that is also self-compactable. A light weigh self-compacting geopolymer concrete may be useful for a varaiety of applications such as new construction or retrofitting.

2. Materials and methods

Five mixes ECA0, ECA25, ECA50, and ECA100 were prepared. ECA represents Expanded Clay Aggregates and 0 stands for employment of ECA percentage in the mix. The ECA0 was prepared using locally available M-Sand, and conventional Coarse Aggregate (CA) with Alkaline Activator (AA).

2.1. Binder

Low Calcium Fly Ash (Class F FA) procured from coal-fired Thermal Power Plant was employed as binder material. Ground Granulated Blast Furnace Slag (GGBS) procured from a local fabricator in Coimbatore, India, was employed as binder material for the production of the concrete.

2.2. Filler

2.2.1. Fine aggregate

M-Sand (crushed stone sand) was employed as fine aggregate, and its fineness modulus, specific gravity (SG), and water absorption (WA) properties were 2.56, 2.66, and 1.36%, respectively.

2.2.2. Coarse aggregate

The well-graded natural coarse aggregate employed in the present investigation was broken granite chips of size 10 mm and below, with specific gravity and water absorption of 2.81 and 0.61%, respectively.

2.2.3. ECA

ECA (Expanded Clay aggregate) is a light weight aggregate made by heating the clay in the rotary kiln to a temperature of 1200 °C; the gases in the clay tend to expand the clay in the form of a honeycomb, thus resulting in rounded aggregates. The ECA was procured locally. The physical properties of the ECA were obtained from the local dealers. Fig. 1, shows the ECA particles.

Table 1 illustrates the physical properties of ECA. For the comparative study, test results with SCLGC were referred to as reference specimens. For ECA25 to ECA100, the traditional aggregates are gradually replaced with ECA in the range of 25%–100% by weight of aggregates.

2.3. Alkaline activator

The preparation of the mix starts with the preparation of an Alkaline Activator (AA) (combination of NaOH (SH) and Na_2SiO_3 (SS)) (Kanagaraj et al., 2022b, 2022e, 2022f). The AA ratio was kept constant at 1.5

Fig. 1. Image of ECA particles.

Table 1
Physical properties of ECA.

Material	Particle Size (mm)	Density (kg/m^3)	Water Absorption (%)
ECA	2–8	440–520	15–25

for all the mixes. The FA and GGBS were used as binder materials. The selected combination of these two raw materials (as 0.5) is adopted based on the previous studies (Kanagaraj et al., 2022g; Prusty and Pradhan, 2020; Xie et al., 2019). The SH concentration was varied from 4 to 12 M at an interval of 4 M. The water-to-binder ratio adopted in the present investigation was 0.52 for 4 M concentration, 0.70 for 8 M concentration, and 0.89 for 12 M concentration. The Superplasticizer (SP) adopted in the present investigation is Master Sky Glenium 8233 (a combination of water reducing admixture and viscosity modifying admixture) at a dose of 6%. Due to high calcium oxides in GGBS, external heat curing need not be resorted (Kanagaraj et al., 2022c). The primary function of GGBS in the mixture is to generate heat, which is required for the polymerization reaction to occur between AA and the other constituents of the mix, namely filler materials. An increase in the GGBS beyond the threshold value may lead to a rapid setting of the GPC mix. The mix design associated with the preparation of SCLGC followed ACI 211.1 (2006) and EFNARC (2002) guidelines, and the details of mix proportions are illustrated in Table 2.

3. Determination of concrete properties

3.1. Test on fresh concrete

The flow of SCLGC can be determined using a slump flow test which measures the concrete spread diameter. ACI 237R-07 (2007), IS 10262: 2019 (2019), and EFNARC (2002) classify slump flow based on different applications. For normal use, the concrete spread should be in the range of 660–750 mm. The time it takes to reach a diameter of 500 mm during a slump flow test is called the T_{500} mm slump flow.

In addition to the flow test, the filling ability can be measured using the V-funnel test. The V shape of the tool controls the flow of concrete, and an increase in duration indicates a reduction in the rate of flow. The time taken for the concrete to empty the funnel is recorded, which indicates the mixture's viscosity. After 5 min, the concrete is allowed to flow through V-funnel, and the time required to empty the funnel is noted, which indicates the segregation resistance of the composites. The J-ring test measures the ability of concrete to pass through reinforcement, measuring the height difference between the inner and outer edges of the J-ring. If the height difference is close to zero, the concrete has better penetration capacity. After observation of the fresh concrete properties, it is poured into the molds to determine the hardened properties according to ASTM C 39 (2014), ASTM C 496C (2011), (IS 516, 2004), and (IS 5816, 2004).

3.2. Test on hardened concrete

3.2.1. Compressive strength (CS)

The test for the compressive strength (CS) was conducted to examine the maximum load-carrying capacity of the material. 150 mm diameter and 300 mm long cylinders and 150 mm cube specimens were employed to measure the CS of the SCLGC. The cylinders were tested in the Digitalized Compression Testing Machine (CTM) as per (ASTM C 39, 2014).

3.2.2. Tensile strength (TS)

The split tensile strength test was conducted to investigate the tension capacity of SCLGC. Similar to CS, split tensile strength was performed on 150 mm in diameter, and 300 mm in length cylindrical specimens and tested in the CTM to examine the tensile strength of the SCLGC.

The following expression is used to calculate the TS of the specimens:

Table 2
Concrete ingredients for the preparation of SCLGC mixture.

SCLGC Mix	Binder (kg/m^3)		Aggregates (kg/m^3)			Alkaline Activator (kg/m^3)		Molarity (M)	Type of Curing
	FA	GGBS	Fine	CA	ECA	SH	SS		
ECA0-4-A	275	275	510	999	–	29	74	4	A
ECA0-4-S	275	275	510	999	–	29	74	4	S
ECA0-8-A	275	275	510	999	–	59	147	8	A
ECA0-8-S	275	275	510	999	–	59	147	8	S
ECA0-12-A	275	275	510	999	–	88	221	12	A
ECA0-12-S	275	275	510	999	–	88	221	12	S
ECA25-4-A	275	275	510	749	250	29	74	4	A
ECA25-4-S	275	275	510	749	250	29	74	4	S
ECA25-8-A	275	275	510	749	250	59	147	8	A
ECA25-8-S	275	275	510	749	250	59	147	8	S
ECA25-12-A	275	275	510	749	250	88	221	12	A
ECA25-12-S	275	275	510	749	250	88	221	12	S
ECA50-4-A	275	275	510	499	500	29	74	4	A
ECA50-4-S	275	275	510	499	500	29	74	4	S
ECA50-8-A	275	275	510	499	500	59	147	8	A
ECA50-8-S	275	275	510	499	500	59	147	8	S
ECA50-12-A	275	275	510	499	500	88	221	12	A
ECA50-12-S	275	275	510	499	500	88	221	12	S
ECA75-4-A	275	275	510	250	749	29	74	4	A
ECA75-4-S	275	275	510	250	749	29	74	4	S
ECA75-8-A	275	275	510	250	749	59	147	8	A
ECA75-8-S	275	275	510	250	749	59	147	8	S
ECA75-12-A	275	275	510	250	749	88	221	12	A
ECA75-12-S	275	275	510	250	749	88	221	12	S
ECA100-4-A	275	275	510	–	999	29	74	4	A
ECA100-4-S	275	275	510	–	999	29	74	4	S
ECA100-8-A	275	275	510	–	999	59	147	8	A
ECA100-8-S	275	275	510	–	999	59	147	8	S
ECA100-12-A	275	275	510	–	999	88	221	12	A
ECA100-12-S	275	275	510	–	999	88	221	12	S

Note: ECA represents Expanded Clay Aggregates, 0, 25, 50, 75 and 100 represents replacement percentage, 4, 8, and 12 represent the SH concentration, and A and S represent the curing methods ambient and sunlight, respectively.

$$T = 2P/\pi ld \tag{1}$$

where, T is the split tensile strength (MPa), P is the applied load indicated by the CTM (kN), l is length (mm), and d is the diameter (mm).

3.2.3. Ultrasonic Pulse Velocity test (UPV)

The cube specimens were also assessed via the UPV test. The results of UPV confirm the consistency of material in the hardened state of SCLGC concerning the CA replacements with ECA. Although the SCLGC has a sizeable mass reduction, the homogeneity and uniformity of the generated mix are to be evaluated. The UPV was done as per (ASTM C 597 (2003)) guidelines.

3.2.4. Impact strength (IS)

Lightweight composites are extensively used in modern construction sectors; some commonly employed structures are bridge decks, wall panels, slabs, and a few precast members. Therefore, the response against impact load is evaluated to withstand such environmental conditions. The impact test was performed using a drop hammer test on the SCLGC disk of size 150 mm × 65 mm following (ACI 544.2R-89, 1999). The following equation (2) was employed to determine the impact of energy;

$$E_{\text{Impact}} = m \times g \times h \times N \tag{2}$$

Where m is the weight of the hammer (4.5 kg), g is the gravity (9.81 m/s^2), h is the free fall height (0.45 m), N is the number of blows that cause cracks, and E is the energy in Joules. The findings were used to investigate the effect of ECA on energy absorption and the behavior of SCLGC during sudden loading.

4. Results and discussion

4.1. Workability

The workability of SCLGC was examined in accordance with (ACI 237 R, 2007), (IS 10262, 2019), (IS 1199, 2018), and (EFNARC, 2002) guidelines. GPC's self-compactibility was achieved by adjusting the binder content and changing the superplasticizer (SP) dosage. The results obtained are plotted in Figs. 3–5. These figures show the results of the various performance tests used to study the fresh properties of ECA-based SCLGC.

Findings from the tests indicate that increasing the SP dosage positively affects the fresh properties of the GPC composites (Pradhan et al., 2022). The mass of SH and SS required for the polymerization reaction of the alumino-silica source in ECA-based GPC affects the fresh properties of the mix. The amount/quantity of SH required for the polymerization process is a product of the SH's water content and concentration. The amount of SS required for the mixture to be the product of the SH content and the AA ratio. Total liquid (L) content is the sum of water (W), SH, and SS. Therefore, the (L/B) ratio directly impacts the fresh properties of SCLGC, as shown in Fig. 2. Fig. 2-a shows the concrete diameter in the slump flow for the 2% SP.

