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Research Article

Synthesis and Characterization of High Strength Sand using Bauxite

B. Shiva Kumar[1], Kadali Srinivas[2*], P. Arti Sudam[3]
1) Post Graduate student, Department of Civil Engineering, "V N R Vignana Jyothi Institute of Engineering and Technology, Bachupally, Hyderabad, India."
bonushivakumar@gmail.com
2) Associate Professor, Department of Civil Engineering, "V N R Vignana Jyothi Institute of Engineering and Technology, Bachupally, Hyderabad, India."
srinivas_kadali@vnrvjiet.in *Corresponding Author
3) Assistant Professor, Department of Civil Engineering, "V N R Vignana Jyothi Institute of Engineering and Technology, Bachupally, Hyderabad, India."
artisudam_p@vnrvjiet.in

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ABSTRACT

High-strength sand often refers to sand that has been processed or selected for certain properties that enhance its strength or performance in various applications. Sand usage is more, which makes the issue worse, resulting in negative effects like erosion of riverbanks, damage to aquatic habitats, and a drop in the water table. There is an immediate demand for conventional granular alternatives to support the construction industry. In this connection, investigations were carried out on unconfined compressive strength test for 4M, 6M, and 8M NaOH for molarity optimization. Synthesized raw bauxite granules were prepared using 6M NaOH solution at 110°C for 1hr and the granules produced were used as an alternative for natural river sand. The granulated material was assessed for its physical (specific gravity, water absorption, particle size distribution, Atterberg limits), chemical (pH, electrical conductivity, total dissolved solids, and engineering (direct shear test) properties, compared to conventional river sand (RS). Further, the materials were investigated through microlevel analysis by using x-ray diffraction, x-ray fluorescence & scanning electron microscopy analysis. In addition, a compressive strength test was performed on SRBG and RS mortar. It was noted that SRBG mortar attained higher strength than RS mortar. Based on the experimental investigations and microanalysis, it can be concluded that SRBG granules have the potential for use as a substitute to natural river sand.

Keywords: Raw Bauxite, River Sand, Sodium Hydroxide

INTRODUCTION

Sand is a conventional material in construction, widely used in concrete, mortar, and other structural applications. However, the excessive extraction of river sand (RS) has led to environmental degradation and a growing shortage of this resource. This issue is exacerbated by the rapid urbanization and increasing demand for construction materials, which has resulted in unsustainable mining practices (Poonia et al. 2024). Many researchers are trying to find alternative materials to replace natural river sand. Before using it, sand must be investigated for its strength characteristics, which are impacted by various parameters such as the shape of the grain (Bisht & Das 2021), size (Yan and Dong 2011), stress–strain rate, and particle aspect ratios (Bartake and Singh 2007; Marketos and Bolton 2007; DeBono & McDowell 2020; Govender & Pizette 2021; Liu et al. 2022). In this regard, experimental studies have focused on the stress–strain relationship and its effect on engineering properties (Sazzad & Rahar 2017; Xiao et al. 2020), the relevance of roundness and fracture of particles on crushing strength (Guerrero et al. 2006; Cavarretta

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et al. 2017), and the influence of particle angularity on the mechanical behaviour of granular materials such as void ratio, strain shear modulus, and friction angle (Marketos & Bolton 2007; Shin and Santamarina 2013; Sazzad & Rahar 2017; Chen et al. 2023). Sudam et al. (2023) investigated the strength characteristics of geopolymer synthetic sand (GPSS) produced using fly ash and confirmed that such materials can achieve comparable performance to natural river sand in terms of physical, chemical, and mechanical properties. The high content of amorphous components in bauxite waste allows it to serve as a pozzolan, thus contributing to the development of alternative building materials (Azevedo et al., 2022). Further studies by Sudam et al. (2025) focused on the crushing strength behaviour of artificial fly ash sand (AFAS) and compared its performance with conventional materials such as Ennore sand, glass beads, and natural river sand. While previous research has largely concentrated on the use of fly ash in the synthesis of geopolymer sands, limited work has explored the potential of raw bauxite as an alternative precursor material. However, its behaviour in granule formation and its mechanical properties as a synthetic sand replacement remain less explored.

The present study aims to synthesize and characterize high-strength sand using raw bauxite as a replacement for sand. A disc granulation technique is adopted to produce bauxite-based granules, followed by detailed characterization through physical, chemical, mineralogical, and mechanical tests. This research seeks to contribute to the development of sustainable alternatives for natural sand by utilizing raw bauxite, expanding the scope beyond fly ash-based materials, and addressing the global demand for eco-friendly construction resources.

