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Experimental study on the strength of lightweight geopolymer concrete with eco-friendly material

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Professional paper

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Experimental study on the strength of lightweight geopolymer concrete with eco-friendly material

The differences in properties between the lightweight aggregate concrete and normal conventional concrete at the selected equivalent mix ratios have forbidden the former from being used widely in construction industry. Studies have shown that the use of GGBS as a partial replacement of cementitious material, and M-sand as a replacement of fine aggregate, results in an increased strength in geopolymer normal weight concrete. In this study, Coconut shell is used as a replacement of conventional coarse aggregate to produce lightweight geopolymer coconut shell green concrete.

Key words:
coconut shell, lightweight concrete, GGBS, geopolymer

Stručni rad

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Eksperimentalno istraživanje čvrstoće laganog geopolimernog betona s dodatkom ekološki prihvatljivih materijala

Razlike između svojstava betona s laganim agregatom i normalnog uobičajenog betona za odabrane ekvivalentne omjere u mješavinama, onemogućile su šire korištenje betona s laganim agregatom u građevinarstvu. Dosadašnja su istraživanja pokazala da primjena proizvedenog pijeska, kamene prašine, zgure iz visokih peći, gline, letećeg pepela itd., kao djelomične zamjene cementnog materijala, te primjena proizvedenog pijeska kao zamjene za sitni agregat, dovodi do porasta čvrstoće u odnosu na čvrstoću betona s uobičajenim agregatom. Ljuske kokosovog oraha koriste se kao zamjena za uobičajeni krupni agregat, kako bi se proizveo beton s laganim agregatom.

Ključne riječi:
ljuske kokosovog oraha, lagani beton, zgura visokih peći (GGBS), geopolimer

Fachbericht

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Experimentelle Untersuchung der Festigkeit von leichtem Geopolymerbeton unter Zusatz von umweltfreundlichen Materialien

Die Unterschiede zwischen den Eigenschaften von Beton mit leichtem Aggregaten und normalem üblichen Beton für ausgewählte äquivalente Verhältnisse in Mischungen verhinderten die breitere Verwendung von Beton mit leichtem Aggregat im Bauwesen. Die bisherigen Untersuchungen haben gezeigt, dass die Verwendung von produziertem Sand, Steinstaub, Hochofenschlacke, Ton, Flugasche usw. sowie der teilweise Ersatz von Zementmaterial, wie auch die Verwendung von produziertem Sand als Ersatz für feines Aggregat zu einer Erhöhung der Festigkeit im Verhältnis auf die Betonfestigkeit mit üblichem Aggregat führt. Kokosnussschalen werden als Ersatz für übliches grobes Aggregat verwendet, um Beton mit feinem Aggregat herzustellen.

Schlüsselwörter:
Kokosnussschalen, Leichtbeton, Hochofenschlacke (GGBS), Geopolymer

1. Introduction

An increasing demand for concrete in construction industry that uses conventional aggregates has greatly reduced the natural stone deposits, which is why there is a pressing need to discover a suitable replacement material as a substitute to natural stone [1, 2]. All over the world, many naturally available materials like pumice, scoria, and volcanic debris, and various industrial by-products like blast-furnace slag, vermiculite, clinker, etc., are used in construction work as substitutes for natural stone aggregates. Similarly, the agricultural waste like coconut shell, which is organic in nature, can also be successfully used as lightweight aggregate [3-5].

India is the third largest country by coconut production with about 1.78 million hectares [3-7]. The annual production of coconuts is about 7562 million nuts. The coconut industry in India accounts for over a quarter of the world's total coconut oil output [8]. The coconut shell production is shown in Table 1.

This bulk production creates a huge solid waste disposal problem. These wastes, which are abundantly available, can be used as a potential material in construction industry [3, 7, 10-12]. Besides, Kambli et al. [13] claim that coconut shells possess good material properties and can be used in the manufacture of new composite materials. The use of agricultural waste in concrete will contribute to the sustainability of environment by reducing the use of conventional aggregates to produce green concrete. However, the commercial use of non-conventional aggregates in concrete construction has not as yet started in India [3]. As the coconut shell disposal poses serious problems, these wastes can be used as an impending material in construction industry.

The exploitation of river sand endangers the stability of river banks and creates environmental problems, such as flooding and reduction in ground water levels [14]. Manufactured sand is an artificial sand manufactured in industry which possesses physical properties of texture and shape similar to river sand. An alternative material for river sand used in india is M-sand which gives the pores distribution and strength equivalent to that of river sand.

