

Chemical and Microstructural Characteristics of Soils Treated with Pulverised Charcoal and Gum Arabic

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Research Article

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Abstract

Chemical and microstructural characterisation provides a basis for understanding interactions between locally available additives and soil. This study examined pulverised charcoal, gum arabic, and two soils from Ibadan treated with nominal charcoal–gum proportions of 2%–2%, 4%–2%, and 2%–4%. Proximate and ultimate analyses, reported oxide compositions, six X-ray diffraction patterns obtained after 14 days, and twelve scanning electron micrographs assigned to 7 and 14 days were evaluated. Charcoal contained 10.60% moisture, 40.40% volatile matter, 30.75% fixed carbon, and 18.25% ash. The revised oxide entries for gum arabic totalled 92.30%, with a loss on ignition of 7.70%. In treated soils, silica and alumina contents ranged from 49.01 to 56.46% and from 22.02 to 32.10%, respectively. The available oxide entries and loss on ignition summed to 99.97–100.00%, although one phosphate entry was unavailable. Changes between curing ages varied across treatments, indicating contrasting compositional patterns. Diffraction annotations identified quartz, feldspar, mica, kaolinite, and illite, while microscopy descriptions indicated heterogeneous granular, plate-like, and aggregated surfaces. This study provides a preliminary description of the reported analytical entries and author-assigned specimens. Interpretation remains subject to confirmation of the analytical reporting bases and specimen traceability, including a potentially repeated microscopy field. The findings inform further investigation of the combined treatment; confirmation of reaction mechanisms and engineering suitability will require complementary controls and performance testing.

1 Introduction

Soil suitability for construction depends on its composition, fabric, and response to moisture. In southwestern Nigeria, Oyelami et al. [1] identified substantial variation in residual soil properties, with some soils requiring improvement for use in pavement foundations. Similarly, Ajayi et al. [2] reported varying levels of suitability among lateritic soils along the Lagos–Ibadan Expressway, including susceptibility to seasonal volume changes, and recommended drainage measures to maintain bearing capacity. These findings underscore the importance of laboratory testing in selecting local soils and assessing potential modifiers.

For carbonaceous amendments, Lu et al. [3] found that engineering responses vary according to the physicochemical characteristics of the additive and the properties of the receiving soil, with physical, hydraulic, and mechanical behaviours differing among materials. Lu et al. [4] further examined biochar ageing and emphasised the importance of field-relevant conditioning. These findings support the independent characterisation of pulverised charcoal, particularly when its production history is insufficiently documented to establish equivalence with the biochars studied.

Prasad et al. [5] characterized gum arabic as a water-soluble natural gum whose composition and processing determine its functional properties. Soldo et al. [6] demonstrated that biopolymers alter soil mechanics, with effects varying according to the polymer and treatment conditions. Vishweshwaran et al. [7] reported that acacia gum enhances the strength of silty and clay soils, depending on soil type and

curing conditions. Kumar et al. [8] emphasized the need for further optimization and research before practical application. Collectively, these studies support the evaluation of charcoal–gum mixtures under specific treatment conditions.

Ceylan [9] integrated X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), and geotechnical testing to examine the treatment of mineralogically contrasting soils with biopolymers. These methods provided complementary insights into elemental composition, crystalline phases, morphology, and engineering behaviour. This approach demonstrates the value of integrating analytical observations while recognising that compositional differences and apparent particle associations require further evidence before they can be attributed to cementation or improved performance.

The present study examines two soils from Ibadan treated with three proportions of pulverised charcoal and gum arabic. Its objectives are to characterise the additives; compare the reported soil oxide compositions after 7 and 14 days; examine the XRD patterns obtained after 14 days; and assess SEM observations at both curing ages, as confirmed by the authors. The study provides a comparative chemical, mineralogical, and morphological description of the combined treatment, with particular attention to distinguishing particle organisation from evidence of mineral formation.

