Chapter

Geopolymer Bricks Using Iron Ore Tailings, Slag Sand, Ground Granular Blast Furnace Slag and Fly Ash

Raghunandan Kumar, Pranab Das, M. Beulah and H.R. Arjun

Abstract

World is pound with million tonnes of industrial wastes such as ground granulated blast furnace slag (GGBS), flyash and mine tailings as a various industrial waste. The best way to make use of these wastes is to incorporate these materials as structural elements, which in turn minimizes the carbon foot print. In this contest, this study focuses on using iron ore tailings and slag sand as a replacement for clay or natural sand for the production of stabilized geopolymer blocks. Also, in this study geopolymer is used as a stabilizer instead of cement. Development of geopolymer binder based bricks using flyash and ground granulated blast furnace slag has been carried out in this research. The study includes mechanical properties of the geopolymer bricks. Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solution have been used as alkaline activators. The ratio of alkaline liquid to aluminosilicate solid ratio and percentage of binder had major influence on the strength of brick. The bricks were casted and cured at ambient temperature. The compressive strength was carried out at 7, 14 and 28 days.

Keywords: iron ore tailings, slag sand, fly ash, GGBS, geopolymer, sodium silicate, sodium hydroxide

1. Introduction

World over there is a huge demand on the natural resources to cater to the housing, commercial spaces and the infrastructure for the ever growing population. Once, it has been decided to build a new building or an infrastructure, a very significant commitment to consume natural resources is made. Designers and contractors may be able to help limit that consumption, but they cannot change the overall commitment [1, 2].

Geopolymer, which is a synthesized inorganic material, is now used as an alternate binder in a wide range of construction applications and products. Davidovits [3] proposed that an alkaline liquid could be used to react with the silicon (Si) and the aluminum (Al) in a source material of geological origin or in a by-product material such as fly ash to produce binders. As the chemical reaction that takes place in this case is a polymerization process, he coined the term 'Geopolymer' to represent these binders.

There are two main constituents of geopolymers, namely the source materials and the alkaline liquids. The source materials for geopolymers should be rich in silicon (Si) and aluminum (Al). These could be natural minerals such as kaolinite and natural clays. By-product materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, slag, rice-husk ash, and red mud can also be used as source materials. The alkaline liquids are from soluble alkali metals that are usually sodium or potassium based. The alkaline liquid used in geopolymerization is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate.

Geopolymers are used to manufacture construction products like, geopolymer bricks [4], tiles and concrete. In geopolymer bricks and in geopolymer concretes, geopolymers do not form C-S-H gel (calcium-silicate-hydrates) unlike the Ordinary Portland Cements (OPC), for matrix formation and strength in a geopolymer concrete, but it utilizes the polycondensation of silica and alumina and high alkali content.

Earth is the oldest building material used by man for millennia. All over the world there are thousands of earth buildings which are over 500 years old. All these structures are still in sound condition and are well occupied. Even if earth is an ancient building material [1], the earth building tradition has been kept blooming in many countries and the technology is constantly being adapted to the requirements of modern civilization. In terms of sustainability, un-stabilized earth outdoes any other building material, including timber, owing to its low carbon footprint, its durability and its unlimited recyclability. The advantages of earth buildings are as follows [1]:

a. 100% natural local resource

b. Very low carbon footprint

c. Good for indoor climate

d. Low life cycle cost

e. Detoxifying effect

f. Moisture control

g. Fire resistance

h. Noise control

i. Affordable

j. Zero waste

The earth as a construction material has the following disadvantages:

a. Low resistance to water penetration resulting in structural failure due to crumbling.

b. High shrinkage and swelling resulting in structural cracks when exposed to changing weather conditions.

c. Low resistance to abrasion requiring frequent repairs and maintenance.

Sand is one such material which is highly used in the construction industry. Sand has by now become the most widely consumed natural resource on the planet after fresh water. Depletion of sand in the stream bed and along coastal areas leads to the deepening of rivers and estuaries, and enlargement of river mouths and coastal inlets. Therefore, the goal of sustainable construction is to use locally available resources without affecting the environment and its people.