About 2 tonnes of raw ingredients like limestone and shale are needed to produce one ton of cement, which emits CO_2, nitrogen oxide, and an air borne particulate matter that is harmful to human health. The manufacturing process used in cement industry applies a lot of new systems to reduce CO_2 release through improvement of the production process. Limestone calcination is the basic process in cement industry. However, limestone mining causes a high environmental impact. In addition to this, high dust emissions also contribute to a considerable environmental impact because cement industries handle millions of tonnes of dry materials. Adopting the waste management process involves the utilization of waste by–products, which reduces the environmental impact to a considerable extent. One of such by-products is the ground granulated blast furnace slag.

In this experimental work, an attempt was made to fully replace conventional concrete with lightweight coconut shell concrete, where the ground granulated blast furnace slag (GGBS) was used as binder, manufactured sand (M-sand) as fine aggregate, and coconut shell (CS) as coarse aggregate, whose density is much lower compared to that of standard concrete. According to ASTM C330/C330M- 14 [15], aggregate is defined as lightweight when its bulk density is less than 880kg/m^3 for coarse lightweight aggregate, and less than 1120kg/m^3 for fine lightweight aggregate [16].Also an attempt was made to produce a GGBS based geopolymer lightweight coconut shell concrete. It produces inorganic polymer composites which have the potential of forming a substantial component of an environmentally sustainable construction exhibiting the strength equivalent to the strength of an ordinary conventional concrete. Experimental investigations were carried out to find out the compressive strength, stress-strain behaviour, and modulus of elasticity.

2. Materials and mix design

2.1. Coconut shell (CS) as coarse aggregate

Coconut shell used in this research was collected from the oil mill near Erode, Tamilnadu, India. It was mechanically broken into small pieces and sieved and segregated to test its properties. The sieved and segregated coconut shell is shown in Figure 1. Coconut shell properties are presented in Table 2.

Table 1. Production of coconut shell

Country	Coconut production 2014 [metric tonnes]	Percentage of world total [%]
Indonesia	18300.000	35.8
Philippines	15353.200	30.0
India	11930.000	23.3
Brazil	2890.286	5.66
Sri Lanka	2513.000	4.9
Source: *The daily records* (*Latest news around the globe* 2018) [4, 9]		

Table 3. Chemical composition [%] of materials based on XPS analysis

Chemical composition	CaO	SiO_2	Al_2O_3	MgO	Na_2O	SO_3	P_2O_5	K_2O	MnO	Fe_2O_3	LOI
Coconut shell	63.11	20.7	5.75	1.89	0.6	2.75	0.05	0.15	0.2	2.5	2.3

Figure 1. Segregated, sieved, untreated, and cold water extracted coconut shell

Table 2. Properties of coconut shell

Properties	Coconut shell
Bulk density (loose air dried coconut shells) [kg/m^3]	695
Void ratio [%]	38
Moisture content [%]	10.02
Specific gravity	1.15
Crushing value [%]	1.59
Impact value [%]	8.15
Shell thickness [mm]	8 - 10
Fineness modulus [%]	6.11

Coconut shell cannot be broken into specific shapes and sizes; hence, it was randomly broken into smaller pieces using mechanical means. The broken coconut shell was sieved using a standard sieve for coarse aggregate as per IS2386–Part 1 [25]. Two sizes of coconut shell were selected to achieve good grading. The packing density method was used to achieve a dense and stiff particle structure. In the packing density method, coconut shell was proportioned and adjusted to achieve dense packing in such a way that smaller size coconut shell occupies the interplanetary space between the larger size coconut shell, and the same was determined with bulk density. The packing density of the proportioned coconut shell was calculated using the formula given in equation (1) :

$$\text{Packing density} = \frac{\text{bulk density}}{\text{specific gravity of coconut shell}} \tag{1}$$

An optimum packing density is given in Figure 2. The maximum packing attained, which gives the minimal percentage of voids to achieve the required dense pack, is shown in Figure 2. It can be seen in this figure that the maximum bulk density was achieved for 60 % of coconut shell passing through a 10mm sieve and 40 % for coconut shell passing through a 12.5mm sieve, which results in minimum percentage voids and it requires less cement and water content in the mix. The chemical composition of coconut shell is given in Table 3. The percentage of metal oxides in the coconut shell was lower, and it will act as a filling material when hardened [26, 27].