1.1 Analytical framework and working hypothesis

Characterising carbonaceous additives requires complementary bulk and elemental measurements. Proximate analysis determines moisture, volatile matter, fixed carbon, and ash content, whereas ultimate analysis determines elemental composition. Because these analyses describe distinct properties, the reporting basis should be specified. ASTM D1762-84(2021) [10] covers moisture, volatile matter, and ash in wood charcoal and provides a relevant reference; any claim of compliance should be supported by documentation of the procedures used.

The working hypothesis is that gum influences particle association, while charcoal modifies the particulate matrix. This hypothesis guides the interpretation of chemical and morphological observations without presupposing covalent bonding, mineral precipitation, or long-term water resistance. Distinguishing these mechanisms from physical mixing, drying, and other processes requires analytical evidence.

The framework distinguishes among composition, mineralogy, and morphology. Rigaku [11] describes XRF as a method for elemental analysis and XRD as a method for identifying crystalline phases. Accordingly, oxide-equivalent chemical results are interpreted separately from mineral assignments based on diffraction.

JEOL USA [12] discusses the effects of specimen preparation and coating on SEM imaging. When acquisition conditions are taken into account, micrographs can reveal particle surfaces, contacts, and visible openings. For complementary elemental analysis, JEOL USA [13] describes specimen- and matrix-

related limitations in quantitative energy-dispersive X-ray spectroscopy (EDS). Together, these sources support the integration of traceable chemical, diffraction, and microscopy observations while ensuring that each interpretation remains within the capabilities of its respective method.

2 Methods

2.1 Study design and evidence sources

This descriptive laboratory study investigated two soil types using three combined additive proportions. Chemical and microstructural assessments were carried out using characterisation worksheets, additive analyses, treated-soil summaries, six annotated XRD plots, and twelve SEM panels. The reported measurements were verified arithmetically and interpreted qualitatively, based on the descriptions of diffraction and microscopy findings.

The observational units documented in the laboratory records comprised soil specimens and additive samples. As the dataset did not establish representative sampling, independent site replication, or the number of analytical replicates, the findings should be interpreted as descriptive comparisons between the two soils rather than as estimates applicable to a broader population. Single reported values were not used to calculate significance tests, confidence intervals, or analytical variability.

2.2 Study area, soil sampling and identification

The soils were collected in Ibadan, Nigeria, and designated as Samples A and B. The sampling records list the coordinates 7°31'50"N, 3°55'01"E and 7°19'29"N, 3°52'52"E. Worksheet descriptions associate Sample A with Lead City and Sample B with Ojo Mutlat; however, the correspondence among these localities, coordinates, and specimen codes remains provisional. A 14-day C2G4 worksheet contains a heading for Sample A and an internal entry for Sample B, which must be reconciled with the field register. The supplied chemical dataset does not establish the sampling dates, depths, number of collection points, or compositing procedures.

Reported preparation involved transporting the samples in sealed containers, air-drying and disaggregating them, then removing particles larger than 2 mm. The resulting material represents the prepared laboratory fraction. Sample A had 18.10% passing the 0.075 mm sieve. An earlier summary reported 2.10% gravel, 79.80% sand and 18.10% fines; however, the grading record places the 2.10% fraction above 1.180 mm and contains no 2.000 mm sieve entry. The fines content is retained, but the gravel–sand partition remains provisional pending confirmation of the classification boundaries and grading calculations. Sample B had a liquid limit of 37.00%, a plastic limit of 23.85% and a plasticity index of 13.15%.

2.3 Additives and treatment preparation

Charcoal obtained from a vendor at Bodija Market, Ibadan, was pulverized and passed through a 2 mm sieve (Fig. 1). It is described as pulverized charcoal because the available records do not specify its

feedstock, carbonization atmosphere, residence time, or storage conditions sufficiently to define a reproducible production process. The gum arabic was identified in the study records as *Acacia senegal* and dissolved in distilled water (Fig. 2). Supplier grade, independent botanical verification, solids content, and solution concentration were not documented.