Iron ore tailings (IOT) [6], are waste material obtained from the process of smelting of iron. The rapid growth in the surface mines led the production of Iron Ore tailings which remains as overburden. The safe disposal or utilization of such vast mineral wealth in the form of ultra- fine slime remains a major unsolved and challenging task. Use of iron ore tailing will help in finding a new construction material and also help in finding a proper solution for disposal of tailings. In order to reduce the adverse impact of indiscriminate mining of natural sand, iron ore tailings which is the waste products of mining industries is used as an alternative to the river sand in the manufacturing of concrete and bricks.

Geopolymer is a type of inorganic polymer that can be formed at room temperature by using industrial waste or by-products as source materials to form a solid binder that looks like and performs a similar function to Ordinary Portland Cement (OPC). Geopolymer binder can be used in applications to fully or partially replace OPC with environmental and technical benefits, including an 80–90% reduction in CO_2 emissions and improved resistance to fire and aggressive chemicals.

Mud bricks are made by mixing earth with water [7], placing the mixture into molds and drying the bricks in the open air. Straw or other fibers that are strong in tension are often added to the bricks to help reduce cracking. Mud bricks are joined with a mud mortar and can be used to build walls, vaults and domes.

To summarize, geopolymer, an inorganic polymer, made using sodium hydroxide and sodium silicate with the prescribed molarity, can be used as binder with industrial waste/reject materials rich in silicon (Si) and aluminum (Al), such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, slag and rice-husk ash, to make geopolymers bricks and tiles which conform to the standards of commercially available burnt bricks, and are environmental friendly and can also be called as green bricks since they do not use fuel for firing and also do not contribute to the greenhouse gases.

2. Materials and methods

2.1 Materials

A good brick earth, which is available as a natural resource, usually consist of 50–60% of silica, 20–30% of alumina, 5% of lime and 5–6% of oxide of iron [7].

However, for non-fired green bricks which can be made by using industrial wastes, materials to be used includes iron ore tailings (IOT), slag sand, fly ash and ground granulated blast furnace slag (GGBS), which can replace good brick earth of similar constituents [4]. Geopolymer is synthesized by using fly ash, GGBS, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and water. These bricks can be manufactured without firing, but using geopolymer as binder.

2.1.1 Iron ore tailings

Iron ore tailings (IOT) [6, 8] are the waste materials obtained during the process of separating the valuable fraction of iron from the iron ore. The different steps involved in this process are crushing, screening, grinding, washing, jigging, cyclizing etc. The Iron ore tailing usually contains about 20–30% of iron. Further extraction of iron is too expensive. The composition of the ore and the process of mineral extraction adopted have a direct influence over the composition of the tailings. The iron ore tailings are obtained from Bellary, Karnataka, India, where steel companies are located (Please refer to **Table 1** for the chemical composition and **Table 2** for the physical properties of the iron ore tailings used).

Similar iron ore tailings are available in other parts of India and world too which have different percentage of iron in the tailings.

2.1.2 Slag sand

Slag sand, is an eco-friendly building material obtained as a by-product of the industrial process which can replace conventional river sand in the construction of buildings. It caters to the increasing demand and quality requirements of the fine aggregates. Slag sand as an alternative to river sand will protect river banks and save the environment (Please refer to **Table 3** for chemical composition and **Table 4** for the physical properties of slag sand).

Therefore, replacing river sand with slag sand leads to a better environment and becomes an economically viable solution for the shortage of fine aggregates.

2.1.3 Fly ash

Fly ash is extracted from flue gases by means of electrostatic precipitator in dry form. It is a fine material and possesses good pozzolanic property. Fly ash is a by-product of thermal power stations of India and it is of good quality as it contains low sulfur and very low un-burnt carbon. The pozzolanic property of fly ash makes

Constituents	Percentage (%)
SiO_2	16.05
Fe	44.82
Al_2O_3	6.34
CaO	1.52
MgO	0.28
MnO	1.20
TiO_2	0.38
L.O.I	10.09

Table 1.
Chemical composition of iron ore tailings.

Properties	Results
Specific gravity	3.4
Fineness modulus	2.81
Optimum moisture content	13%
Bulk density	2.54
Maximum dry density	2.25

Table 2.
Physical properties of iron ore tailings.

Constituents	Percentage (%)
SiO_2	30.73
Fe_2O_3	0.56
Al_2O_3	16.32
CaO	38.47
MgO	6.41

Table 3.
Chemical composition of slag sand.