4.1.1. Slump flow for SCLGC

Past studies (Nahhab and Ketab, 2020; Nepomuceno et al., 2018) show that the ability to fill is an essential property of self-compacting concrete and is greatly affected by the ECA content. Herein, five different mixes with varying proportions of ECA (0%, 25%, 50%, 75%, and 100%) are adopted to achieve self-compactibility with the help of SP. Fig. 2-a and Fig. 3 indicate the concrete flow diameter of the newly

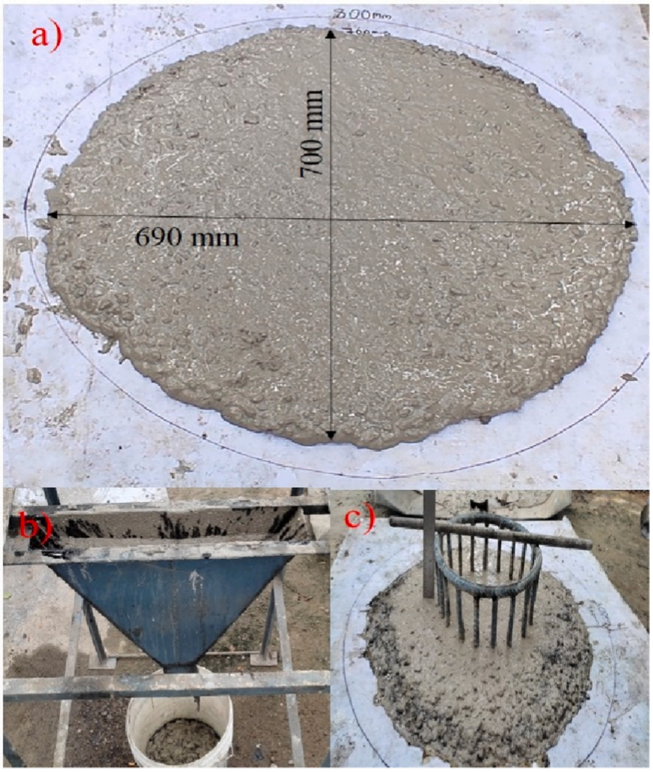

Fig. 2. Workability tests on SCLGC mixture; a) Slump flow; b) V-funnel Test; c) J-ring test.

prepared ECA-based SCLGC composite.

4.1.2. T_{500} test for SCLGC

In addition to the slump flow test, the T_{500} test was performed on a newly prepared ECA-based SCGLC composite using SP. The time taken to reach a diameter of 500 mm is recorded during the test. All SCGLC composites with five different ECA have shown a slump flow time between 10.94 and 3.5 s from the experimental trials. Fig. 2a indicates the slump flow time for the five ECA mixes with various SH concentrations. As mentioned above, an increase in the ECA content increases the flow of concrete by satisfying the acceptance value recommended in the (EFNARC, 2002).

4.1.3. V-funnel test for SCLGC

The segregation resistance of the developed SCGLC was measured using a V-funnel apparatus. Fig. 2-b depicts the ECA-based SCGLC flow derived obtained from the V-funnel instrument. Concrete flow time is recorded during the test. As measured for mixtures with different ECA content and varying SH concentrations, concrete flow time ranged from 18.2s to 7.38s. The minimum concrete flow time value was recorded as 7.38 s for the ratio of water to binder (W/B) is 0.56. From Fig. 4, the concrete flow time of SCLGC is reduced for the mix with higher percentages of conventional CA. This may be due to differences in the specific gravitational force of the concrete mix material.

4.1.4. J-ring test for SCLGC

The J-ring test was used to evaluate the passing ability of the prepared SCGLC. Fig. 2-c depicts the ECA-based SCGLC tested by the J-Ring apparatus. Concrete is allowed to flow through vertical bars, and the height difference is measured. According to EFNARC guidelines, the average difference in the height of the concrete should be between 0- and 10-mm. Mix with W/B ratios of 0.18, 0.37, and 0.56 shows a J-ring value of 14.39 to 6.78 mm, as shown in Fig. 5. The mix with 0% and 25% ECA content did not meet the requirements of EFNARC, whereas mixing with 50%, 75%, and 100% ECA was found to satisfy the EFNARC guidelines.

The European Guidelines for Self-Compacting Concrete favors the use of coarse aggregate in a ratio up to 50% of the total aggregates (EFNARC, 2002). The increase in fine aggregates will be helpful in accomplishing the necessary fluidity and cohesiveness (Rahman and Al-Ameri, 2021). Researcher (Muttashar et al., 2018) used "spent garnet" as a replacement for sand in the making of self-compacting geopolymer concrete and obtained a desirable mechanical strength. In the year 2017 (Reddy and Elavenil, 2017), have replaced river sand with manufactured sand in the preparation of SCGC and reported that comparatively less compressive strength in comparison with mixing with river sand (Babu and Kumar, 2015). used crushed quartzite as a partial replacement of fine aggregate in the production of SCGC and reported satisfactory mechanical behavior in achieving target strength (Muhammed et al., 2019). used recycled waste rubber as a replacement for aggregate in SCGC and the compressive strength was slightly enhanced (Hasnaoui et al., 2021). used recycled coarse and fine aggregate in metakaolin/GGBFS-based SCGC and concluded that the addition of recycled coarse aggregate (RCA) reduces workability loss over time and also reported that the incorporation of recycled aggregates decreases the mechanical performance. However (Uddin and Shaikh, 2016), reported incorporating RCA in fly ash-based geopolymer concrete made a significantly adverse effect on mechanical and durability

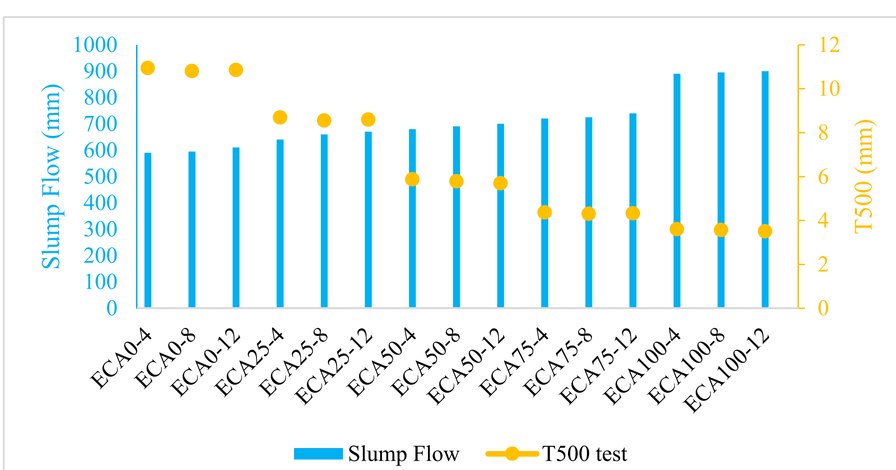

Fig. 3. Test results of SCLGC mixture (Slump flow).

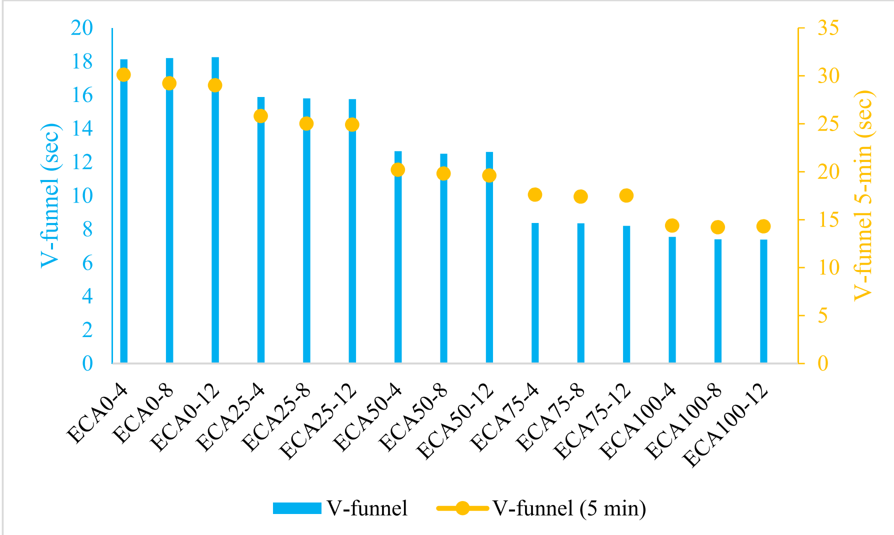

Fig. 4. Test results of SCLGC mixture (V-funnel test).

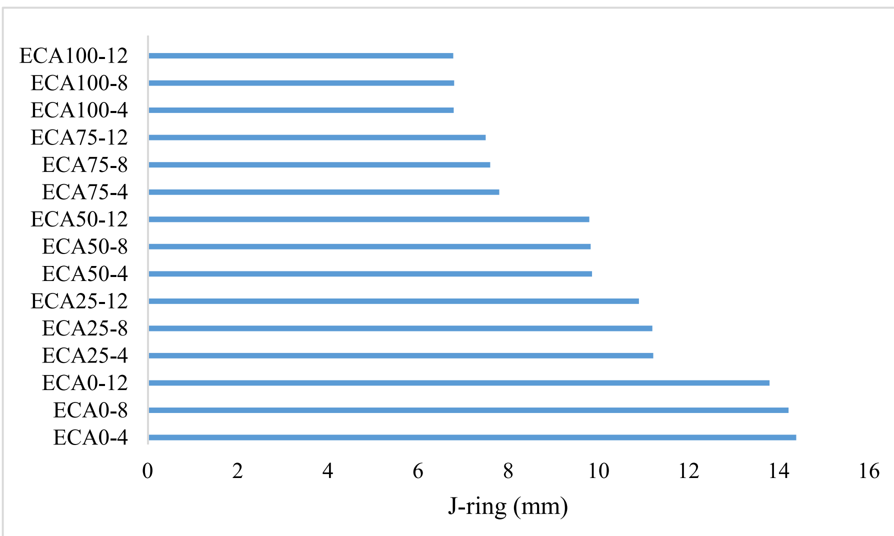

Fig. 5. Test results of SCLGC mixture (J-ring test).

properties (Mesgari et al., 2020). utilized recycled geopolymer aggregate as a substitution against natural aggregate in both geopolymer concrete and Portland concrete and observed a decrease in compressive strength and elastic modulus of concrete (Babu and Kumar, 2015). studied both NCA and RCA with GGBFS as the sole binder. They reported that the performance of SCGC mix with NCA towards mechanical properties is better than RCA.