The treatment codes C2G2, C4G2, and C2G4 indicate nominal charcoal–gum proportions of 2%–2%, 4%–2%, and 2%–4%, respectively. The basis for these percentages was not specified, so a dry-soil mass denominator has not been assumed. The preparation account describes conditioning for 24 hours, while the chemical entries are labelled 7 and 14 days. These recorded ages have been retained; the authors report XRD testing at 14 days and SEM imaging at both ages.

2.4 Charcoal characterisation

The laboratory record reports moisture, volatile matter, fixed carbon, ash, elemental composition, and calorific value (Table 1). It also documents a thermal programme of 15°C min⁻¹, 550°C, and 30 minutes; however, it does not specify whether these conditions apply to a particular analytical stage or production treatment. The available information does not fully document the analytical atmospheres, conditions for moisture and ash determination, calibration procedures, or percentage bases. Accordingly, the reported central values are retained under their original analytical categories.

Central values were transcribed without interpreting the annotations. For example, “10.60 + 0.4” does not specify the number of replicates or whether the second value represents a standard deviation, standard error, or another quantity; therefore, error bars were not constructed. Fixed carbon was verified as 100% minus the other proximate constituents, and the ultimate-analysis subtotal was calculated separately. Calorific value is reported in kJ/g and its numerically equivalent MJ/kg; no gross or net heating-value basis is inferred.

2.5 Chemical analysis and reporting

Samples were crushed and ground for 60 s using a Herzog gyro-mill equipped with a Simatic C7-621 controller. Approximately 20 g of powdered sample was mixed with 0.4 g of stearic acid and ground for a further 60 s. An additional 1 g of stearic acid was placed in an aluminium cup before filling it with the prepared powder. The contents were pressed at 200 kN for 60 s to produce a pellet approximately 2 mm thick.

Chemical results were expressed as oxide equivalents, with loss on ignition (LOI) presented separately. Oxide concentrations were interpreted as chemical composition rather than quantified mineral phases. Results were organised by soil, treatment proportion and curing age. Summary statistics and reference values were excluded where their calculation basis or reference-material identity could not be established.

2.6 X-ray diffraction

X-ray diffraction patterns were examined for the C2G2, C4G2 and C2G4 treatments of Samples A and B after 14 days of curing. The six patterns were assessed qualitatively using the displayed reflections and accompanying phase annotations. T

2.7 Scanning electron microscopy and specimen traceability

Air-dried specimens were mounted on carbon adhesive for SEM examination at 7 and 14 days, yielding twelve micrographs across six soil–blend combinations. Acquisition metadata indicated an accelerating voltage of 20 kV, a pressure of 70 Pa, working distances of 9.6–10.6 mm, and magnifications of $\times 8,000$ – $\times 10,000$. Scale bars measured 50 μm for the assigned 7-day specimens and 100 μm for the 14-day specimens.

Images were assessed qualitatively for particle morphology, local associations, and visible gaps. Quantitative measurements of pores and particles were excluded because calibration and acquisition consistency had not been established.

2.8 Descriptive analysis and consistency checks

Constituent subtotals, percentage-point differences and relative changes between 7 and 14 days were calculated. For values x_7 and x_{14} the percentage-point difference was $x_{14} - x_7$, and the relative change was $100 (x_{14}/x_7 - 1)$. These comparisons were descriptive; no kinetic modelling or inferential statistical tests were performed.

2.9 Use of generative artificial intelligence

ChatGPT (OpenAI) assisted with language editing, manuscript organization, document formatting, reference-style conversion, and arithmetic consistency checks of numerical entries supplied by the authors. It was not used to generate experimental measurements. The manuscript retains the documented limitations regarding analytical reporting bases, laboratory authentication, and specimen provenance.