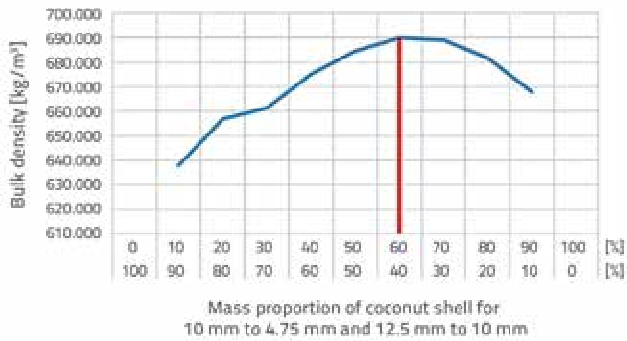

Figure 2. Packing density – coconut shell

2.2. Manufactured Sand (M-sand) as fine aggregate

M-sand is treated and produced in a controlled environment that is free from debris, minerals & oversized material, resulting in an eco–friendly and good quality product. Fine aggregate sand is classified as Zone – I, II, III & IV as per IS : 383-2016 [28]. The particle size distribution curve of M-sand is given in Figure 3, and properties of M-sand tested are presented in Table 4.

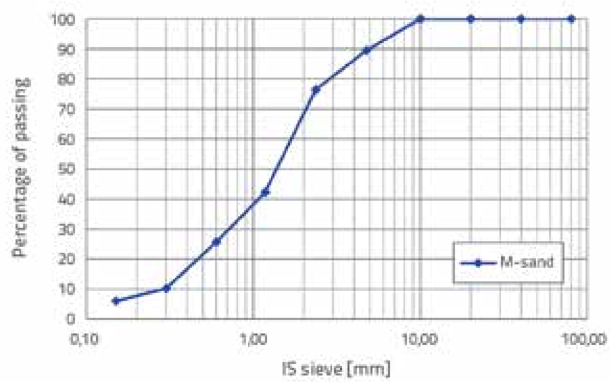

Figure 3. Gradation of M- sand

Table 4. Properties of M-sand

Properties of the ingredients	Coconut shell
Compacted bulk density [kg/m³]	1520
Loose dry bulk density [kg/m³]	1500
Bulking [%]	42
Specific gravity	2.60
Sieve analysis	Zone II
Fineness modulus [%]	2.91
Water adsorption [%]	2.25

2.3. Ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS)

The ordinary Portland cement grade conforming to Indian Standard IS 8112 – 2013 [29] is used as a binder. Properties of ordinary Portland cement are given in Table 5.

Table 5. Properties of OPC

Physical test for OPC	Test results	IS:8112-2013
Initial setting time [min]	46	> 30
Final setting time [min]	243	< 600
Normal consistency [%]	33	-
Fineness [%]	4.0	< 10
Specific gravity	3.10	-

Properties of the ground granulated blast furnace slag are similar to cement properties. It is a glassy, non-metallic, silvery, white, granular material consisting of a high amount of silicates and aluminates of calcium similar to cement. The particle size of GGBS is almost the same as that of cement, as shown in Figure 4.

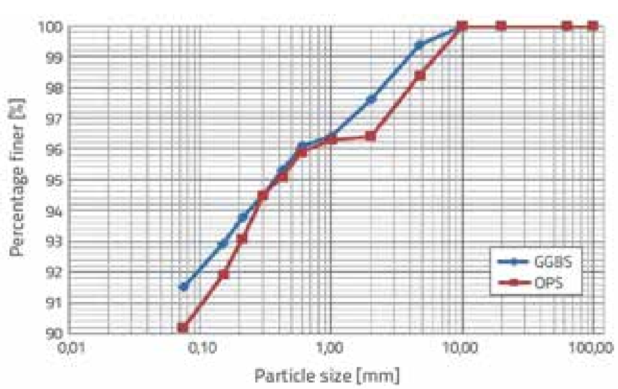

Figure 4. Grain size distribution of GGBS & OPC

GGBS, frequently blended with Portland cement as a fine filler, improves the density, durability, and workability of concrete, as well as its resistance to alkali-silica reaction. GGBS properties are given in Table 6. Also, particle size is an important property and is used to characterize powder in bulk. It affects the properties such as surface area, packing density, strength of the compacts, tensile strength and flow properties. It is therefore necessary to analyse the size distribution of the powder. Figure 4 gives the grain size distribution of the OPC and GGBS.