In addition to mechanical attributes, advanced analytical techniques were employed to explore the physicochemical details of the material. X-ray fluorescence (XRF) analysis will reveal elemental compositions. X-ray diffraction (XRD) provides insights into the crystalline structure, and scanning electron microscopy (SEM) will offer a magnified view of surface morphology. Further research is needed compare the performance of bauxite granules to conventional sand in specific construction uses like hydraulic fracturing and high-grade concrete. Investigate the long-term durability and environmental impact of bauxite granules. By engaging in these areas, this research could significantly help develop sustainable and efficient alternatives to sand in the construction industry.

METHODS

Materials and Experimental Program

Materials

Raw Bauxite: Bauxite is a naturally occurring, heterogeneous material composed primarily of one or more aluminum hydroxide minerals, plus various mixtures of silica, iron oxide, titania, aluminosilicate, and other impurities in minor or trace amounts. Raw Bauxite was obtained from Gujarat State, India. Raw Bauxite and alkaline activators such as Na_2SiO_3, NaOH, and geopolymer solutions were used to prepare SRBG. Alkaline binders with a purity of 90% were procured and their properties, chemical composition of sodium silicate and sodium hydroxide, and the constituent components percentage are presented in Tables 1 and 2, respectively.

Fig 1. Raw Bauxite

Sodium Hydroxide (NaOH): Sodium Hydroxide pellets (NaOH) also known as caustic soda is a colorless crystalline solid, highly soluble in water. It absorbs moisture from the atmosphere and liberates heat when neutralized with an acid or when water is added. Sodium Silicate (Na_2SiO_3) is effectively a solution of silica in sodium hydroxide.

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Research Article

Fig 2. Sodium Hydroxide Pellets

Fig 3. Sodium Silicate

Table 1. Specifications of Sodium Hydroxide

Parameters	Quantity (%)
Minimum Assay (Acid metric)	97
Carbonate (as Na_2CO_3)	2
Chloride (CI)	0.12
Sulphate (SO_4)	0.04
Zinc (Zn)	0.02
Potassium (K)	0.1
Iron (Fe)	0.006
Silicate (SiO_2)	0.05

Table 2. Specifications of Sodium Silicate

Parameters	Quantity (%)
pH	8 to 14
Assay (of Na_2O)	7.5-8.5
Assay (as SiO_2)	25-28
Weight as per ml 20° C	1.35g/ml

The raw bauxite sample was firstly crushed into small fragments and then grounded into a fine powder using a pulverizer. The prepared sample was placed in a small aluminium dish and subjected to X-ray fluorescence (XRF) to determine the chemical composition using a (Fischer ED-XRF) instrument; the chemical composition in oxide form shows Al_2O_3 (52.96%), SiO_2 (23.24%), Fe_2O_3 (5.47%), TiO_2(3.60%) and CaO (2.32%), and raw bauxite was classified as per Non-Metallurgical Grade of Bauxite (IS 10817-1984), as shown in Table 3. The Physio-chemical and engineering properties of raw bauxite such as specific gravity, water absorption, grain size distribution, angle of shearing resistance, Atterberg's Limits determined and tabulated in table 5. The particle size distribution of raw bauxite was determined [IS: 2720 (Part 4) (BIS 1985a)] and the results are presented in Fig. 4. It was observed that most raw bauxite particles passed through a 75 μ sieve. The uniformity coefficient (Cu) and coefficient of curvature (Cc) were determined, and the results are presented in table 5.

Table 3. Chemical Composition of Raw Bauxite from XRF

Elements	% by weight
Al_2o_3	52.96
SiO_2	23.24
Fe_2O_3	5.47
TiO_2	3.60
CaO	2.32

Journal of Information Systems Engineering and Management
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MgO	0.03
Na_2O	0.01
Loss of ignition (LOI)	11.72
Others	0.65

Table 4. Crystalline moisture contents of raw bauxite at different temperatures

Temperature	Crystalline Moisture Content (%)
100 - 200	30 - 34
200 - 300	25 - 30
300 - 400	15 - 20
400 - 500	5 - 10

Source: (Liu et al.,2014).