3 Results

3.1 Soil properties and charcoal characterisation

Sample B had higher recorded moisture content and specific gravity (9.71%; 2.64) than Sample A (2.78%; 2.34), although the Sample A moisture calculation requires reconciliation. The highest tabulated dry densities were 1646.2 and 1745.3 kg/m^3 , respectively; these observations do not establish compaction optima.

As presented in Table 1 and **Fig. 3**, charcoal comprised 40.40% volatile matter, 30.75% fixed carbon, 18.25% ash and 10.60% moisture, totalling 100.00%. This combination supports investigating both

carbonaceous and inorganic contributions to soil modification, although ash content alone does not establish cementing activity.

Elemental carbon was 65.70%, and the ultimate-analysis subtotal was 84.40% (Table 1). These quantities remain distinct from fixed carbon and proximate ash because their reporting bases were unspecified. The calorific value of 20.62 MJ/kg characterises energy content; its relevance to soil treatment requires separate evidence of engineering performance.

Table 1
Reported charcoal characterisation.

Category	Constituent	Central value	Original annotation
Proximate (%)	Moisture	10.60	+ 0.4
Proximate (%)	Volatile matter	40.40	+ 0.7
Proximate (%)	Fixed carbon	30.75	+ 0.4
Proximate (%)	Ash	18.25	+ 0.2
Ultimate (%)	Carbon	65.70	+ 0.3
Ultimate (%)	Hydrogen	5.98	+ 0.3
Ultimate (%)	Nitrogen	1.12	+ 0.1
Ultimate (%)	Oxygen	10.80	+ 0.2
Ultimate (%)	Sulphur	0.80	+ 0.3
Energy (kJ/g)	Calorific value	20.62	-

Figure 3 Charcoal composition and calorific value

3.2 Additive chemical summaries

As shown in Table 2, SiO₂ was the largest listed oxide in charcoal (28.45%) and gum arabic (84.30%). Oxide-plus-LOI totals were 50.45% and 100.00%, respectively. These totals describe arithmetic closure; interpreting the gum values as bulk composition requires confirmation of the analytical basis. Charcoal LOI (7.04%) remains distinct from proximate ash (18.25%) because their measurement bases were unresolved.

Table 2
Additive oxide entries and loss on ignition.

Constituent (%)	Charcoal	Gum Arabic
Na ₂ O	0.12	0.05
MgO	4.32	0.17
Al ₂ O ₃	3.96	0.51
SiO ₂	28.45	84.30
P ₂ O ₅	0.29	0.08
K ₂ O	0.40	0.07
CaO	1.90	6.29
TiO ₂	1.24	0.54
Fe ₂ O ₃	2.10	0.28
MnO	0.63	0.01
LOI	7.04	7.70
Oxide subtotal	43.41	92.30
Oxides + LOI	50.45	100.00

3.3 Treated-soil oxide composition

Silica and alumina were the largest reported oxide components, ranging from 49.01–56.46% and 22.02–32.10%, respectively (Table 3; Fig. 4). When the additional constituents listed in Table 4 were included, the oxide-plus-LOI totals ranged from 99.97–100.00%. The unavailable phosphate value for A C2G4 at 7 days was excluded rather than treated as zero.

Compositional changes observed between 7 and 14 days varied across treatments. In Sample A, silica increased only in C4G2, whereas alumina increased in C2G2 and C2G4. In Sample B, C2G2 exhibited a 10.71% relative increase in silica and a 25.71% decrease in alumina. C2G4 displayed the opposite pattern, with silica decreasing by 9.55% and alumina increasing by 36.33%. C4G2 showed more modest increases in both oxides.

Table 3
Selected soil oxide entries and analytical totals.