4.2. Density

The density of the freshly prepared mix is tested as per ASTM C 138 (2017). Fig. 6 depicts the densities of SCLGC mixtures with different proportions of ECA. The primary significance of the investigation was to produce a lightweight GPC without any significant reduction in strength properties. Although strength properties are often compromised, researchers (Heath et al., 2014; Murali et al., 2021; Roces et al., 2021) have noticed that the use of lightweight composites reduces density. The current research primarily focuses on producing GPC with a lower density and a higher strength value. ECA is a porous material with more than 50% voids; a significant weight reduction is noticed for conventional GPC with an increased fraction of ECA.

The mix with 0% ECA content possesses a density between 2390 and 2365 kg/m^3. The variation in density is observed for different replacement levels of ECA in the mix. For the mix with 25% ECA the density, range is between 2220 and 2135 kg/m^3, and for the mix with 50% ECA the tested density values are 2050 to 1980 kg/m^3. In the case of mix with 75% ECA, the values are 1760 to 1630 kg/m^3, whereas mix with 100% replacement of natural CA with ECA results in the density reduction of 1190 and 1075 kg/m^3 for various SH concentrations and curing periods. The decrease in the densities was found to be 52–54% in 100% CA replacement. The tendency to reduce density is similar to previous studies (Andressa F Angelin et al., 2020; Bicer, 2021a; Murali et al., 2021; Nahhab and Ketab, 2020; Nepomuceno et al., 2018; Roces et al., 2021).

Furthermore, due to the porous nature (formed during the production process) of ECA aggregates (Roces et al., 2021), the prepared GPC exhibited an enhanced water retention capacity. Considering this fact, the need for additional water is significantly reduced in the development of GPC composites. The authors conducted pilot experiments with a prepared GPC having natural CA and found that the GPC composites

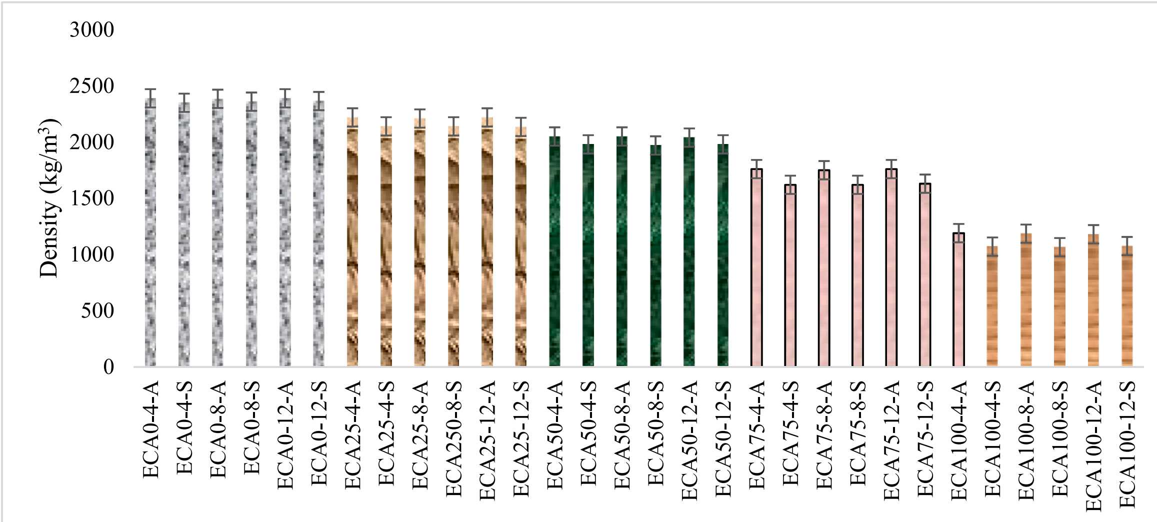

Fig. 6. Effect of ECA on the density of SCLGC.

required additional extra water of approximately 5–10% to maintain a working composition. In the case of GPC prepared with ECA, this extra water content was not required. On the other hand, a plasticizer was added to reduce the flash setting of GPC.

4.3. Compressive strength

The ECA incorporation altered the strength attributes of SCGLC, as can be seen in Fig. 7. Overall, the gradual replacement of natural CA with 25% of ECA reduced the compressive strength of concrete. The compressive strength of the mix is influenced by the strength of the binder gel, compaction condition, and inter-molecular bonding of composites. This may be attributed to the ECA aggregates that exhibit mediocre properties to conventional CA. One of the reasons for the cube strength reduction could be due to the lightweight nature of ECA, and cautiously it may not be mixed with the AA, unlike conventional CA. This may affect the cohesive bonding between the binder and filler, resulting in a porous internal structure. Researchers (Hassan et al., 2019; Rickard et al., 2016) reported that the strength of the mix could be affected by the inter-transitional bonding between fine aggregate and ECA. This motivates academics to expand their research to include microstructural analyses of ECA mixed GPC mixtures. Cement-based binder material behavior is quite different from AA with alumino-silica sources (FA and GGBS) (Kanagaraj et al., 2022a). Therefore, further investigations are required to examine the microstructural properties in further studies.

The current study is a primary investigation on the strength evaluation property of GPC containing ECA replacing conventional CA with various concentrations of SH cured under different curing regimes. The ECA of sizes ranging from 10 mm and below were employed in the GPC mixture; therefore, the only possible strength reduction may be attributed to filler materials' interfacial molecular behavior with AA solution alumino-silica source (Hassan et al., 2019). The strength test results of SCLGC under compression exhibit a linear downward trend while increasing the percentages of ECA. An increase in SH concentration and the curing temperature has a significant role in strength development (Hardjito et al., 2004). Fig. 7 depicts the testing process of SCLGC composites. Fig. 7 shows that the strength reduction was significant,

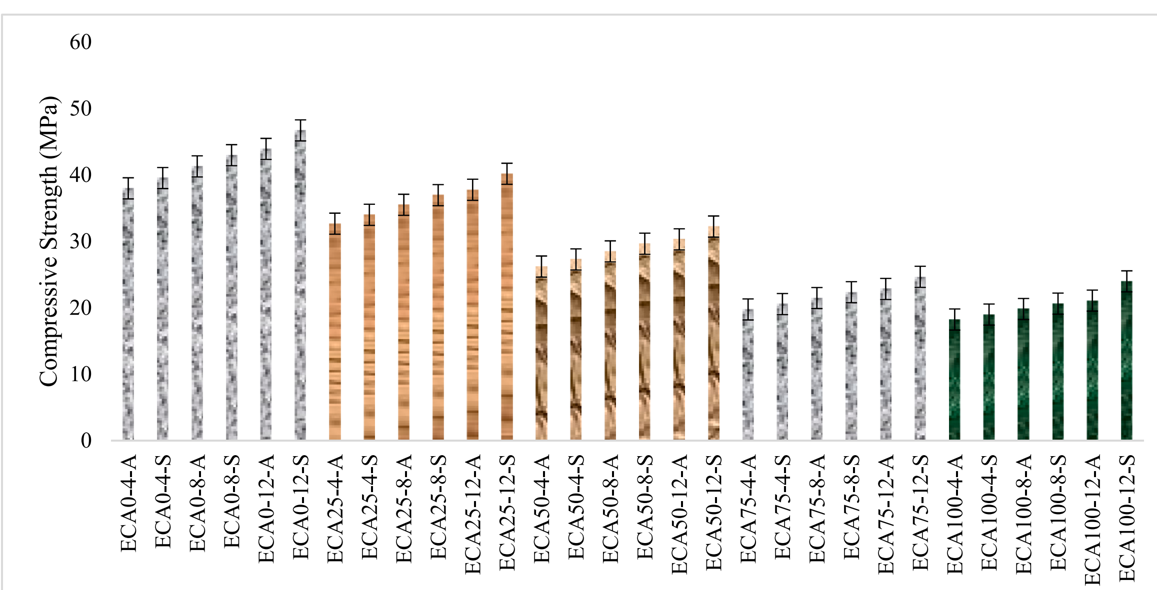

Fig. 7. Influence of ECA on compressive strength of SCLGC

between 25% and 100% replacement of CA with ECA. At the moment, the authors are planning for future studies on the mechanical properties, namely, the stress-strain relationship, elastic properties, and stiffness.

Molecular constituents of used materials heavily influence the formation of SCLGC. To accomplish the desired mechanical strength, it is preferable to have an amorphous structure of the geopolymer. SiO_2/Al_2O_3 ratio, R_2O/Al_2O_3, SiO_2/R_2O ratio (R = Na + or K +), and liquid-solid ratio; are the main elements that influence the properties of the GPC or SCLGC. An increase in alkali content or abatement in silicate content increases the compressive strength of geopolymer inferable to the arrangement of aluminosilicate network structures; this can be known from the relationship between the compressive strength and SiO_2/R_2O proportion. At higher activator dosage, the porosity reduces, and the diminished porosity enhances the strength characteristics of GPC or SCLGC. It can be concluded from the study that the effect of molecular and structural arrangements in materials is responsible for forming SCLGC through geo-polymerization. The concentration of the activator enhances the strength of SCLGC as it reduces porosity.

The study of the effect of NaOH molarity on SCGC shows that by increasing the molarity of NaOH solution from 8 M to 12 M, the compressive strength of the sample increases. But by increasing molarity from 12 M to 14 M, strength decreases. Increasing NaOH molarity concentration shows a lower rate of polymerization, which results in decreasing strength. The performance of the activator with NaOH solution of 18 M is less than that of 12 M. Considering the microstructure, the sample with NaOH of 10 M and 12 M, gives enhanced ITZ with less pore size than 8 M. As the concentration of NaOH increases from 8 M to 12 M, viscosity rises, fresh properties decrease, and the compressive strength of the SCGC mix increases.

As far as non-destructive testing (NDT) is concerned, ultra-sonic pulse velocity (UPV) results show when the molarity of NaOH increases, the corresponding velocity increases so that compressive strength increases. The compressive and split tensile strengths increases by enhancing NaOH molarity concentration and give an optimized result at 16 M with fly ash content of 400 kg/m^3. The properties of fly ash-based geopolymer concrete enriched when sodium hydroxide molarity rises to 16 M. Beyond 16 M the asserting properties decline (Hardjito et al., 2016). Enhancing molarity from 4 M to 16 M, water absorption and porosity of the mix reduced (Hardjito et al., 2004). The discussion on molarity can be concluded like by increasing molarity, though workability decreases but mechanical strength increases, yielding better quality concrete.