Table 6. Properties of GGBS

Particulars	GGBS
Chemical composition	
Silica (SiO_2) [%]	29.61
Alumina (Al_2O_3) [%]	17.25
Iron oxide (Fe_2O_3) [%]	0.58
Lime (CaO) [%]	35.46
Magnesia (MgO) [%]	5.65
Sulphur tri oxide (SO_3) [%]	1.72
Physical properties	
Specific gravity	2.65
Fineness [kg/m²]	390

2.4. Superplasticizer

A high-grade superplasticizer based on naphthalene, CERAPLAST 300, was used in this study. It is highly recommended for enhancing workability and achieving desired concrete strength based on IS 9103-1999 [30].

2.5. Proportion of coconut shell in lightweight coconut shell concrete

Mix design is the process of selecting appropriate percentage of cement(C), fine aggregate (FA) and lightweight coconut shell coarse aggregates (LWCSA) and water to produce concrete of sufficient strength. The normal mix design that is used for conventional concrete cannot be used for lightweight concrete (LWC) [10, 11, 17]. Hence it is always better to go for trial mix to achieve LWC [10, 18-22]. The best mix involves a proper balance between the economy and required properties of concrete [18].

Mix proportions adopted in various research works on coconut shell concrete are given in Table 7. It should be noted that all LWCSA were used with high cement content and lesser amount of aggregate since the strength of the concrete is influenced by aggregate which can be used for structural applications. Based on relevant literature [18, 20] it was established that the strength decreases with an increase in coconut shell content. In addition, binder and water cement ratio also play an important role in workability.

Table 7. Mix design summary

Authors	Water cement ratio	Mix C : FA : LWCSA	Remarks
Kalyanapu Venkateswara Rao et al. [18]	0.45	1 : 1.09 : 0.35 1 : 1.09 : 0.27	10 % replacement 20 % replacement
Amarnath Yerramalaa Ramachandrudu [20]	0.6	1 : 2.5 : 0.39 1 : 2.5 : 0.585 1 : 2.5 : 0.78	10 % replacement 15 % replacement 20 % replacement Cement content is constant 300 kg/m^3
K. Gunasekaran et al. [21] K. Gunasekaran et al. [22]	0.42	1 : 1.47 : 0.65	FA with river sand, 100 % CS replacement and cement content is constant 510 kg/m^3
K. Gunasekaran et al. [10]	0.42	1 : 1.47 : 0.65	FA with river sand, 100 % CS replacement and cement content is constant 510 kg/m^3
K. Gunasekaran et al. [19]	0.42	1 : 1.47 : 0.65	FA with quarry dust,100 % CS replacement and cement content is constant 510 kg/m^3
A. Jaya prithika et al. [17. 23]	0.35 0.35 0.35	1 : 1.73 : 0.48 1 : 1.75 : 0.49 1 : 1.77 : 0.49	Cement was replaced with GGBS, FA was replaced with M-sand and 100 % CA was replaced with CS .In addition superplasticizer was added to increase the workability.
M. Santhosh Kumar et al. [24]	0.28	1 : 0.5 : 0.55	GGBS 50 %, SF 15 % and 825 kg/m^3 of cement binders' content

2.6. Mix design of lightweight coconut shell concrete

Initially, the coconut shell concrete mix design was made in accordance with ACI211.2-98 [31] code related to for lightweight concrete. Based on the mix design, several trial mixes were made and the mix which gave the strength closer to higher limit was considered in the analysis [17, 23]. The final trial mix proportions were 1 : 1.80 : 0.50, with 1 % of superplasticizer. Various w/c ratio were tested for the selected mix, with three test specimen for each ratio, and the average value was taken into consideration, as shown in Table 9. A total of 18 cubes measuring 100mm x 100mm x 100mm in size were cast initially to optimize the mix content. All specimens were cast in two layers and thoroughly compacted using tamping rods conforming to IS : 516 [32]. After casting, the specimens were covered with a plastic sheet and left in the mould for 24 hours. After 24 hours, the cubes were removed from the moulds and cured for 28 days [33].

2.6.1. Sample mix design for trial mixes

The sample mix design for trial mixes was conducted using the weight method as per ACI211.2-98 [31].