Soil	Blend	Age (d)	SiO ₂ (%)	Al ₂ O ₃ (%)	CaO (%)	Fe ₂ O ₃ (%)	LOI (%)	Listed total (%)
A	C2G2	7	52.37	29.24	1.45	3.65	10.55	100.00
A	C4G2	7	49.01	31.10	0.07	1.78	12.67	99.97
A	C2G4	7	53.87	29.20	1.30	2.50	10.24	100.00
A	C2G2	14	50.00	30.70	1.52	3.83	11.08	100.00
A	C4G2	14	52.19	30.66	1.37	2.02	10.74	100.00
A	C2G4	14	49.46	31.00	0.07	1.57	12.30	100.00
B	C2G2	7	49.04	31.12	0.09	1.72	12.69	100.00
B	C4G2	7	49.04	31.12	0.09	1.72	12.69	100.00
B	C2G4	7	56.46	22.02	1.75	4.75	7.02	100.00
B	C2G2	14	54.29	23.12	1.84	4.99	7.37	100.00
B	C4G2	14	49.09	32.10	0.09	1.81	11.32	100.00
B	C2G4	14	51.07	30.02	1.44	3.71	10.99	100.00
Note. Totals include all available numerical constituents in Tables 3 and 4 and LOI. The first Sample B 7-day row carries the author-corrected C2G2 label. C2G2 and C4G2 have identical reported values and are retained as distinct treatments. The missing P₂O₅ entry for A C2G4 at 7 days is excluded from the sum and is not a measured zero.								

Table 4
Additional soil oxide entries.

Soil	Blend	Age (d)	Na ₂ O (%)	MgO (%)	P ₂ O ₅ (%)	K ₂ O (%)	TiO ₂ (%)	MnO (%)
A	C2G2	7	0.28	0.46	0.01	0.94	1.04	0.01
A	C4G2	7	1.20	1.05	0.08	0.09	2.91	0.01
A	C2G4	7	0.25	0.50	—	0.90	1.23	0.01
A	C2G2	14	0.29	0.48	0.01	0.99	1.09	0.01
A	C4G2	14	0.26	0.52	0.00	0.94	1.29	0.01
A	C2G4	14	1.26	1.10	0.08	0.09	3.06	0.01
B	C2G2	7	1.26	1.02	0.08	0.09	2.88	0.01
B	C4G2	7	1.26	1.02	0.08	0.09	2.88	0.01
B	C2G4	7	0.90	4.75	0.04	0.98	1.25	0.08
B	C2G2	14	0.94	4.99	0.04	1.03	1.31	0.08
B	C4G2	14	1.32	1.07	0.08	0.09	3.02	0.01
B	C2G4	14	0.27	0.50	0.01	0.92	1.06	0.01

These contrasting patterns indicate treatment-specific compositional differences rather than uniform enrichment during curing. Without replicated measurements and confirmed reporting bases, they do not establish reaction rates, mineral formation or statistically significant treatment effects.

3.4 Mineralogical evidence

The 14-day XRD patterns exhibited prominent quartz reflections across all treatments (Figs. 5 and 6). Laboratory annotations also identified feldspar, mica, illite, and a phase labelled “Kaoline,” provisionally interpreted as kaolinite. Quartz produced the highest displayed peak in each pattern; however, peak intensity alone does not establish mineral abundance. These observations support qualitative descriptions of the phases, but quantitative phase proportions and treatment-induced mineral formation were not established.

Treatments from left to right: C4G2, C2G4 and C2G2.

Treatments from left to right: C2G2, C4G2 and C2G4.

3.5 Microscopy observations

SEM observations revealed heterogeneous particle arrangements among the treatments (Table 5; Figs. 7 and 8). Sample A exhibited layered, plate-like fragments with overlapping edges and localized openings, whereas Sample B comprised granular aggregates alongside coarser, angular fragments. These features

characterize local particle organization but do not, on their own, demonstrate binder formation or cementation.

Differences in field selection and acquisition conditions limited comparisons across curing ages and precluded quantitative assessments of porosity or densification. The potentially duplicated field assigned to A C2G2 and B C2G4 remained excluded from independent soil comparisons pending verification of its provenance.

Table 5
SEM panel inventory at the assigned curing ages.