Table 5. Properties of Raw Bauxite

Parameters	Test Results
Specific Gravity	2.42
Plasticity Index	Low Plastic
Liquid Limit (%)	30.07
Particle Size Distribution (%)	
Sand (75 µm–4.75 mm)	-
Silt (75–2 µm)	78
Clay (<2 µm)	22
Coefficient of uniformity (Cu)	0.56
Coefficient of curvature (Cc)	1.05
Soil Classification	SP
Electrical Conductivity(µS/cm)	0.322
pH	8.94
TDS (ppm)	423.2
Friction Angle (ϕ)	30.06°
Cohesion (c)	0.26

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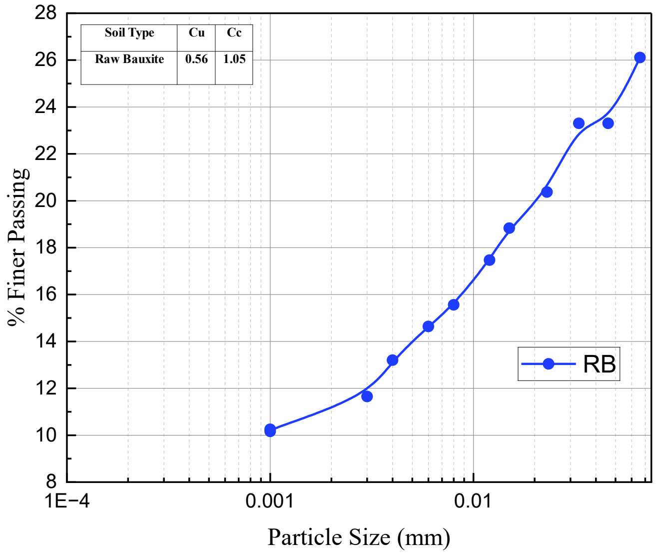

Fig 4. Indian Standard classification (ISC) for Raw Bauxite

To validate and support the results obtained from sieve analysis, the consistency limits (Atterberg limits) of the sample were determined as per Indian Standard (IS) code (BIS 1985b) and plasticity index of Raw Bauxite was shown as being low plastic in nature, as illustrated in Table 5.

Raw Bauxite was classified as poorly graded sand (SP) and typically exhibits a high percentage of fine particles. For instance, studies have indicated that raw bauxite from Bukit Goh contains an average of 38.40% fine material, exceeding the IMSBC standard of 30% (Muzamir et al., 2017). The coarse fraction is often less than 70%, which is a concern for compliance with IMSBC standards (Zaini et al., 2024). Crystalline moisture content is the amount of water that is present in a crystalline substance.

The crystalline moisture content in bauxite, primarily from minerals like gibbsite and boehmite, is released at a temperature range between 200°C and 500°C depending on the specific composition of the bauxite ore, with the majority of the water being released between 250°C and 400°C; this process is typically referred to as calcination, where the hydrated aluminium oxides transform into anhydrous alumina (Al_2O_3) by releasing water vapor (Liu et al.,2014).

other materials such as RS were obtained from Bachupally, Hyderabad, India, and used for comparative study. The Specific gravity of raw bauxite was determined with the help of pycnometer bottle available in Geotechnical laboratory. The average of three values of the specific gravity was reported as final value of specific gravity, as shown in Table 5 [IS.2720 (Part 3) (BIS 1980)].

Experimental Methodology

Preliminary attempts were made to minimize the volume of alkaline binders and the temperature to synthesize SRBG. Na_2SiO_3 and NaOH were selected at varying molarity. Then, the optimization of Raw Bauxite is done using Unconfined Compression Test to choose the best from the following i.e. 4M,6M,8M. An optimized liquid solution; comprising 4M, 6M, and 8M (RB) alkaline activators mixed sodium hydroxide in a 1:1 ratio, was thoroughly blended. The bauxite and alkaline activator were mixed in a solid-to-liquid ratio of 3:1 for 15 minutes, resulting in a dry mixture. Subsequently, it is put into the split-spoon sampler and tampered with 25 times, layer by layer, until it is compacted.

The Specimen is tested using UCS apparatus. Then the unconfined compressive strength (UCS) of raw bauxite exhibited an upward trend with an increasing binder concentration, specifically an increase in the activator molarity from 4 M to 6 M resulted in an elevation of UCS.

However, a further increase in the activator molarity to 8 M led to a subsequent decrease in UCS. From this 6M raw bauxite attained maximum strength and it is selected. The obtained Shaer Strength Values are shown in table 6. Furthermore, the synthesized granules were characterized for their specific gravity, electrical conductivity, pH, total

Journal of Information Systems Engineering and Management
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dissolved solids, grain size distribution, water absorption, angle of shearing resistance, optimum moisture content and these were compared with the properties of RS.