Step 1 : Choice of slump
As per ACI211.2-98 clause 3.2.2.1
Initially the slump was assumed as 2 in i.e., 50.80 mm (2)

Step 2 : Choice of maximum size of lightweight aggregate
The size of aggregate passing through sieves 10 mm – 4.75 mm and 12.5 mm – 10 mm was selected using the packing density method. The average of these selected samples is 9.3125mm.
As per ACI211.2-98 clause 3.2.2.1
Considering 3/8 in i.e., 0.375 x 25.4 = 9.525 mm (3)

Step 3 : Estimation of mixing water content and air content
The estimation is based on equations (2) and (3) from table 3.2.2.2 given in ACI211.2-98.
For slump 50mm and aggregate size 9.525 mm, the amount of water content = 350 lb/yd^3, i.e. 350 x 1.09 x 3/2.2 = 206 kg/m^3.
Therefore, the water content is 206 kg/m^3 (4)

Step 4 : Selection of appropriate water/cement ratio
As per ACI 211.2-98, clause 3.2.2.3(a).
The required strength of concrete = 6000 psi,
i.e. 6000 x 9.81/ (2.2 x (25.4)2) = 41.46 N/mm^2
for the compressive strength of 41.46 N/mm^2,
w/c - 0.41 (for non air entrained concrete) (5)

Step 5 : Calculation of cement content
From equation (4) and equation (5), water content = 206 kg/m^3 and w/c - 0.41
Therefore, the cement content is calculated by :
206/0.41 = 502.4 kg/m^3 (6)

Step 6 : Estimation of lightweight coarse aggregate content
As per ACI 211.2-98, clause 3.2.2.4
For aggregate size 9.525 from equation (3) and fineness modulus of sand 2.91 (Table 4)
For fineness modulus of sand amounting to 2.91, 0.531 is the volume of coarse aggregate per unit volume. And, also, the bulk density from Table 2 (695 kg/m^3) and water content from Table 2 (10.02 %) were used.

Since its dry bulk density = bulk density - water content = 695 - (695 x 0.1002) = 625.36 kg/m^3, thus, the volume of coarse aggregate per unit volume is calculated as follows:
625.36 × 0.531 = 332.068 kg/m^3 concrete.
Therefore, the volume of coarse aggregate is 332.068 kg/m^3.

Step 7 : Estimation of fine aggregate content

The fine aggregate content was calculated from the specific gravity and density of the other composition, as shown in Table 8.

Table 8. Composition of mixes

Composition	Oven dry condition [kg/m³]	SSD condition [kg/m³]
Water	206	206
Cement	502	502
Coarse aggregate	332.068	431.6
Fine aggregate	766.20	815.64

Step 8 : Trial proportion for the mix

water : cement : fine aggregate : coarse aggregate
206 kg/m^3 : 502 kg/m^3 : 815.64 kg/m^3 : 431.6 kg/m^3
1 : 1.62 : 0.85

Table 9. Initial trial mixes with varying w/c ratio

Cement content [kg/m³]	Water /cement ratio	Hardened density [kg/m³]	Compressive strength [MPa]
400	0.60	1946	9.78
400	0.55	2109	10.09
400	0.50	2060	11.54
400	0.45	1978	12.45
400	0.40	2005	17.56
400	0.35	2019	22.45

The density, air content, and slump value were measured for each fresh concrete mix. The density of the freshly mixed concrete varied from 1946 kg/m^3 to 2109 kg/m^3 (Table 9) and the measured slump value varied from 55mm to 62 mm, which gave a medium workability that falls within the range of workable concrete. The air content of the mix varied from 6.2 to 8 % which is relatively high but falls within the range of 4 to 8 % as per ACI 213R–87 [34]. These high amounts of air content are mainly due to the texture of coarse aggregate used in the mix, which prevents good compaction thus resulting in higher air content.

3. Experimental test and discussion of results

In the experimental study, an attempt was made to do a comparative study on the performance of CSC incorporating OPC, GGBS, M-sand, and geopolymer. Three scenarios were considered to compare the effect of OPC, GGBS, and Geopolymer based GGBS binder in coconut shell concrete to produce a high strength lightweight coconut shell concrete.