Soil	Blend	Magnification (7 d; 14 d)	WD (mm; 7 d; 14 d)	Provenance note
A	C4G2	9000; 8000	10.5; 10.5	Two supplied fields
A	C2G4	10000; 8000	10.2; 10.4	First external caption says 1000
A	C2G2	9000; 8000	9.8; 9.6	Reported possible repeat of B C2G4; verify
B	C4G2	9000; 8000	10.6; 10.4	Second external caption says 4C–2G
B	C2G4	9000; 9000	9.8; 10.4	Reported possible repeat of A C2G2; verify
B	C2G2	9000; 8000	9.8; 9.6	Two supplied fields

Figure 7 Scanning electron micrographs of treated Sample A

Panels (a–b): C4G2; (c–d): C2G4; (e–f): C2G2. Panels (a), (c) and (e): 7 days; panels (b), (d) and (f): 14 days.

Panels (a–b): C4G2; (c–d): C2G4; (e–f): C2G2. Panels (a), (c) and (e): 7 days; panels (b), (d) and (f): 14 days.

4 Discussion

4.1 Charcoal characterisation

The charcoal comprised both carbonaceous constituents and an inorganic residue (Table 1; Fig. 3), providing a basis for evaluating the physical and chemical contributions to soil modification. The proximate total of 100.00% confirms arithmetic consistency but does not establish analytical validity. Elemental carbon (65.70%) and fixed carbon (30.75%) represent distinct analytical quantities and are not directly interchangeable. Similarly, the elemental subtotal of 84.40% cannot be combined with proximate ash unless they are reported on compatible bases.

The 18.25% ash content indicates inorganic matter, but its stabilising effect depends on mineralogy and reactivity. Ash content or silica concentration alone cannot establish pozzolanic activity; complementary evidence is needed to distinguish reactive effects from particle rearrangement.

4.2 Gum arabic chemical composition

The gum oxide subtotal of 92.30% and LOI of 7.70% sum to 100.00% (Table 2); however, arithmetic closure does not establish a whole-material composition. The 84.30% SiO₂ entry requires clarification as to whether it represents bulk gum or an inorganic residue, particularly given gum arabic's organic character [5]. Oxide equivalents, including Fe₂O₃, describe chemical reporting forms rather than identified mineral phases or reaction products. Similarly, the charcoal oxide-plus-LOI total of 50.45% cannot account for the remaining fraction without compatible analytical bases. Interpretation therefore depends on verified sample identity, normalization, and ignition conditions.

4.3 Treatment composition and curing age

Silica and alumina changed in contrasting directions between 7 and 14 days (Table 3; Fig. 4). In Sample A, C4G2 exhibited a 3.18-percentage-point increase in silica, whereas C2G2 and C2G4 showed decreases in silica accompanied by increases in alumina. In Sample B, C2G2 exhibited relative changes of + 10.71% in silica and - 25.71% in alumina, while C2G4 showed changes of - 9.55% and + 36.33%, respectively. These patterns do not support uniform oxide enrichment during curing. Changes in compositional percentages may reflect specimen heterogeneity, preparation, or normalization rather than changes in absolute elemental mass. Accordingly, attributing these changes to chemical transformation requires consistent reporting bases, replicated specimens, and complementary phase evidence.

4.4 Chemical composition and mineralogy

Prominent quartz reflections (Figs. 5 and 6) are consistent with the silica-rich compositions reported in Table 3, although oxide concentrations do not establish mineral abundance. XRF characterizes elemental composition, whereas XRD identifies crystalline phases [11]; their combined interpretation supports qualitative characterization rather than demonstrating treatment-induced mineral formation. In the absence of diffraction patterns for untreated soil and the additive, pre-existing phases cannot be distinguished from treatment-related changes. No new cementitious phase was identified; however, poorly crystalline or low-abundance products cannot be ruled out. Accordingly, the available evidence does not establish a mineral-based cementation mechanism.