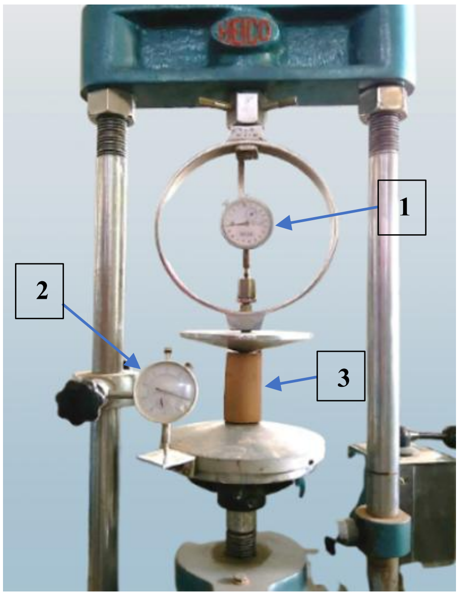

Fig 5. Test Setup of UCS with Raw Bauxite Specimen

Table 6. Unconfined Strength Test Values

S. No	Material	qu (Kg/cm²)
1.	Raw Bauxite	0.661
2.	4M RB	0.737
3.	6M RB	0.992
4.	8M RB	0.816

Synthesis of SRBG

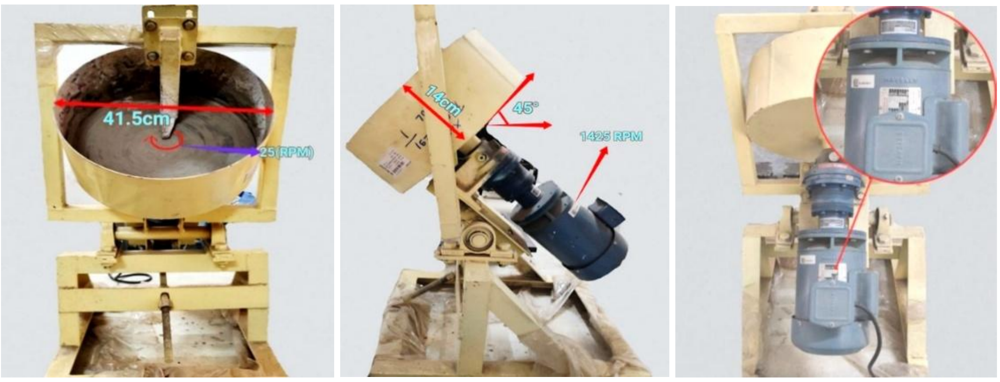

Fig 6. Disc Granulator Front and Back View

A disc granulator is a type of granulation equipment used to produce granular materials, particularly in the fertilizer industry. It plays a crucial role in converting fine powder materials or small particles into larger, more uniform granules. The key component of a disc granulator is a rotating disc with 45˚C angle and diameter with 41.5cm, typically mounted on a central shaft. The SRBG granules were created by heating at 110°C to ensure complete dryness. An optimized geopolymer liquid solution, comprising 4M, 6M, and 8M (RB) alkaline activators mixed with sodium silicate and sodium hydroxide in a 1:1 ratio, was thoroughly blended. The raw bauxite and alkaline activator (geopolymer liquid solution) were mixed in a solid-to-liquid ratio of 3:1 for 15 minutes, resulting in a dry mixture. The granules were then oven-dried at 110°C for 1h to complete the polymerization process. Subsequently, the oven-dried particles were allowed to cool at room temperature for 24 hours. Subsequently, the granules were sieved

Journal of Information Systems Engineering and Management
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through a 4.75 mm sieve and characterized for their physical, chemical, engineering, and durability properties, which were then compared with those of river sand (RS).

Fig 7. Synthesized Raw Bauxite Granules

RESULTS AND DISCUSSIONS

In the present study, the SRBG and RS were characterized for particle size distribution. The coefficient of uniformity (Cu) and curvature (Cc) obtained for SRBG were Cu = 2.85 and Cc = 1.21 and for RS were Cu = 2.5 and Cc = 0.9; thus, SRBG was classified as poorly graded (SP) sand as per IS 1498:1970 (BIS 2016) (Table 7). The specific gravities of raw bauxite, SRBG, and river sand was measured as per IS 2386-Part III (BIS 1963b) and the results are presented in Table 7. It can be observed that the specific gravity of SRBG (G = 2.82) increased compared to raw bauxite (G = 2.42) due to gepolymerization (Parhi et al., 2017; Jorjani et al. 2015), which implies that SRBG fine aggregate density is high compared to that of RS (G = 2.61). The strong bond of aluminium silicate developed during the geopolymer reaction reported higher specific gravity than raw bauxite (Parhi et al., 2017; Jorjani et al.2015) (Table 7). The water absorption of SRBG was 12.64 % indicating more absorption of water than that of RS (0.96%) due to the presence of porosity on the surface of the particles. The SRBG was composed of coarse sand (36.6%), medium sand (56.44%) and fine sand (4.96%) while RS is composed of medium sand (80%) and fine sand (20%), as shown in Fig. 9. pH was determined as per [14] for SRBG and RS material as per IS 2720 - 26 (BIS).