3.1. Materials, mix proportion and curing of CSC

Three scenarios were considered to find the compressive strength. For each scenario, the trial mix ratio was kept constant as 1 : 1.80 : 0.50 as established for trial mix in Table 9, with the water binder ratio of 0.35 and superplasticiser content of 1.0 % conforming to IS 9103-1999 [30]. A total of 18 cubes measuring 100 mm x 100 mm x 100 mm were cast for the Methodology 1, Methodology 2, and Methodology 3. In addition, three cylindrical specimens measuring 150 mm and 300 mm and conforming to IS516 [27] were cast for Methodology 3. The specimens cast were demoulded after 24 hours and concealed cured [22] as per ASTM C 1761 -13B [28] by wrapping the specimens in polythene sheets to prevent evaporation of moisture from the surface of CSC.

3.2. Methodology 1

In Methodology 1, an ordinary Portland cement conforming to Indian Standard IS 8112 – 2013 [29], was used as binder with M-sand and CS as fine and coarse aggregate replacement, as shown in Figure 5. Three mixes, M11, M12 & M13, were tested and the average was taken for the compressive strength. The proportions used were tabulated in Table 10. The average compressive strength of the three mixes was 19.50 N/mm^2.

Figure 5. Material proportions in Methodology 1

Table 10. Compressive strength for Methodology 1

Mix	Unit weight of concrete W [kg/m³]	OPC addition [%]	Compressive strength [MPa]
M11	2005	100	18.30
M12	2013	100	19.90
M13	2020	100	20.30

Table 11. Compressive strength for Methodology 2

Mix	Unit weight of concrete [kg/m³]	OPC replacement with GGBS [%]	Compressive strength [MPa]	Average compressive strength [MPa]
M21	1987	25	18.50	18.433
M22	2017	25	17.50	
M23	1945	25	19.30	
M31	1949	50	14.60	14.167
M32	2055	50	14.00	
M33	2091	50	13.90	
M41	2013	75	12.56	12.22
M42	1994	75	10.70	
M43	2056	75	13.40	
M51	1994	100	10.20	11.43
M52	2034	100	11.80	
M53	2029	100	12.30	

3.3. Methodology 2

The ordinary Portland cement conforming to Indian Standard IS 8112 – 2013 [29] was used in Methodology 2. The methodology involves partial replacement of cement with GGBS at 25 %, 50 %, 75 % & 100 % as binder, as well as the use of M-sand and CS as fine and coarse aggregate replacement, as shown in Figure 6. Three mixes were tested for each GGBS replacement percentage and the average compressive strength was determined for each proportion, as presented in Table 11.

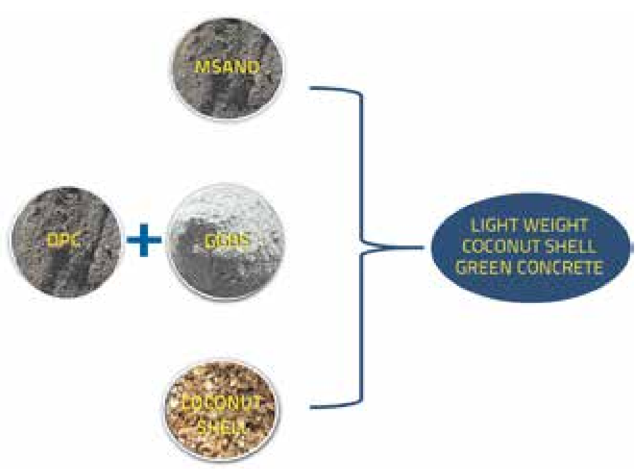

Figure 6. Material proportioning according to Methodology 2

Table 11 shows that a value close to Methodology 1 was obtained only with 25 % replacement of GGBS. This may be due to the flaky texture of the coconut shell and its bonding behaviour.

3.4. Methodology 3

In Methodology 3, geopolymer, an inorganic binder, was used with GGBS, M-sand, and Coconut shell, as shown in Figure 7. The father of geopolymers, Dr. Joseph Davidovits [35] stated in 1970s that geopolymerisation is the process that involves a chemical reaction between an Al–Si material, which develops a strong alkaline solution resulting in formation of three-dimensional polymeric structures, consisting of Si-O-Al bonds. In 1978, Davidovits suggested that an Al-Si compound will polymerise well with an alkaline solution [35]. Davidovits (1988) discovered that concrete used in ancient structures was an alkali-activated alumina silicate binder, and he named it geopolymer concrete. This led to the idea of cement replacement and development of "geopolymer concrete". Geopolymer binders are used together with aggregates to produce geopolymer concretes that are ideal for achieving a very high strength earlier than conventional concrete [36]. The strength of geopolymer depends on the nature of the source materials [37]. The following parameters were selected for the development of GGBS based geopolymer concrete. In the presented mix, an alkaline mix was prepared