Properties	Results
Specific gravity	2.65
Water absorption	1%
Fineness modulus	3.363

Table 4.
Physical properties of slag sand.

it a reserve for making cement and other ash based products. The specific gravity of fly ash used is 2.17 in the present work. (Please refer to **Table 5** for chemical composition of Fly ash used).

2.1.4 Ground granulated blast furnace slag (GGBS)

Granulated blast furnace slag (GGBS), is obtained by rapidly chilling (quenching) the molten ash from the furnace with the help of water. During this process, the slag gets fragmented and transformed into amorphous granules (glass). This granulated slag is then ground to the desired fineness for producing GGBS. It is one of the greenest construction materials. GGBS replaces something that is produced by a highly energy-intensive process. The specific gravity of GGBS used in this work is 2.61. (Please refer to **Table 6** for the chemical composition of GGBS).

2.1.5 Sodium hydroxide

Sodium hydroxide is obtained from sodium carbonate which is formerly known as caustic soda. At room temperature, sodium hydroxide exists as a white crystalline odorless solid which absorbs moisture from the air. When dissolved in water or neutralized with acid it liberates substantial heat, which may be sufficient to ignite combustible materials. It is very corrosive. It is generally used as a solid or as 50% solution. Sodium hydroxide is one of the widely used chemical substances in laboratory and in industries. It is also used in the manufacture of other products like paper pulp and various chemical products like plastics, synthetic textiles, geopolymers etc. (Please refer to **Table 7** for the specification of sodium hydroxide, NaOH).

2.1.6 Sodium silicate

Sodium silicate is usually known as water glass or liquid glass. It is well-known due to its wide commercial and industrial application. It is composed of oxygen-silicon polymer backbone lodging water in molecular matrix pores. Sodium silicate products are manufactured as solids or thick liquids, depending on proposed

Constituents	Percentage (%)
SiO_2	66.87
Fe_2O_3	4.41
Al_2O_3	23.34
CaO	1.17
MgO	0.31

Table 5.
Chemical composition of fly ash.

Constituents	Percentage (%)
SiO_2	31.79
Fe_2O_3	0.49
Al_2O_3	17.07
CaO	38.78
MgO	6.23

Table 6.
Chemical composition of GGBS.

Specifications of NaOH	
M	40.0 g/mol
Assay (NaOH)	≥97%
Carbonate (Na_2CO_3)	≤2%
Heavy metals (as Pb)	≤0.002%

Table 7.
Specifications of sodium hydroxide (NaOH).

function. Sodium silicate is a versatile, inorganic chemical manufactured by combining different ratios of sand and soda ash at high temperature.

This process gives a variety of products with unique chemistry that are used in many industrial chemistry that are used in many industrial and consumer applications.

2.1.7 Water

Potable water is used for the manufacturing of geopolymer bricks.

2.2 Mix proportion

Six different mix proportions shall be considered viz.; GB-1, GB-2, GB-3, GB-4, GB-5 and GB-6. The slag sand shall be mixed with portions of IOT as a partial replacement with the following percentages; 20, 30 and 40% of the total dry mix. Fly ash (15%) and ground granulated blast furnace slag (15%), which are kept constant, all together contribute 30% of the total dry mix. The molarity of the sodium hydroxide solution adopted shall be 8 and 10 M. The alkaline solution shall contribute 10% of the total mix. The optimum moisture content adopted shall be 8%. The Na_2SiO_3 to NaOH ratio adopted shall be 2.5. Alkaline solution to binder

	Quantity of ingredients/stabilizer				
Brick ID	**IOT%**	**Sand%**	**Fly ash%**	**GGBS%**	**Alkaline solution%**
GB-1	20	40	15	15	10 (8 M NaOH Soln.)
GB-2	30	30	15	15	
GB-3	40	20	15	15	
GB-4	20	40	15	15	10 (10 M NaOH Soln.)
GB-5	30	30	15	15	
GB-6	40	20	15	15	

Table 8.
Mix proportions of geopolymer bricks.

material ratio adopted shall be 0.35. (Please refer to **Table 8** for the mix proportion including the molarity).