4.4. Split tensile strength

Fig. 8 shows the split tensile strength of SCLGC mixes. The developed SCLGC mixes exhibited excellent resistance to split action because the maximum strength reduction was within the range of 14%–21% for every 25% replacement of CA with ECA. The test results indicate that the inclusion of ECA does not contribute to the strength gain. ECA inclusion of 25, 50, 75, and 100% shows 14, 29, 41, and 62% strength reduction. Irrespective of curing type and alkaline activator concentration, the strength reduction varies for different replacement level of CA with ECA. Furthermore, it has to be noted that the inclusion of ECA in the geopolymer mix has a negative impact on strength. However, past studies (Bicer, 2021a; Murali et al., 2021; Nahhab and Ketab, 2020; Nepomuceno et al., 2018) on the strength properties of ECA-incorporated GPC have shown fluctuations in response by the composite mix (Nepomuceno et al., 2018). show that incorporating ECA by 5, 15, and 20% reduced the split tensile strength by 0.15, 4.45, and 40.54%, respectively. However, in the present study, it has been found that due to the different particle sizes, it can sustain a lowered rate of strength during splitting acts.

On the contrary, as in the previous investigations Ref. (Nepomuceno et al., 2018), mechanical strength, mainly compressive and tensile strength, has been increased due to the presence of ECA. SH concentration and chemical composition of AA largely governs the strength properties of GPC. As a result, GPC's strength test results cannot be compared. Both the compression and splitting actions are influenced by the ECA's adherence to the geopolymer in the solidified condition of the mixture gel. The mechanical qualities of the mix are unaffected by replacing natural CA with ECA 100%. The behavior of SCLGC under splitting and compression actions with ECA ensured the possibility of using ECA for weight loss without compromising strength properties.

4.5. UPV response

The Ultrasonic Pulse Velocity (UPV) technology helps verify the homogeneity and integrity of hardened concrete. The UPV response of SCLGC cube samples is investigated. Fig. 9 depicts the test results of UPV. The addition of ECA decreases the waves' travel velocity. UPV was reported to be 3.34–3.44 km/s for specimens made with SCLGC100

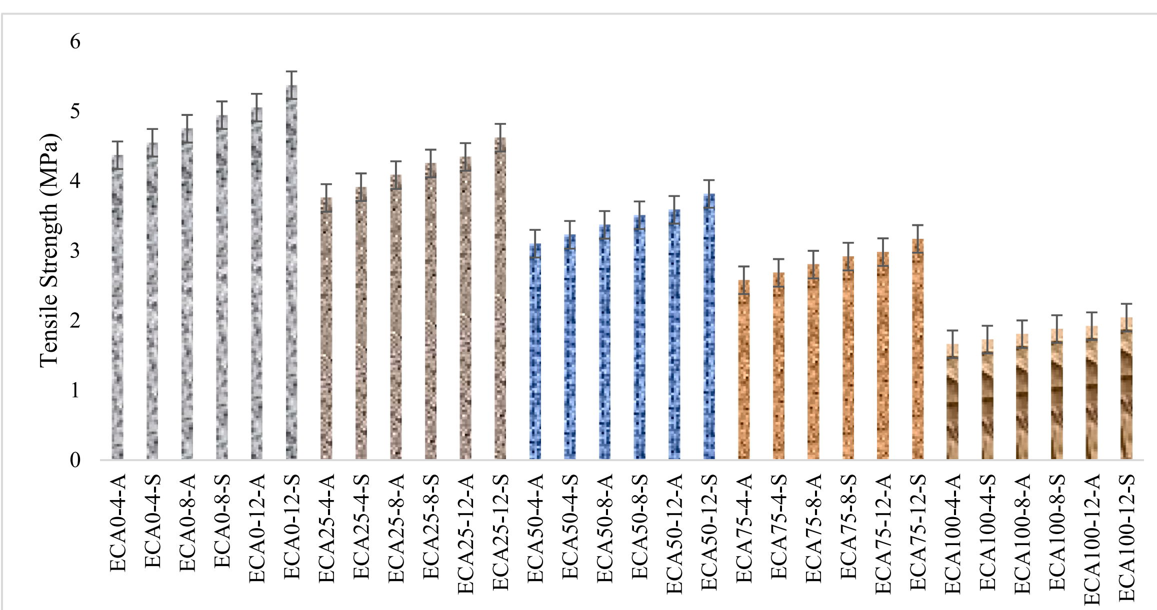

Fig. 8. Influence of ECA on tensile strength of SCLGC

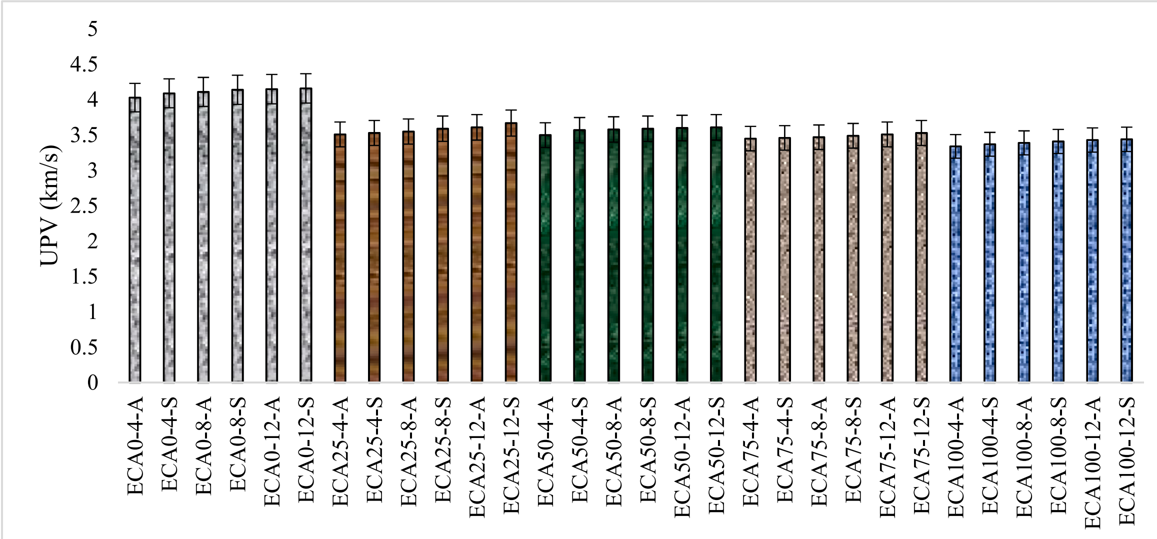

Fig. 9. UPV test results of SCLGC.

composites, completely replacing natural CA with ECA. When compared to GPC without ECA, this velocity was 17 percent lower. The inclusion of ECA enhanced the wave absorption of SCLGC mixes, even though the strength capacity of SCLGC is not larger than that of reference concrete. For UPV testing, the code for non-destructive concrete testing is suggested, testing following ASTM C 597, 2003. The UPV test values were extremely encouraging to satisfy the performance of SCLGC following the velocity range for a "good" grade concrete. The UPV values for the mixes, namely, SCLGC25, SCLGC50, SCLGC75, and SCLGC100, are reduced by 12, 13, 15, and 17%. The composite maintained its reliability and quality. ECA has a rough surface structure with spaces between the particles, which could be one cause for the waves scattering velocity across the hard mass (Murali et al., 2021). With GPCs prepared with natural CA, a direct comparison of UPV test results of GPC mixtures with ECA is not possible, as previously explained (Rickard et al., 2016). However, for a more comprehensive view of the whole substitution of CA with ECA in the GPC, a comparison of the GPC's performance with comparable lightweight products may be recommended. For example, replacing natural CA with pumice (Kurt et al., 2016), oil palm shells (Kupaei et al., 2013), vermiculite (Liu et al., 2022), and expanded clay aggregates (Nepomuceno et al., 2018) shows significant improvements in resistance against thermal conductivity. The velocity of the ultrasonic waves is low in the current study, and the material's response was determined to be comparable to that found in the literature (Murali et al., 2021). The ECA can serve as an effective wave barrier while retaining its strength. However, the authors recommend a detailed microstructural analysis of SCLGC in wave propagation through the composite's hard state be carried out.

From the UPV test results, it is clear that the inclusion of ECA in the geopolymer mix tends to influence the mix's density and microstructure, leading to a reduction in compressive strength and UPV value. For similar values of UPV, the strength is higher in SCLGC of higher density. Conversely, the lower the density of ECA, the higher the UPV for a given compressive strength. This trend is likely to be primarily related to the: lower proportional increment of UPV in relation to *fc* (characteristic strength of the mix) for higher strength levels and; simultaneously, reduction of density and stiffness in SCLGC, which means a smaller variation of UPV; slight variation of *fc* for SCLGC with rich mortars and more porous aggregates; higher compacity of rich mortars in more porous SCLGC of the same strength.

4.6. *Impact resistance*

Lightweight concrete is used for precast members to reduce the self-weight of the structures. Such components are often subjected to impact loads and must resist impact events. The vulnerability distribution across member cross-sections is to be examined for composites used in construction for any constituent modifications, such as alteration of natural CA by ECA in SCLGC. Although compression and tensile strength tests of SCLGC show that the mechanical properties are not significantly reduced due to ECA modification, response evaluation for impact loading or abrupt loading in developed SCLGC composites is required. As noted in the literature, the impact load instrument was fabricated in the laboratory following the standard guidelines of the (ACI 544.2R-89, 1999) recommendations.

Total strikes caused by initial and final cracks were recorded on SCLGC discs subjected to impact stresses. The ACI 544.2 R-89 equation calculates the amount of energy absorbed by the specimens. As depicted in Fig. 10, the impact resistance decreases with a rise in ECA content. The impact value of the concrete should not exceed 40% of the total weight of the sample, according to standard criteria (ACI 544.2R-89, 1999). The strength of the GPC mixtures decreases as the amount of ECA in the mix increases. However, there was no noticeable decrease in resistance by up to 75 percent substitution of natural CA by ECA. The reduction in resistance of the mix with 25, 50, 75, and 100% ECA is found to be 5, 6, 10, and 16% for the initial crack. Whereas in the case of the final crack, the reduction resistance is found to be 8, 13, 23, and 29%. After the initial surface cracking appeared, the ECA blended mix failed to sustain the impact load. This can be explained by the low energy absorption resistance and the weak stress distribution mechanism between conventional filler and ECA particles, and the lack of molecular attachment capabilities.