The results reveals that the SRBG is more alkaline (pH = 10.36) in nature due to the blending of raw bauxite in geopolymer alkaline solution compared with RS (pH = 7.53), implying that SRBG is the appropriate material for granulation to form granules like RS as reported in Table 7. Raw bauxite had a slightly higher clay content (22%).

River sand and SRBG, were found to have an electrical conductivity of 1.16µS/cm, 1.96 µS/cm, and TDS of 473 ppm and 513 ppm, respectively. In comparison to river sand, synthesized raw bauxite granules are bound with alkaline binders, indicating higher electrical conductivity and TDS which are shown in table 7.

Direct shear test was performed for SRBG and RS to determine the angle of shearing resistance as per IS Code 2720-Part13 (BIS 1986) for normal stresses of 0.5, 1, and 1.5 kPa and the sample was allowed to shear, as shown in Fig 10. It was observed that SRBG developed excellent angle of shearing resistance (33.5°), which was more than RS (27.2°) due to compact packing of granules showing angularity (Table 7).

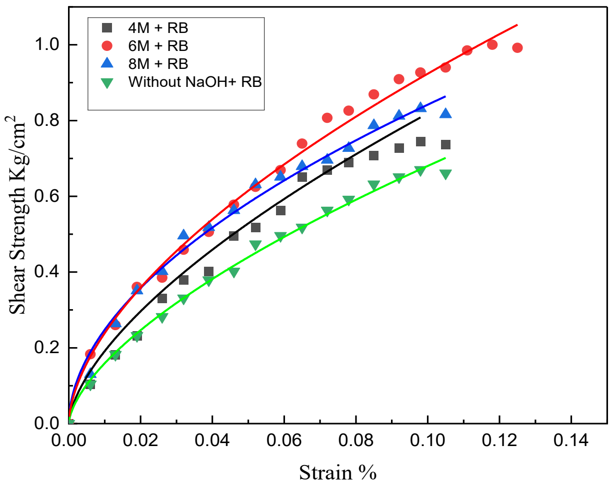

Fig 8. Graphical Representation of UCS with and without adding alkaline solution.

Journal of Information Systems Engineering and Management
2025, 10(58s)
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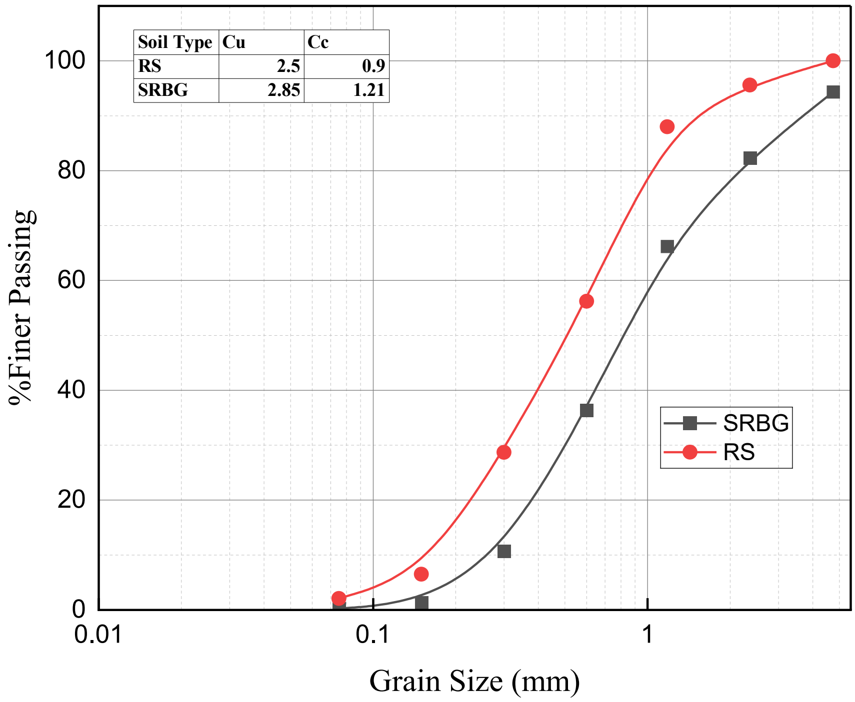