2.3 Process of block making

'MARDINI' is the advanced version of the mud block press machine developed at the Department of Civil Engineering/ASTRA, Indian Institute of Science, Bengaluru, India. The size of stabilized mud block manufactured in the machine shall be 230 × 110 × 100 mm. The process of block making involves a series of sequential steps as below:

a. Soil preparation

b. Alkaline solution preparation

c. Mixing of soil and stabilizer

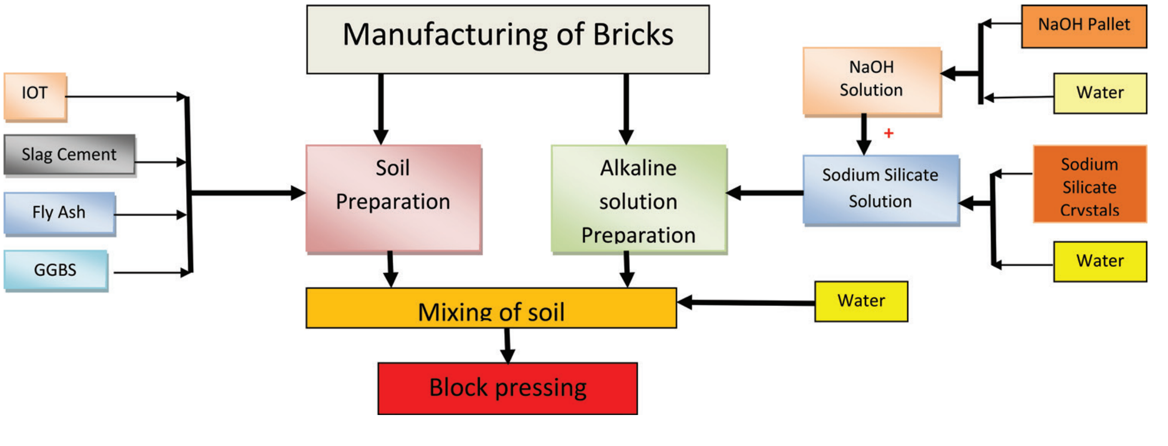
d. Addition of extra water

e. Weighing of soil in scoop

f. Block pressing

g. Block ejection and stacking

h. Curing of the block (7, 14 and 28 days)



2.4 Tests on bricks

2.4.1 Compressive strength

The compressive test of a brick is considered as an index of its durability and ability in a masonry wall to resist crushing loads [5, 7]. Even though most of the bricks are specified in terms of strength, it is important not to sacrifice on the properties of durability and bond for higher compressive strengths. Most of the bricks will a have strength generally ranging from 3.5 MPa to over 10 MPa. The dry compression test shall be carried out according to IS: 3495-Part [1]—1992 specification (or alternate as per the local relevant codes **Figure 1**). Five bricks per mix shall be taken for testing and their average value turns will be the "Dry Compressive Strength" of the brick. (Please refer to **Table 9** for the results of the compressive strength of the samples tested).

$$\text{Compressive Strength} = \text{Failure Load/Area of Bed Face.}$$

2.4.2 Brick density

Brick density is one of the primary tests on bricks. This test shall be done for both dry and wet bricks [5]. The formula used for finding brick density is as below:

$$\text{brick density} = \frac{\text{dry weight}}{\text{volume of brick}} = \frac{\text{kg}}{\text{m}^3}$$

Figure 1.
Compression test of geopolymer bricks.

Brick ID	Dry compressive strength (N/mm^2)			Wet compressive strength (N/mm^2)
	7th day	14th day	28th day	
GB-1	15.41	17.79	21.86	13.79
GB-2	13.04	14.82	18.46	11.70
GB-3	11.86	13.44	16.68	10.67
GB-4	17.59	20.16	25.3	20.95
GB-5	15.22	17.39	21.58	17.39
GB-6	13.24	15.02	18.38	15.18

Table 9.
Compressive strength of geopolymer bricks.

Brick ID	Dry density (kg/m^3)	Wet density (kg/m^3)
GB-1	1978	2110
GB-2	2001	2086
GB-3	2055	2152
GB-4	2006	2127
GB-5	2061	2136
GB-6	2120	2180

Table 10.
Density of geopolymer bricks.

Figure 2.
Water absorption test of geopolymer bricks.