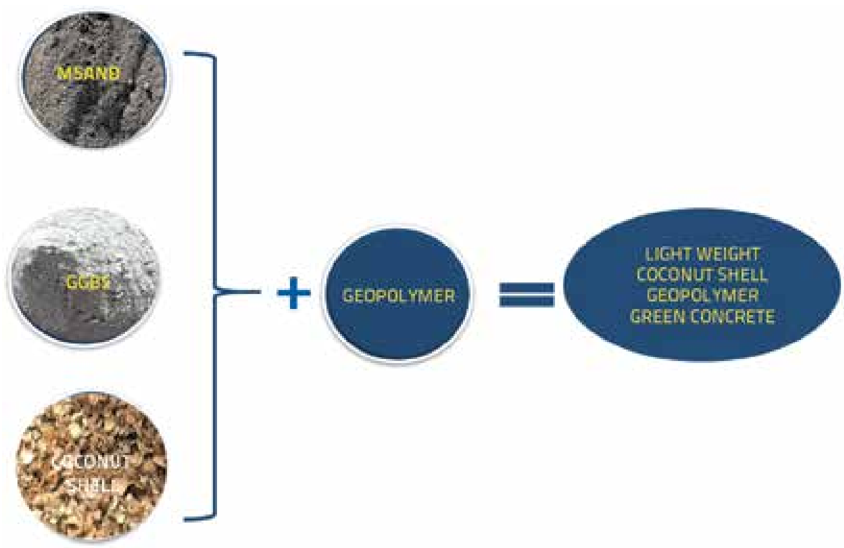

Figure 7. Material proportioning according to Methodology 3

Table 12. Compressive strength for Methodology 3

Mix	Unit weight of concrete W [kg/m³]	GGBS as binder [%]	Compressive strength [MPa]
M61	2078	100	39.30
M62	2013	100	40.50
M63	2043	100	41.40

by combining sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solution with molarity 10. The molecular weight of sodium hydroxide is 40. To prepare molar 10 (10M) sodium hydroxide solution, 400 g of sodium hydroxide flakes were weighed and added slowly to distilled water to form 1000 ml solution. The sodium hydroxide solution was prepared in laboratory 24 hours before casting in a weigh proportion of 1 : 2.5.

Compressive strength of the GGBS based geopolymer concrete is shown in Table 12. The average value is 40.40 N/mm², which results in a high strength lightweight concrete.

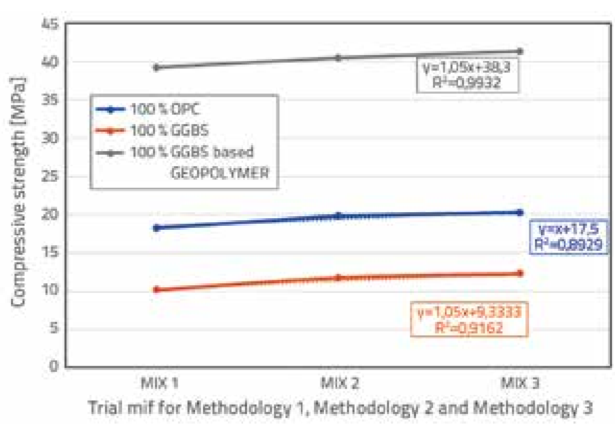

Figure 8. Comparison of compressive strength values of trial mixes

4. Results and discussions

4.1. Comparison of compressive strengths between three methodologies

The compressive strength was determined using cubes as per IS 516 - 1959 [32]. It can be seen in Figure 8 that the desirable strength of 40Mpa can be obtained for the selected molarity and ratio when geopolymer is used. The strength obtained in Methodology 3 was more that 51 % and 54 % greater when compared to methodologies 1 and 2. This increase in strength was mainly due to the reaction of polymer and its bond with binding materials. When comparing all three methodologies used in the testing, it was established that Methodology 3 produces green concrete with full utilization of sustainable materials. So, the mix proportion used in Methodology 3 was considered for studying the modulus of elasticity and stress strain behaviour as per ACI codes.