However, the intermolecular binding capacity of conventional coarse and fine aggregates is improved by adding polymeric bonding agents, which enhances the strong bonding between the filler materials. The energy absorbed by the SCLGC mixes is used to understand better the material's tendency to lose its ductile characteristics. As shown in Figs. 11 and 12, the failed samples revealed final cracking across the geopolymer binder gel and ECA. A 50% inclusion of ECA reduced the impact strength for initial and final cracking to 6% and 13%, respectively, recommending the ECA's ideal replacement level in the SCLGC. The key conclusion of the trials indicated the ECA's limitations in resisting impact pressures.

It is advised that the proper chemical binding agent be used to

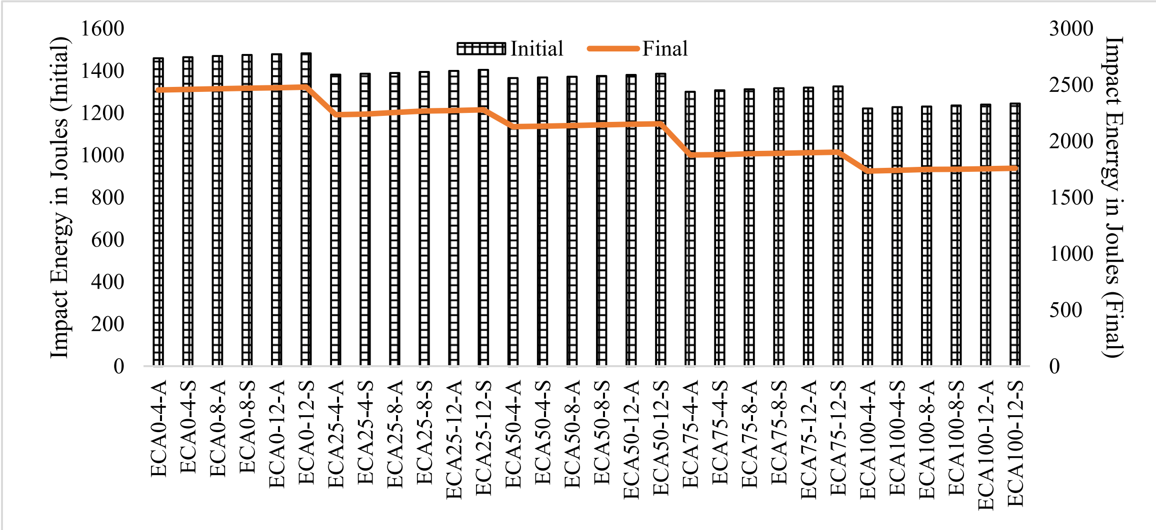

Fig. 10. Impact resistance of SCLGC specimens.

Fig. 11. Failure of SCLGC specimens under impact load.

Fig. 12. Failed Specimen of SCLGC under impact loading.

establish an acceptable or desirable binding between the composite materials. However, chemical binding agent ratios are to be carefully balanced. Because the presence of such agents can induce a change in the GPC's chemical reaction, it is chosen according to applicable standards or standard literature. In the present investigation, the utilization of ECA as a lightweight constituent for the production of GPC has limitations on attaining the strength properties. The strength qualities, including the final failure produced by impact loading, are unaffected by replacing ordinary CA with ECA. The current research yields promising early results for future research to develop lightweight GPC with ECA.

5. Microstructure analysis

Microstructure analysis is conducted on ECA blended SCLGC mix with varying SH concentrations. Fig. 13(a–d) represents SCLGC specimens cured under ambient conditions, and Fig. 13(e–h) represents SCLGC specimens cured under sunlight conditions. Fig. 13 (a) and (e) represent the reference specimens ECA0-12-A and ECA0-12-S; whereas (b) represents ECA100-4-A; (c) represents ECA100-8-A; (d) represents ECA100-12-A; (f) represents ECA100-4-S; (g) represents ECA100-8-S; (h) represents ECA100-12-S.

From the SEM analysis, it is clear that the internal structure of the SCLGC was more compact. In all the cases of ECA substitution, the hydration products developed in the GPC composites were alumino-silicate gel (Wang et al., 2020) with some unreacted binder particles, and it was denser than the CSH gel. The alumino-silicate gel in the SCLGC composites became denser with increasing calcium rich binder material. An increase in curing temperature from 20 °C to 30 °C, results in a more compact microstructure than the specimens cured under room temperature. This could be attributed to the combined effect of GGBS and higher temperature curing, which accelerates the hydration process of the geopolymeric gel. This is the reason for the strength development in SCLGC, and similar findings were reported by the researchers (Peng et al., 2019; Zahid et al., 2018).

The SEM test indicates that all the mixes possess superior packing density irrespective of curing type. This shows that all the mixture with similar proportions of ECA with varying SH concentration has retained the strength; marginal variation in the strength is noticed. The GPC exhibits a close bonding between the filler materials, where the

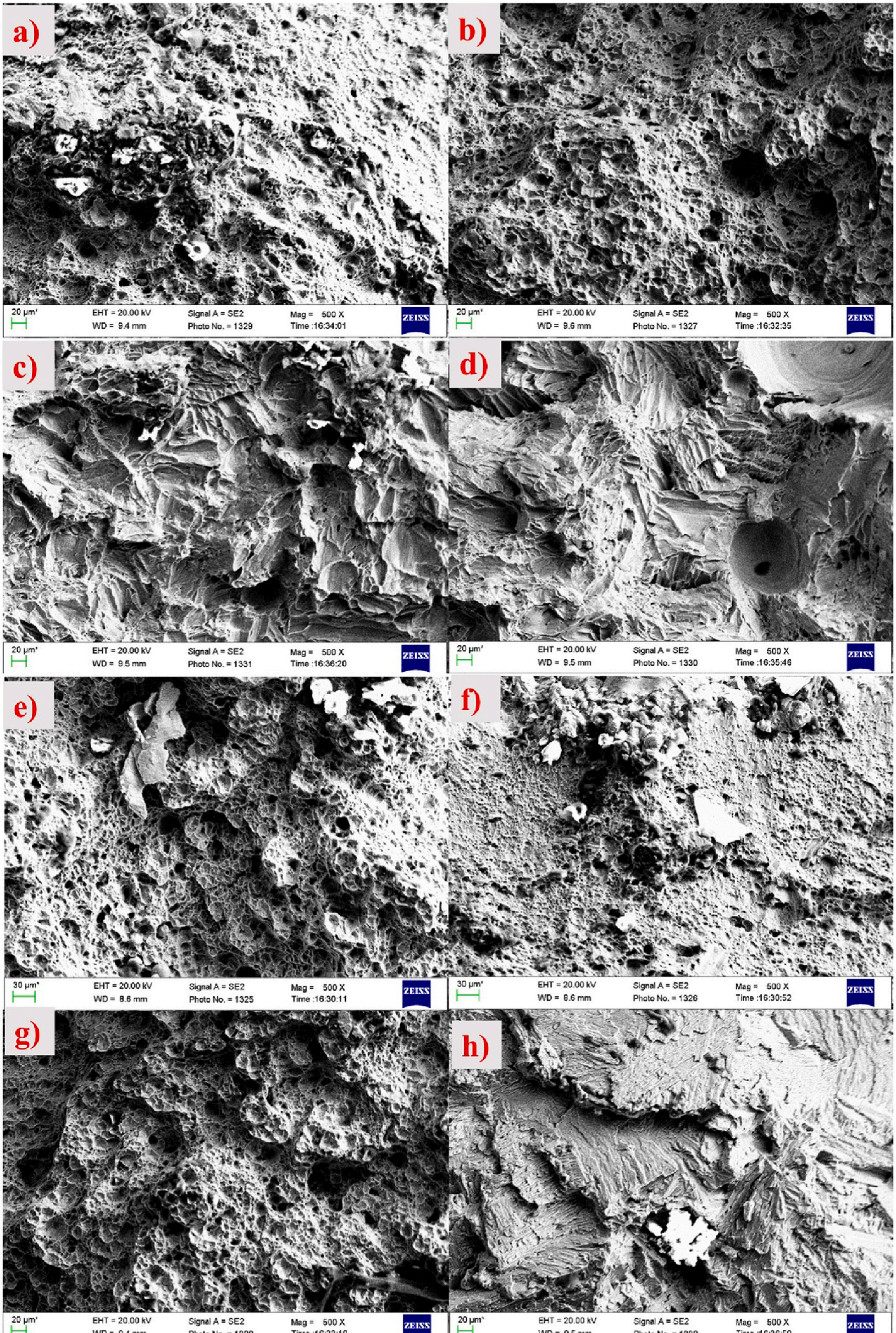

Fig. 13. SEM investigations of ECA blended FA-GGBS based SCLGC.

geopolymeric gel penetrates the voids in the surface of the ECA (Bicer, 2021a; Rickard et al., 2016). The higher internal porosity within the ECA particles was evident in the SEM images (Andressa F Angelin et al., 2020; Nahhab and Ketab, 2020). The SEM images depict a close and dense packing of binder and filler materials (Murali et al., 2021; Roces et al., 2021), and unreacted binder particles were not found in the results - attributed to the strong dissolution of precursor material with alkaline solution (Hardjito et al., 2004).

6. Life cycle assessment (LCA) of SCLGC

The sustainability of the SCLGC is taken into account as the functional unit of the LCA. Particularly, the procedures involved from the point of development to demolition and final disposal. Though the GPC or even SCLGC are not in full-length practice at this stage for the construction activities, the potential of reuse or recycling of the SCLGC may be discussed with an appropriate hypothesis.

The scope of the LCA in the present article can be limited to the overall utilization of SCLGC in its demolished state and ready to get reused or sent for possible recycling and even, to an extent, to the landfill with no alternative to the disposal option. These aspects are elaborated by suitable discussion in the inventory analysis (IA). The optimal route of defined goals eventually leads to subjective attainments. In comparison, the production, use, and application of OPC-based concrete, as well as its destruction or afterlife, are exceptionally full of energy-intensive processes ranging from gas emissions to hazardous consequences. The after-use phase of conventional concrete is far more dangerous due to the recycling and reuse limits of destroyed concrete. The energy consumption is substantial at every step, resulting in significant direct and indirect environmental hazards.