Brick ID	Initial rate of absorption (kg/m^2/min) or (g)	Water absorption (%)
GB-1	1.06 (27)	6.67
GB-2	0.94 (24)	4.22
GB-3	1.03 (26)	4.71
GB-4	1.28 (32)	6.04
GB-5	1.06 (27)	3.71
GB-6	0.90 (23)	2.83

Table 11.
Water absorption test results of geopolymer bricks.

(Please refer to **Table 10** for the density obtained for the samples tested).

2.4.3 Water absorption

The water absorption for dry bricks should not exceed 20% of the weight of the brick [5]. The acceptable values for initial rate of absorption (IRA) range from 10 to 30 grams. Dry brick with an IRA above 30 should be wetted before using for construction (Please refer to **Figure 2** and to **Table 11**, for the results of water absorption obtained for the samples tested).

2.4.4 Dimensionality test

Dimensionality test shall be carried out according to IS: 2185-Part [1] specification (Refer, **Figure 3**). In this test, 20 or more bricks shall be selected at random and shall be arranged in rows and the dimensions shall be measured to the nearest

Figure 3.
Dimensionality test of geopolymer bricks.

Dimensions	No. of units	Dimension (mm)	Average dimension (mm)	Code recommendations (mm)
L	30	230	230	230 ± 5
B		110	110	110 ± 3
H		100	100	100 ± 3

Table 12.
Dimensionality test results of geopolymer bricks.

millimeter. The overall lengths of the arranged bricks shall be measured with the help of a steel tape. Similarly the width and depth of the arranged bricks are measured along straight line. (Please refer to **Table 12** for the results obtained for the dimensionality test of the geopolymer bricks).

2.4.5 Falling test

In this test, the dried bricks after curing shall be allowed to fall from a height of 1 m from the ground. The ground shall be firm and leveled. Then the observations shall be noted down specifying whether cracks appeared, failure happened etc. All the samples tested show moderate edge failure which is acceptable. (Please refer to **Figure 4** for the results of the falling test).

2.4.6 Efflorescence test

The efflorescence is caused due to the presence of alkalis in bricks. When the bricks get exposed to moisture, water is absorbed by them. Due to evaporation this water absorbed dries out from the exposed faces. As a result of this, the soluble

Figure 4.
Falling test of geopolymer bricks.

Figure 5.
Efflorescence test of geopolymer bricks.

salts contained within them crystallize out on to the surface. This process continues for several years depending on the amount of salts present in the bricks and their solubility. All the samples tested showed very slight effloresce which is acceptable. (Please refer to **Figure 5**).

2.4.7 Soundness test

The soundness test is conducted by striking two bricks against each other or by a light hammer [5]. If the bricks generate a clear metallic ringing sound and do not break, then those are good quality bricks. All the samples tested for soundness showed that they are heavy and good causing a metallic ringing sound when struck against each other.

2.4.8 Hardness test

Hardness of the bricks can be found out with the aid of the scratch of the finger nail [5]. If no impression is left over the surface, the brick is treated to be sufficiently hard. All the samples tested showed very slight indentation, which is acceptable. (Please refer to **Figure 6** for the result of the hardness test).

2.4.9 Structure test

In structure test, a brick is broken and its structure is inspected. It is observed that the bricks are compact, homogeneous and free from any imperfections such as lumps, holes, etc. (Please refer to **Figure 7** for the result of the structure test).

Figure 6.
Hardness test of geopolymer bricks.

Figure 7.
Structure.

2.4.10 Scanning electron microscopy

From the images of the scanning electron microscope (SCM) as seen in **Figures 8** and **9**, it is observed that the bricks are homogeneous, compact and free from defects such as holes and lumps.

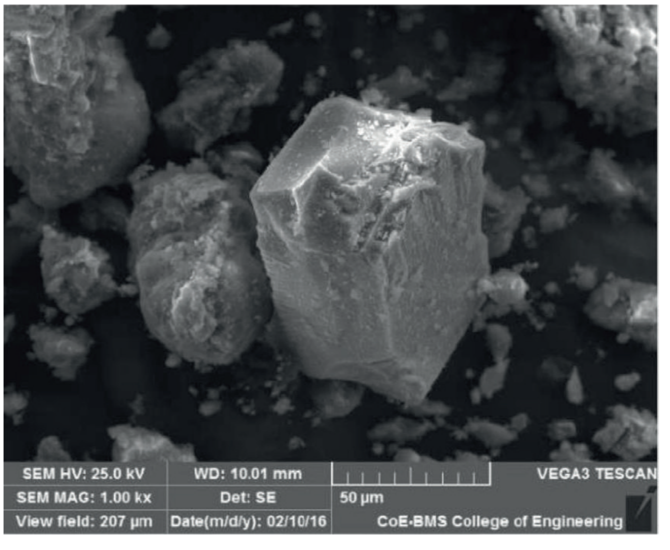


Figure 8.
SEM image of GB-1.