Fig 9. Indian Standard classification (ISC) for SRBG and River Sand (RS)

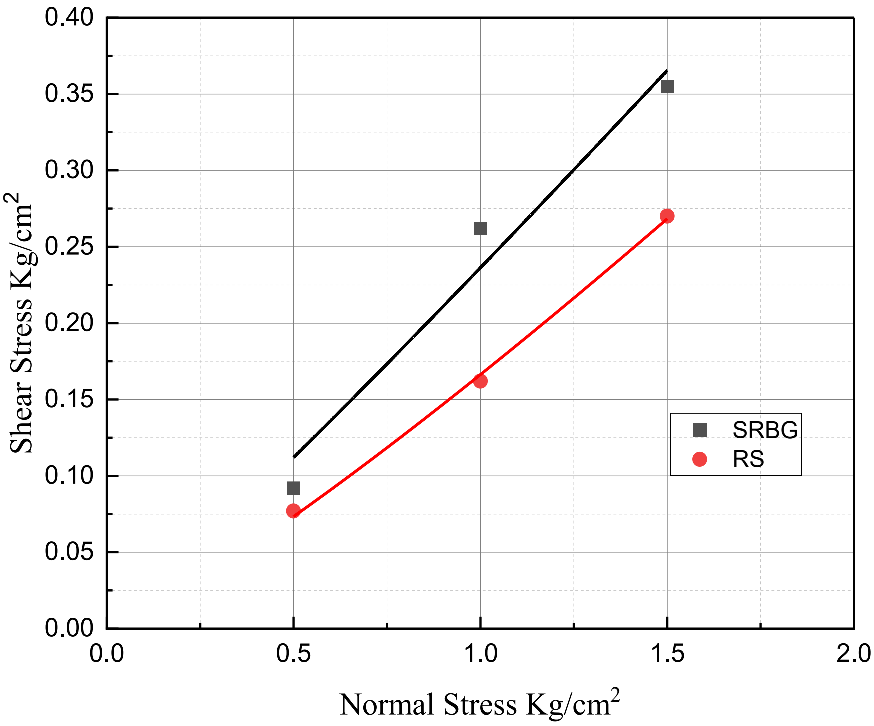

Fig 10. Direct shear test on SRBG and RS materials

Table 7. Properties of SRBG and River Sand

Parameter	SRBG	River Sand
	Physical Property	
Specific Gravity	2.82	2.61

Journal of Information Systems Engineering and Management
2025, 10(58s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Water absorption (1%)	12.64	0.96
Cu	2.85	2.5
Cc	1.21	0.9
LL (%)	30.07	-
PI (%)	2.03	-
Soil Classification	SP	SP
	Chemical Property	
pH	10.36	7.53
EC (μS/cm)	1.96	1.16
TDS (ppm)	513	473
	Engineering Property	
Friction angle (ϕ°)	33.5	27.2
Cohesion (C)	0.26	0.82

Table 8. Chemical Composition of SRBG from XRF

Elements	% by weight
Al_2O_3	55.26
SiO_2	19.86
CaO	5.36
Na_2O	4.43
TiO_2	3.46
Fe_2O_3	2.51
MgO	0.02
Others	0.30
Loss of Ignition (LOI)	8.80

The SRBG was characterized to determine the chemical composition with the help of XRF spectrometer set up (ED - XRF) for the purpose. According to the XRF study, the major oxides form shows presence of Al_2O_3 (55.26%), SiO_2 (19.86%), CaO (5.36%), Na_2O (4.43%), TiO_2 (3.46%) and Fe_2O_3 (2.51%) represented in Table 8.