According to Fig. 14, the GPC, on the other hand, exhibits little possible evidence of damaging consequences. This is owing to the use of pozzolanic binders and the potential usage of other wastes, such as lightweight materials. This is conformed and strengthened by the IA. According to the figure, OPC-based concrete is a high-energy-intensive material at every step of preparation, manufacture, and use. The stage, which includes destruction as well as the after-service span, has a negative impact on the environment. The disposal of destroyed debris is difficult, and the final disposal is primarily through landfill dumping. Cement manufacturing is an important component of OPC-based concrete. When compared to pozzolanic binders used in GPC or SCLGC, the carbon output is quite high. Furthermore, natural aggregates and sand are rapidly depleting in the development process of SCLGC. The SCLGC, on the other hand, uses manufactured aggregates and, to some extent, recycled materials as the principal supply of aggregates. Therefore, the sustainability of the SCLGC proves to be far ahead of conventional materials.

In a similar way, the GPC with normal constituents shows the potential of sustainability over conventional cement-based concrete though valuable natural materials are used. However, the binder content comprising of FA, GGBS is largely waste products.

6.1. Inventory analysis (IA)

Normal weight GPC and lightweight GPC differ in terms of raw material, processing, and application, as well as the stage of recycling and reuse. The SCLGC makes use of wastes that are difficult to recycle or may not be viable to reuse. For example, broken lightweight bricks might be used as aggregate in the SCLGC. The plastic recycled into pallets or grains is regarded to be of inferior strength and quality, although it is suitable for fine and coarse aggregates in the SCLGC.

The development of an IA is beneficial in identifying major concerns, evaluating the process, and leading to a realistic strategy to overcome obstacles. In this article, three approaches were discussed and illustrated concerning the IA of SCLGC: (1) IA based on data collection and source reliability, (2) energy consumption and greenhouse effects of the

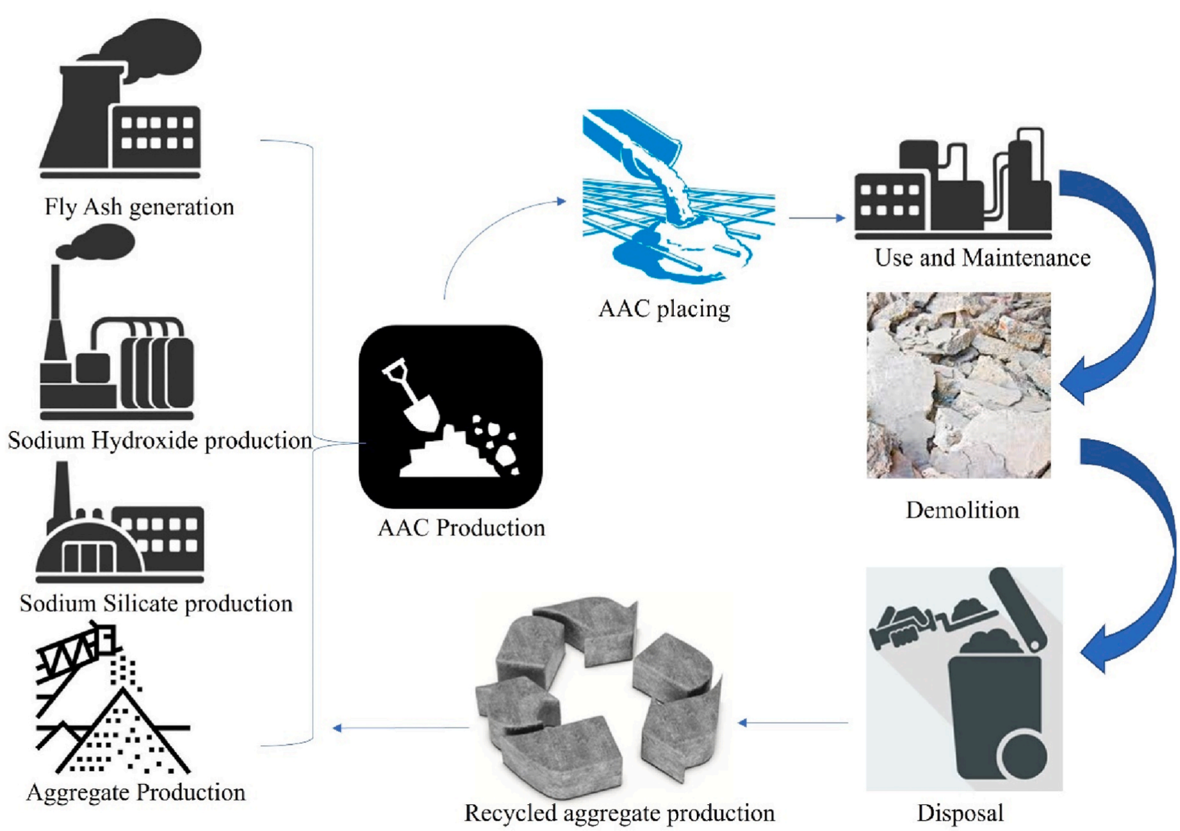

Fig. 14. LCA of GPC

material making processes, and (3) potential for recycling, reuse, and reduce concepts for the SCLGC composites.

Another way for IA of SCLGC is to examine the energy needs and CO_2 emission equivalent (the energy demand and carbon emission of SCLGC were calculated and illustrated in section 6.3). The percentage contribution by the specific component in the entire process may make it apparent. The ingredients are significantly more energy demanding and intensive than traditional concrete or even GPC. Constituents with high energy demands, on the other hand, are difficult to reuse and recycle.

A detailed examination of the SCLGC's recycling and reuse pattern may also result in a favorable aspect of the environmental impact evaluation. Fig. 15, illustrates the LCA of SCLGC. It can be predicted with a detailed study via LCA that the successful recycling of lightweight composite like SCLGC may provide the overall energy efficient construction material.

6.2. Environmental Impact Assessment (EIA) of SCLGC

To investigate the composites' sustainability indices, the environmental impact of SCLGC with ECA is assessed qualitatively. SCLGC's life cycle is also highlighted. In recent years, many researchers have examined the EIA of geopolymer-based compounds with natural CA and manufactured fine aggregates (Kurt et al., 2016; Salas et al., 2018; Wittocx et al., 2022). The literature shows energy requirements for the production of GPC with GGBS were lower than the conventional cement-based mixes. GGBS can initiate the polymerization reaction process of AA and source material without heat curing; this may be attributed to the presence of high calcium oxide content. In creating sustainable concrete, the assessment also stresses the use of non-recyclable materials and industrial waste (Shi et al., 2021). Another study (Kupaei et al., 2013) examines the life cycle of concrete, emphasizing the significance of using alternative composites, such as geopolymer, to increase waste utilization in producing environmentally acceptable chemicals.

The aspects of cement and concrete products, such as energy requirements, material resources, poisonous gas emissions, and wastewater ecological repercussions, were addressed. Researchers (Ghadir et al., 2021; Tinoco et al., 2022) suggest the need to create alternative binders and mixes. Furthermore, the importance of GGBS in the preparation of eco-friendly GPCs has been discussed in the article (Salas et al., 2018), and a similar type of analysis is followed in the present investigation. The purpose of manufacturing ECA blended GPC is to meet sustainability requirements in the construction ecosystem. Fig. 16 depicts common characteristics of the GPC life cycle. The stages involved are procurement, evaluation, testing, use or application, and demolition. It is emphasized that each phase necessitates energy consumption and carbon dioxide emissions (CO_2). Energy is also required for demolition or removal. Ecologically, it is essential to use raw materials derived from waste to reduce energy requirements at an early stage. Furthermore, the production process can be modified, controlled, or reduced by innovative ways to reduce emissions of hazardous gases. Finally, the product is to be recycled to generate fresh material resources. The discussed qualities can be satisfactorily met when comparing GPC with SCLGC cured at room temperature.

The production of SCLGC does not involve natural CA and thereby relatively reduces the overall energy requirement of the material. Furthermore, SCLGC's lightweight mix enhances the versatility of the application. However, it is recommended to carry out a comprehensive EIA for a clearer understanding of the benefits of SCLGC compared to GPC. GPC synthesis with and without lightweight products and GGBS is compared in the comprehensive EIA. Fig. 17 highlights primary characteristics such as energy requirements, CO_2 emissions, recycled materials, waste products, and sustainability features; EIA and LCA tools are scientifically evaluated with a structured analysis. Fig. 17 depicts the EIA for both GPC and SCLGC combinations, highlighting the SCLGC's sustainability characteristics. However, because the current study focuses on ECA as a substitute for natural aggregates and thus demonstrates the sustainability advantages of SCLGC over GPC, a thorough EIA analysis has not been provided. However, since SCLGC replaces natural aggregates and uses a substantial proportion of natural sand in its production, a qualitative examination of the raw material would aid in understanding the environmental characteristics of the material.

Furthermore, SCLGC is made with GGBS instead of fly ash, an added benefit of SCLGC. The literature shows that geopolymers made with GGBS have more potential than fly ash-based GPC in terms of contribution to global warming (Sandanayake et al., 2022). According to another source of information, slag is classified as industrial waste and has no total energy requirements (Garces et al., 2021). Natural