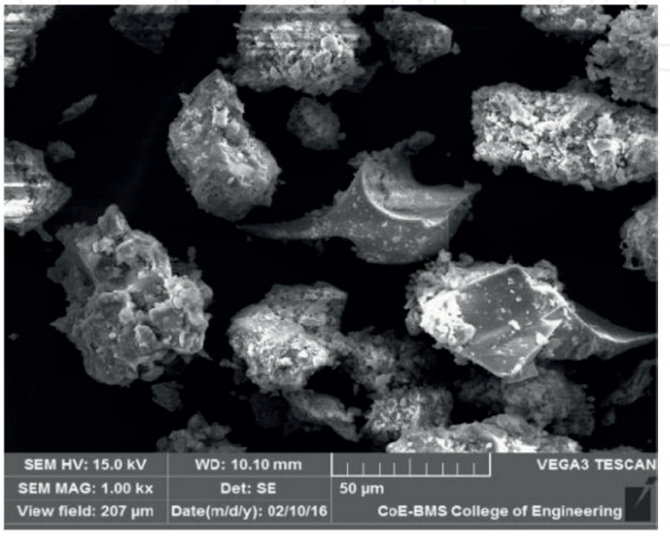


Figure 9.
SEM image of GB-4.

3. Discussions

In this work a series of tests were carried out to study the strength and durability properties of the geopolymer bricks. Also field tests were conducted to check the quality of bricks.

The following are the key points of the discussions:

The compressive strength of the geopolymer bricks is more for the mix which has higher concentration of the alkaline solution, i.e. 10 M as compared to 8 M and which has the highest percentage of Slag sand.

The compressive strength is minimum for the geopolymer bricks, which were having the least percentage of slag sand and with the highest percentage of iron ore tailings. The highest water absorption percentage obtained also showed the same pattern.

The dimensionality test results were within the Indian Standard code recommendations. In falling test, failure of the geopolymer bricks was not severe and maximum pattern failures were restricted to mild edge failure, moderate edge failure and no failure.

The efflorescence test conducted proved that the bricks were prone to efflorescence slightly. Thus, it satisfied the statement "Efflorescence shall not be more than Slight for Higher class bricks" as all the bricks belong to class AA category, the highest category.

The geopolymer bricks produced clear ringing sound when struck with another brick and proved to be sound and good. The bricks when subjected to hardness test by scratching with a nail did not leave any impressions on the surface and proved to be sufficiently hard.

The structure test and the scanning electronic microscope (SCM) conducted on geopolymer bricks helped to understand the microstructure level of the bricks. The bricks are homogeneous, compact and free from defects such as holes, lumps etc.

4. Conclusion

The use of geopolymers proves to be an excellent replacement for cement and can be used as a stabilizer for bricks. Fly ash and ground granulated blast furnace slab acts as excellent solid binders for the synthesis of geopolymers.

The compressive strength of geopolymer bricks with iron ore tailings, slag sand, fly ash, and GGBS increases with the increase in the molarity of the alkaline solution and increases with the increase in the percentage of slag sand. The minimum required compressive strength for geopolymer brick shall be achieved by all the different mixes indicated.

Iron ore tailings (IOT) and slag sand can be used for manufacturing stabilized geopolymer blocks of good quality and strength.

The field tests conducted on geopolymer bricks shows excellent results for being adopting them for sustainable construction. Geopolymer bricks prove to be an excellent replacement for fired bricks based on the studies conducted.

Author details

Raghunandan Kumar*, Pranab Das, M. Beulah and H.R. Arjun
Georgie Ignatius Christ (Deemed to be University), Bengaluru, India

*Address all correspondence to: raghunandan.kumar@christuniversity.in

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