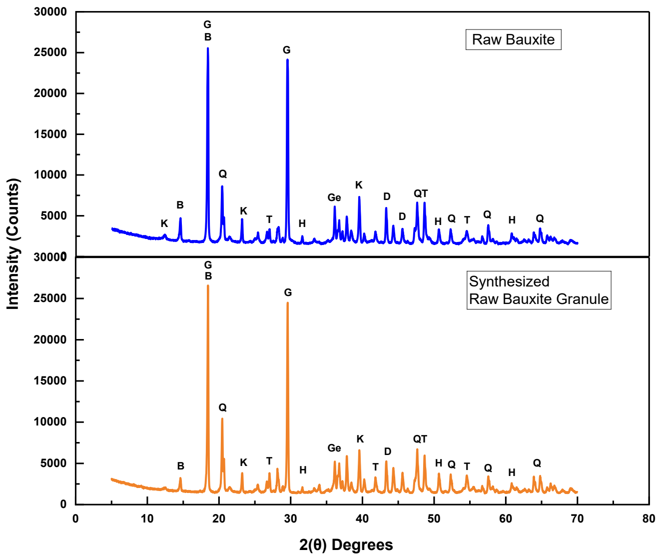

Fig 11. XRD of Raw Bauxite and SRBG

Journal of Information Systems Engineering and Management
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X-ray diffraction (XRD) analysis was performed using a Malvern PANalytical X'pert3 Powder X-ray Diffractometer, with Cu and k-alpha radiation as Shown in Fig 11.
The identified minerals are G – Gibbisite [Al $(OH)_3$], B – Boehmite [AlO (OH)], K - Kaolinite [$Al_2Si_2O_5(OH)_4$], Ge - Goethite [FeO (OH)], D - Diaspore [AlO (OH)], H - Hematite [Fe_2O_3], T - Titanium [TiO_2], Q - Quartz [SiO_2].
This indicates that SRBG and raw bauxite showed major minerals to be gibbsite and boehmite. The peak intensity increased for SRBG (26,589) compared to raw bauxite (25,549) at 18° following the formation of crystals.
The morphological study of SRBG and raw bauxite was performed using SEM analysis, as shown in Fig.12 and Fig.13.
The raw bauxite structure is rough, angular, and uneven. It also contains natural contaminants such as iron oxides and uneven porosity. It appears packed and crowded, has larger particles, and a less uniform morphology.
Synthesized raw bauxite granules (SRBG), on the other hand, has a more homogeneous and refined structure, with regulated porosity and smaller, smoother particles.
Because the synthesis technique improves crystallinity and decreases impurities, SRBG is more appropriate for use such as high-strength materials, catalysis, and adsorption.

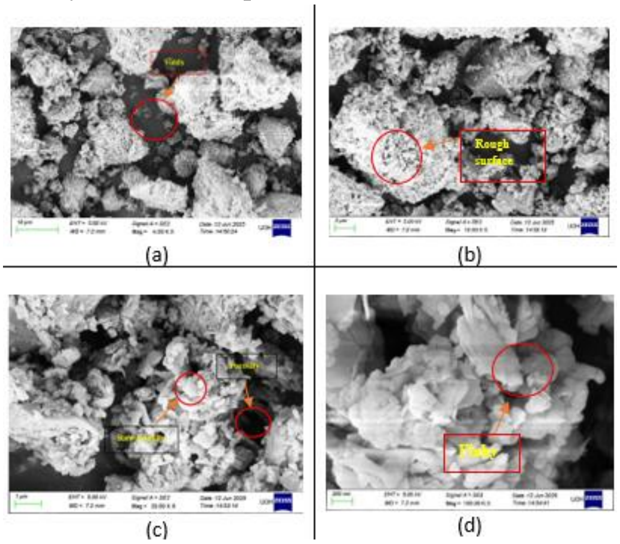

Fig 12. SEM Analysis of Raw Bauxite

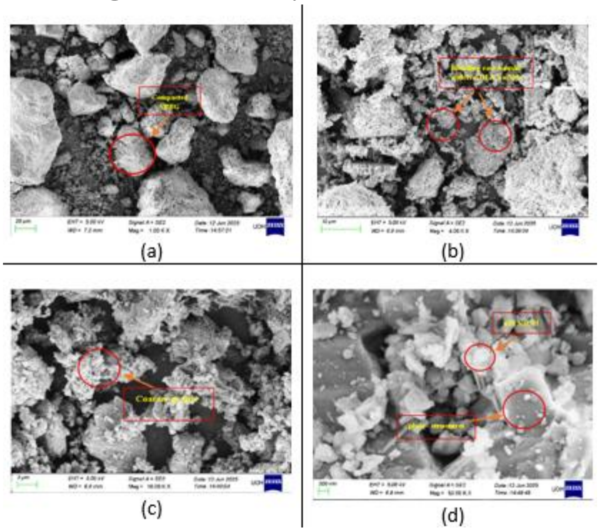

Fig 13. SEM Analysis of Synthesized Raw Bauxite Granules (SRBG)

Compressive strength test was performed on SRBG and RS mortar, as per IS: 2386 (Part VI)-1963 (BIS 1963a) on a cube of size 50 × 50 × 50 mm. A water cement ratio of 0.45 was found adequate for mixing and preparing RS mortar, whereas higher water cement ratio of 0.85 was found to be adequate for SRBG mortar preparation. The six samples were submerged in a water bath for 3,7, and 14 days after curing for 24 h, at room temperature. The specimens were then removed from the water bath to dry, and their compressive strength was measured. In comparison to RS mortar, the strength of SRBG mortar improved quickly from 7 to 14 days of curing, and both SRBG mortar and RS mortar attained compressive strengths of 25.6 and 23.2 MPa, as shown in Fig 15.