4.2. Stress-strain relationship of GGBS based geopolymer coconut shell concrete

The mix design used in Methodology 3 was applied to cast three cylindrical specimens measuring 150mm in diameter and 300 mm in length. These specimens were subjected to the stress, strain and deformation testing using extensometer and compressometer. The compressometer was used to establish the deformation and strain characteristics of cylindrical specimens tested under compression, while the extensometer was used to determine the static modulus of elasticity of cylindrical specimens under compression. The modulus of elasticity was determined as per ASTMC 469 – 02 [38] and ACI 318 [41].

$$E = (S1-S2) / (\varepsilon_2-0.000050) \quad (7)$$

where :

E - chord modulus of elasticity [MPa]

S1 - stress corresponding to 40 % of ultimate load [MPa]

S2 - stress corresponding to longitudinal strain of 50 × 10^{-6} [MPa]

ε_2 - longitudinal strain produced by S2.

All three specimens were loaded up to 40 % of ultimate load as per ASTM C 469-02 [38]. The corresponding results are presented in Table 13. 80 % of the cube strength was taken as the

Table 13. Modulus of elasticity, density and compressive strength (Methodology 3)

Trial mixes	**Density of cube before testing** [kg/m^3]	**% of GGBS**	**Compressive strength of cube** [MPa]	**Experimental modulus of elasticity** [MPa]	**Modulus of elasticity as per ACI** [MPa]
M61	2.078	100	39.3	7040.22	20030.92
M62	2.013	100	40.5	7193.71	19386.89
M63	2.043	100	41.4	7390.02	20040.22

cylinder strength as ACI code deals with cylindrical compressive strength, while cube compressive strength was determined based on IS 516 - 1959 [32]. The stress strain relationship of specimens is shown in Figure 9. The stress-strain graph is parabolic with a maximum strain of 0.0004.

$$\text{Modulus of elasticity as per ACI} = (w_c^{1.5} \cdot 0.043 \cdot \sqrt{f'c}) \qquad (8)$$

where :
w_c - weight of cube in kg/m^3,
$f'c$ - $(0.8 \cdot f_{ck})$ is the characteristic compressive strength [MPa].

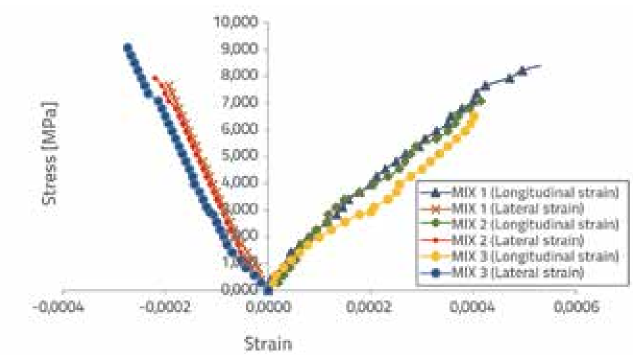

Figure 9. Stress–strain curve at 40 % ultimate load of coconut shell concrete

The static modulus of elasticity describes stiffness of the material tested. The experimental modulus of elasticity, varying between 7.00 and 7.30 GPa, is presented in Table 13. There is a drastic variation of modulus of elasticity with ACI code formula when compared to experimental results, which shows a lower stiffness of coconut shell.

5. Conclusions

Locally available by-products and agricultural waste material such as the ground granulated blast furnace slag (GGBS), manufactured sand (M-sand), and coconut shell (CS) could be used to produce sustainable construction materials.
Geopolymer concrete with GGBS as binder possesses high strength when compared to the conventional coconut shell concrete and GGBS replaced coconut shell concrete.
High strength lightweight CSC with an average compressive strength of 40 Mpa can be developed with complete replacement of conventional concrete and geopolymer binder.
The mix proportion used was 1 : 1.80 : 0.50, where the percentage of coconut shell used was very low, since GGBS reacts with sodium silicate and sodium hydroxide and forms a gel which effectively binds the fine and coarse aggregate; the proportion of coconut shell can be increased to achieve the desired strength.
The elastic modulus from the experimental results ranges between 7.0 and 7.3 GPa. This decrease in the modulus of elasticity is due to lower stiffness of coconut shell in the mix.
Since geopolymer concrete is at the development stage, proper guidelines from the Bureau of Indian Standards are yet to be framed.

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