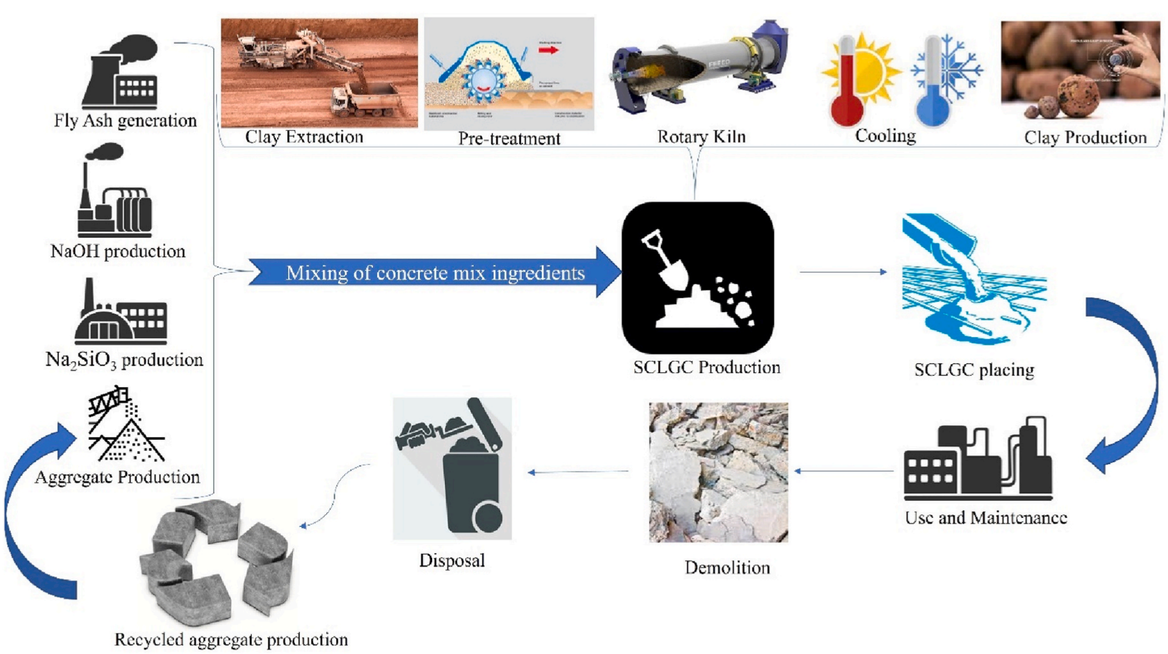

Fig. 15. LCA of SCLGC

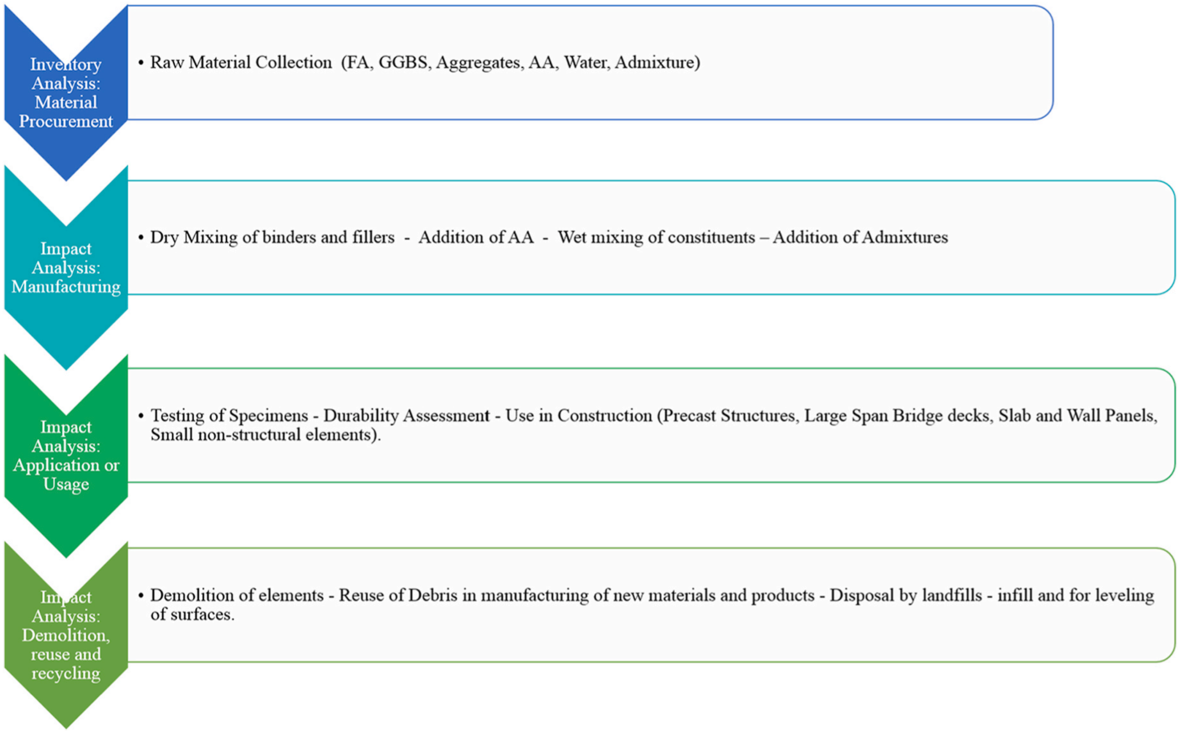

Fig. 16. Life cycle assessment of GPC

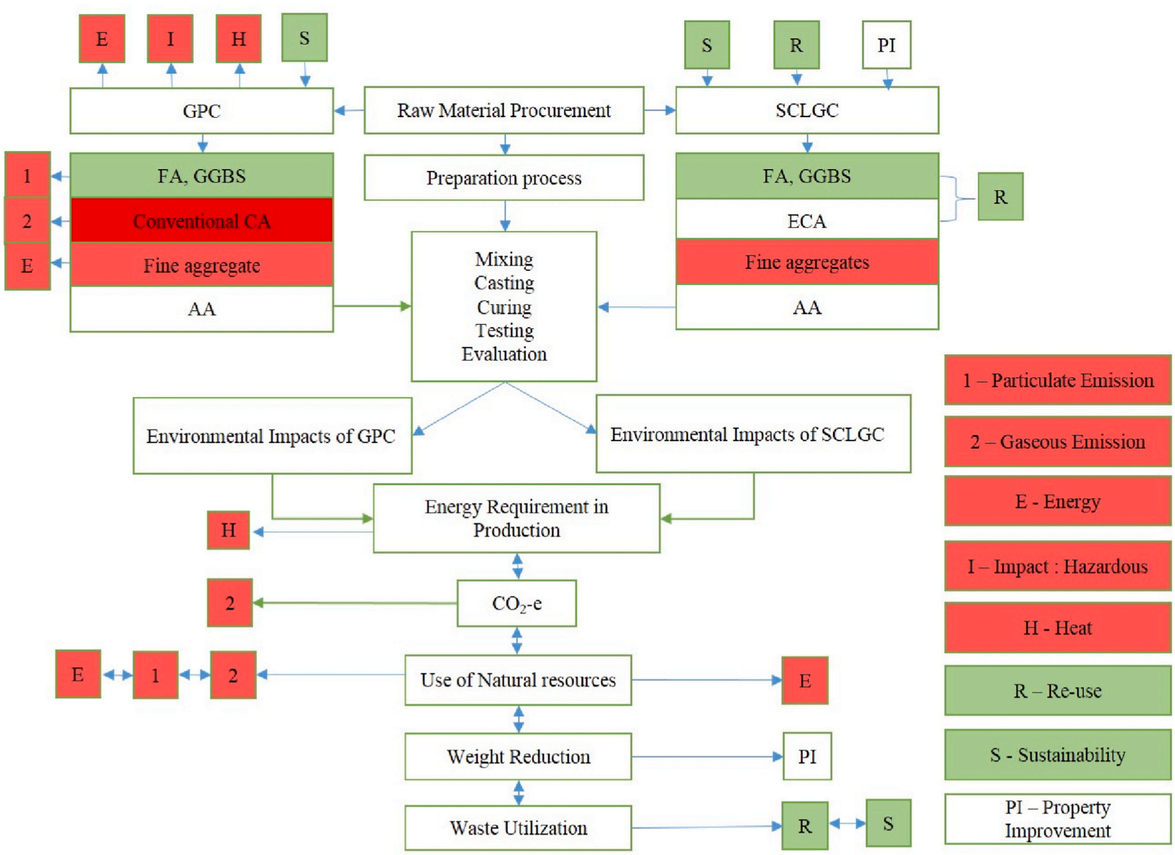

Fig. 17. A comparative study between SCLGC and GPC following EIA.

aggregates produced by mining and crushing rocks emit CO_2, making concrete a high embodied energy product. Furthermore, the self-weight of concrete created with ECA and natural aggregates differs significantly, suggesting that SCLGC with ECA is the best option for creating sustainable construction materials, especially for light weight applications and the precast industry. A complete comparison of GPC and SCLGC is a topic of research for the future.

6.3. Sustainability index

6.3.1. Cost efficiency

The compressive strength-to-cost ratio was evaluated to categorize the cost-efficiency of SCLGC blend (Darvish et al., 2020). The production cost of lain SCLGC is found to be marginal for the mix with the same concentration of NaOH; this could be attributed by the presence of FA, FA is one of the industrial by-products as mentioned earlier; therefore the production cost and transportation of FA is found to be very less when compared to other concrete mix ingredients. The transportation cost of all the concrete mix ingredients is associated with the purchase cost. As discussed, the strength of SCLGC mix decreases with the increase in ECA content. The cost-efficiency of SCLGC mixes was determined and illustrated in Fig. 18.

Higher the cost-efficiency indicates better effectiveness of the SCLGC mix. From the figure, it is clear that an increase in ECA decreases the cost-efficiency compared to the control mix. An initial replacement of 25% increases the production cost, whereas a mix with 50% replacement offers lower cost-efficiency than the control mix. A decline in strength was observed in the mix comprising from 25% to 100% replacement of CA with ECA.

From the analysis, it is clear that the production cost of SCLGC is quite high than its counterpart control mix (0% ECA content); this is due to the employment of sodium hydroxide and sodium silicate solutions. However, the cost rise is offset in the GPC by utilizing cost-effective construction material such as FA and other industrials by-products with high alumina and silica sources. Mix with 4 M concentration comprising 0% ECA possess higher cost efficiency than the mix with higher concentration levels.

6.3.2. Energy efficiency

Based on the research report of (Alsalman et al., 2021), the energy and carbon dioxide emission (CO_2-e) of GPC and OPCC were examined for the individual concrete mix ingredients. The energy requirement for 1 m^3 of GPC production depends on various parameters such as FA, M-sand, coarse aggregates, sodium hydroxide, sodium silicate,

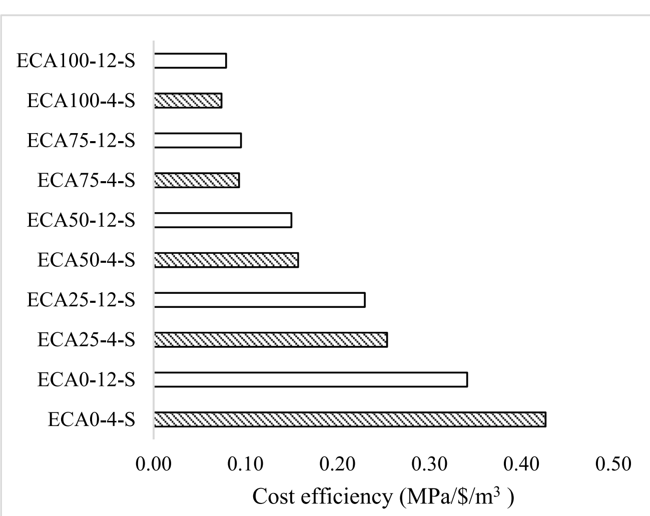

Fig. 18. Cost-efficiency of SCGLC for varying NaOH concentrations.

admixtures (if required), and curing conditions (oven curing, if applicable). As mentioned, the commonly adopted source materials for the production of GPC are industrial by-products namely FA, palm oil fuel shall ash, rice husk ash, etc., As these materials require very less energy for its production than other concrete mix ingredients (Assi et al., 2016). state that for 1 m^3 of GPC production, the energy requirement is zero. Contrastingly (Jones et al., 2011), reported that for better cost and energy estimation comparison, the energy required for collecting, milling, and grinding individual ingredients has to be considered.