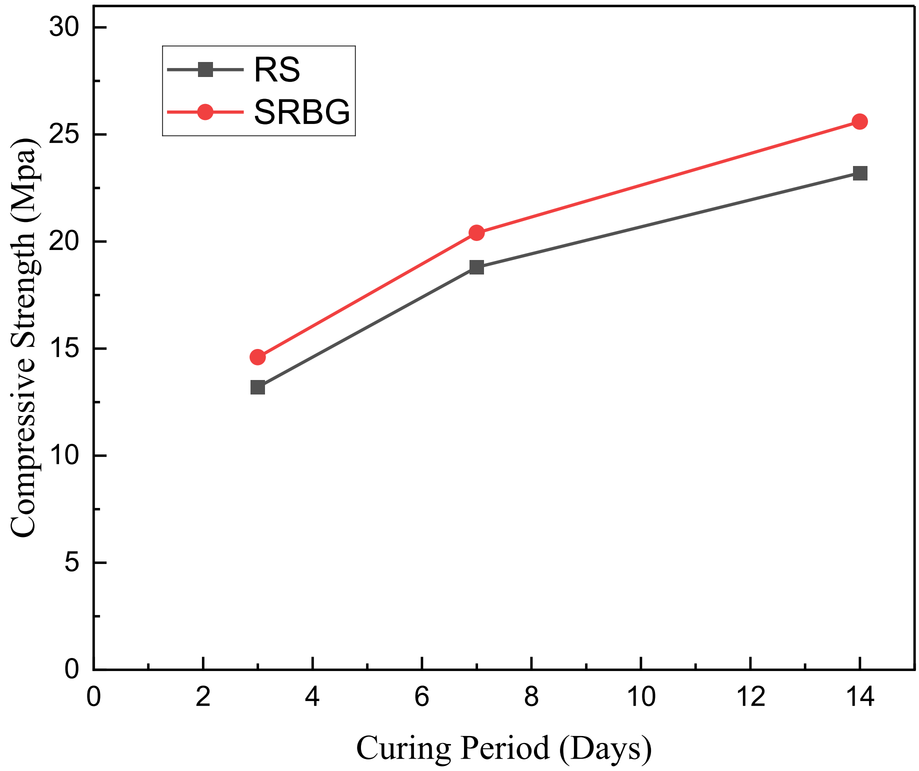

Fig 14. Compressive Strength results of River Sand (RS) and Raw Bauxite Granules (SRBG).

CONCLUSIONS

The following conclusions were drawn from the study conducted:
The specific gravity, water absorption, and grain size distribution of SRBG were compared with the properties of RS. The SRBG granules achieved higher and better specific gravity (2.82) than raw bauxite (2.42) and RS (2.61). The grain size distributions of SRBS and RS was classified as poorly graded soil (SP) because Cc was found to be lower than 4. The reported values of pH (10.36), EC (1.96µS/cm) and TDS (513 mg/L) of SRBG were higher than those of RS. The unconfined compressive strength tests proved that 6M produced maximum strength and could be optimized in comparison with 4M and 8M SRBG granules, suggesting as 6M is perfect. The compressive strength of SRBG improved quickly from 7 to 14 days of curing, and both SRBG and RS attained compressive strengths of (25.6) and (23.2) MPa. The SRBG granules showed more angle of shearing resistance (33.5°) compared to RS granules (27.2°). which proves that all granules formed are angular in shape and with compact packing, thus increasing strength.
The XRF analysis showed that Raw Bauxite and SRBG predominantly have high Alumina. XRD analysis showed that the major components to be Gibbsite and Boehmite. (SEM) revealed that SRBG has a more homogeneous and refined structure, with regulated porosity and smoother particles, exhibiting improved crystalline characteristics and fewer impurities compared to Raw Bauxite. This makes it ideal for high-performance and high-strength applications. It can be used as a sustainable alternative material for RS and used in many civil engineering applications.

Nomenclature

Φ^o	Angle of Shearing Resistance
C	Cohesion
Cc	Coefficient of Curvature
Cu	Coefficient of Uniformity
EC	Electrical Conductivity
G	Specific Gravity

Journal of Information Systems Engineering and Management
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Research Article

M	Molarity
pH	Hydrogen ion concentration
RS	River Sand
SRBG	Synthesized Raw Bauxite Granules
TDS	Total Dissolved Solids

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