The energy requirement for the production of one metric ton of FA was estimated as 0.033 GJ. In contrast, the energy requirement for the fine and coarse aggregate, SH, and SS were estimated as 0.083, 20.5, and 5.37 GJ/t of energy. In the case of Ordinary Portland cement (OPC) concrete, one ton of cement production requires 4.53 GJ of energy.

It is known that 70–80% of the volume is occupied by the aggregates in the concrete (Hardjito et al., 2004), and it is responsible for the stiffness and stability of concrete. Cement is used as the primary binder material in conventional concrete, whereas in the case of GPC alumino-silica source material is employed as the binder material. The source material employed for the production of conventional concrete and geopolymer concrete is different due to the variation in the nature of the hydration and polymerization process. In addition, the aggregate required to occupy the concrete volume varies for the same binder content because of the difference in specific gravity and surface area of the materials (Alsalman et al., 2021). (Hammond and Jones, 2011) reported that for the production of one ton of fine and coarse aggregate, the energy requirement is estimated as 0.081 and 0.083 GJ, respectively (Assi et al., 2016). reported that one of the key factors to be focused on the geopolymer concrete is the Alkaline solution. The energy requirement for the production of one ton of sodium hydroxide and sodium silicate was estimated as 20.5 and 5.371 GJ (Fawer et al., 1999; Tempest et al., 2009). The energy requirement for 1 m^3 of SCLGC production is estimated based on the past literature and discussed below.

For 1 m^3 of SCLGC production, the estimated energy required is 1.74 GJ for 4 M concentration of activator solution, whereas, for 12 M concentration, it is found to be 3.74 GJ. Fig. 19 depicts the energy requirement for individual mix ingredients of SCLGC. An increase in the ECA content increases the energy demand for the production of SCLGC. For 100% replacement of CA with ECA requires 4.16 GJ in case of a 4 M concentration of activator solution, whereas, for 12 M concentration, it is found to be 6.16 GJ. The energy involved in the transportation of materials is not considered in this research.

6.3.3. Eco-efficiency

Concrete production requires huge consumption of energy (due to coal firing, use of electricity, petroleum products, and so on), accounting for Carbon dioxide emission (CO_2-e) in open environment. It is about 0.73–0.85 t-CO_2 for every 1 ton of OPC production (Hills et al., 2016). In comparison among concrete mix ingredients, the aggregate production requires less energy than others which results in lower CO_2-e. The sustainability of SCLGC blend in accordance with CO_2-e was found by eco-efficiency (Alnahhal et al., 2018). states that the ratio between strength and CO_2-e is termed as eco-efficiency. In context to the cost-efficiency analysis, CO_2-e for 1 m^3 of concrete was examined; the CO_2-e factor considered for the analysis was based on the report proposed by (Alsalman et al., 2021). The CO_2-e analysis was made for FA, fine & coarse aggregates, and the Alkaline Solution (Sodium Hydroxide and Sodium Silicate).

(Hammond and Jones, 2011; Heath et al., 2014) estimated the CO_2-e value for every one-ton production of FA, Ground Granulated Blast Furnace Slag, Metakaolin, Silica Fume, and cement is 0.004 t-CO_2/t, 0.052 t-CO_2/t, 0.014 t-CO_2/t, 0.052 t-CO_2/t, 0.84 t-CO_2/t, respectively. For aggregates (fine and coarse), the CO_2-e was estimated as 0.0048 t-CO_2/t (Alsalman et al., 2021; Turner and Collins, 2013). estimated the CO_2-e of binder, filler, and AS such as SH and SS; result from the study reveals that the production of SH (100% solid) requires huge

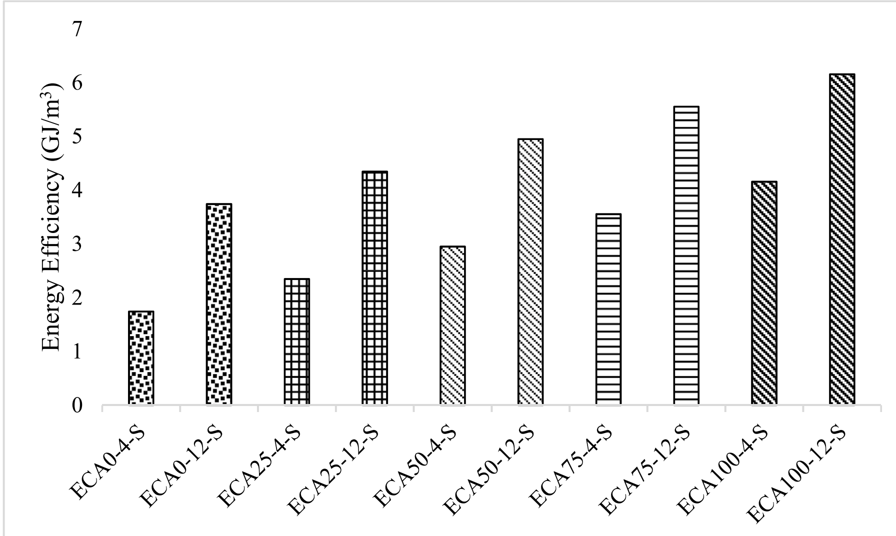

Fig. 19. Energy Efficiency of SCLGC for various NaOH concentrations.

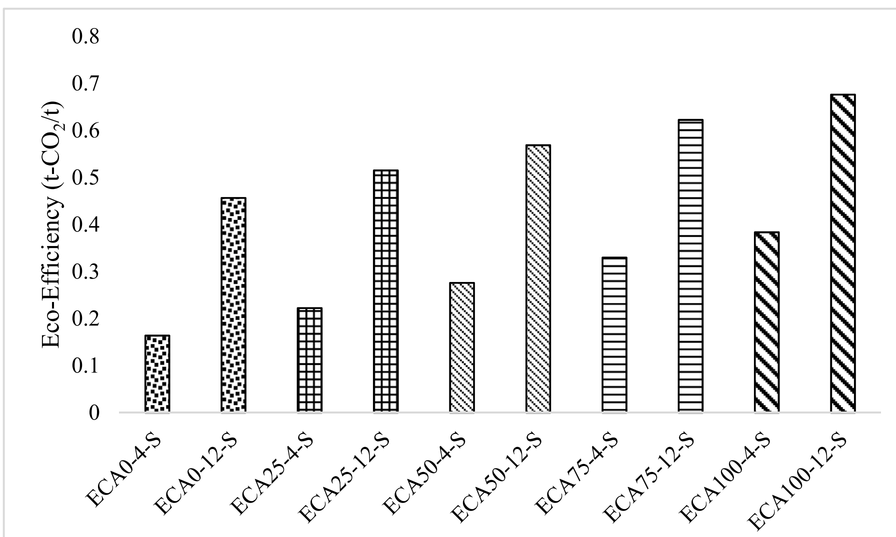

Fig. 20. Eco-efficiency of SCLGC with various concentrations of NaOH.

consumption of energy and emits nearly 1.915 t-CO_2/t, whereas the SS emits 1.222 t-CO_2/t. Based on the proposal, the CO_2-e for the production of 1 m^3 of GPC was estimated as 0.2312 t-CO_2/m^3. Fig. 20 illustrates the CO_2-e of concrete ingredients for 1 m^3 of GPC production. Similar to energy efficiency, carbon efficiency was performed to access the CO_2-e of SCLGC mixes with increasing ECA content. An increase in the ECA content increases the CO_2-e. The estimated carbon efficiency of the SCLGC mixes was found to 0.164 t-CO_2/t for 4 M concentration of activator solution, whereas for 12 M the carbon efficiency was found to be 0.46 t-CO_2/t.

An increase in the ECA content increases the CO_2-e for the production of SCLGC. For 100% replacement of CA with ECA the CO_2-e was estimated as 0.38 t-CO_2/t for 4 M concentration of activator solution, whereas for 12 M concentration, it is found to be 0.68 t-CO_2/t. As mentioned, CO_2-e for the transportation of materials is not considered in the current investigation.

7. Conclusions

The following key findings are observed from the experimental investigations and analysis of GPC and SCLGC behavior.

- Replacement of conventional CA with ECA in the GPC mix improves the fresh state properties, and this may be attributed to the light-weight behavior of ECA.
- An increase in the concentration of SH and curing temperature was found to increase the mechanical properties of the mix with various proportions of ECA.
- The mechanical qualities of the mix are affected by replacing natural CA with ECA 100%. The behavior of SCLGC under splitting and compression actions with ECA ensured the possibility of using ECA for weight loss without compromising strength properties (up to 50% replacement).
- Partial replacement of conventional CA with ECA does not affect the mechanical properties significantly. Therefore, it is suggested that partial replacement of ECA is the optimal dosage in the production process of SCLGC.
- The strength qualities, including the final failure produced by impact loading, are unaffected by replacing ordinary CA with ECA. The

current research yields promising early results for future research to develop lightweight GPC with ECA.

- The chart depicting the SCLGC's EIA with the relevant references indicates the possibilities for in-depth investigations of the topic to evaluate the long-term commercial viability of SCLGC.

Credit author statement

Mr. Balamurali Kanagaraj: Investigation, Writing - Original Draft, Review & Editing; Dr.N.Anand: Conceptualization, Methodology, Supervision, Validation, Review & Editing; Mr. Praveen: Investigation; Dr. M.Z. Naser: Investigation & Review & Editing; Kandasami: Investigation & Review & Editing; Dr.Eva Lubloy: Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

The Authors are thankful to the Karunya Institute of Technology and Sciences for providing lab facilities to conduct the study. The research reported in this paper is a part of project no. BME-NVA-02, implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research Development and Innovation Fund, financed under the TKP2021 funding scheme.

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