4.5 Interpretation of SEM observations

The micrographs show irregular plates, granular fragments, and localized openings, indicating heterogeneous particle organization (Figs. 7 and 8). Differences between curing ages may reflect aging, field selection, or specimen preparation; they do not establish progressive densification. Without additive controls and elemental mapping, apparent bridges or coatings cannot be confidently attributed to gum-mediated bonding.

The potentially repeated field assigned to A C2G2 and B C2G4 remains a reported provenance concern requiring verification and was excluded from independent soil comparisons (Table 5). Unresolved calibration and acquisition differences restricted interpretation to qualitative morphology. Complementary elemental analysis [13] and representative imaging under consistent conditions are needed to assess bonding mechanisms and quantify structural changes.

4.6 Relationship to biopolymer research and study contribution

Soldo et al. [6] demonstrated that biopolymers can modify soil mechanical behaviour, while Vishweshwaran et al. [7] highlighted the influence of soil type and curing conditions on acacia-gum treatment. These findings support the investigation of charcoal–gum mixtures but do not establish equivalent mechanisms or performance in the soils examined in this study. This study provides a preliminary description of the reported analytical entries and author-assigned specimens, integrating chemical composition, 14-day diffraction patterns, and microscopy at two curing ages. Its contribution lies in relating these observations while distinguishing particle association from verified mineral cementation, thereby providing a basis for subsequent mechanistic and engineering assessments.

4.7 Implications for Nigeria

The findings provide a foundation for further evaluation of locally available charcoal and gum arabic for Nigerian earthworks and pavement foundations. Practical assessments should establish material consistency, reproducibility of mixing, strength, durability, and moisture resistance, in addition to cost and environmental performance. Applications in facilities managed by the Federal Airports Authority of Nigeria (FAAN) would also require compliance with relevant project specifications and field validation. The present chemical and microstructural evidence supports further investigation of these materials but does not establish their suitability for airport construction.

5 Conclusions

This study provides a preliminary description of the reported analytical entries and author-assigned specimens for two soils treated with pulverized charcoal and gum arabic. The proximate constituents of the charcoal totaled 100.00%, while the gum oxide entries and LOI summed to 100.00%; these totals indicate arithmetic consistency rather than analytical validity. In the treated soils, silica and alumina ranged from 49.01–56.46% and 22.02–32.10%, respectively, with contrasting changes observed between 7 and 14 days. Diffraction annotations indicated quartz and associated crystalline phases, while SEM observations revealed heterogeneous particle arrangements. Collectively, these findings support comparative characterization but do not establish treatment-induced mineral formation, quantified densification, or an optimum blend. Further assessment requires reconciliation of analytical bases and specimen identities, verification of the potentially repeated microscopy field, and replicated testing with untreated and additive controls. Mechanical performance, durability, and moisture resistance must be established before engineering application.

Abbreviations

EDS

energy-dispersive X-ray spectroscopy

FAAN

Federal Airports Authority of Nigeria

LD

detection limit

LOI

loss on ignition

SEM

scanning electron microscopy

WD

working distance

XRD

X-ray diffraction

XRF

X-ray fluorescence

Declarations

Ethics approval and consent to participate

Not applicable. The study did not involve human participants or animals.

Consent for publication

Not applicable.

Availability of data and materials

The numerical data analysed are presented in Tables 1–4, with microscopy metadata summarised in Table 5.

Competing interests

The authors declare no competing interests.

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Authors' contributions

Gambo Apagu Thliza: Conceptualisation, methodology, investigation, data curation, formal analysis, software, validation, visualisation and writing—original draft.

A. S. Akolade: Conceptualisation, methodology, supervision, project administration, validation and writing—review and editing.

I. D. Odunewu: Supervision, validation and writing—review and editing.

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Use of generative artificial intelligence

ChatGPT (OpenAI) assisted with language editing, manuscript organisation, formatting and arithmetic consistency checks. It was not used to generate experimental measurements.

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Figures



Figure 1

Pulverised charcoal



Figure 2

Gum arabic

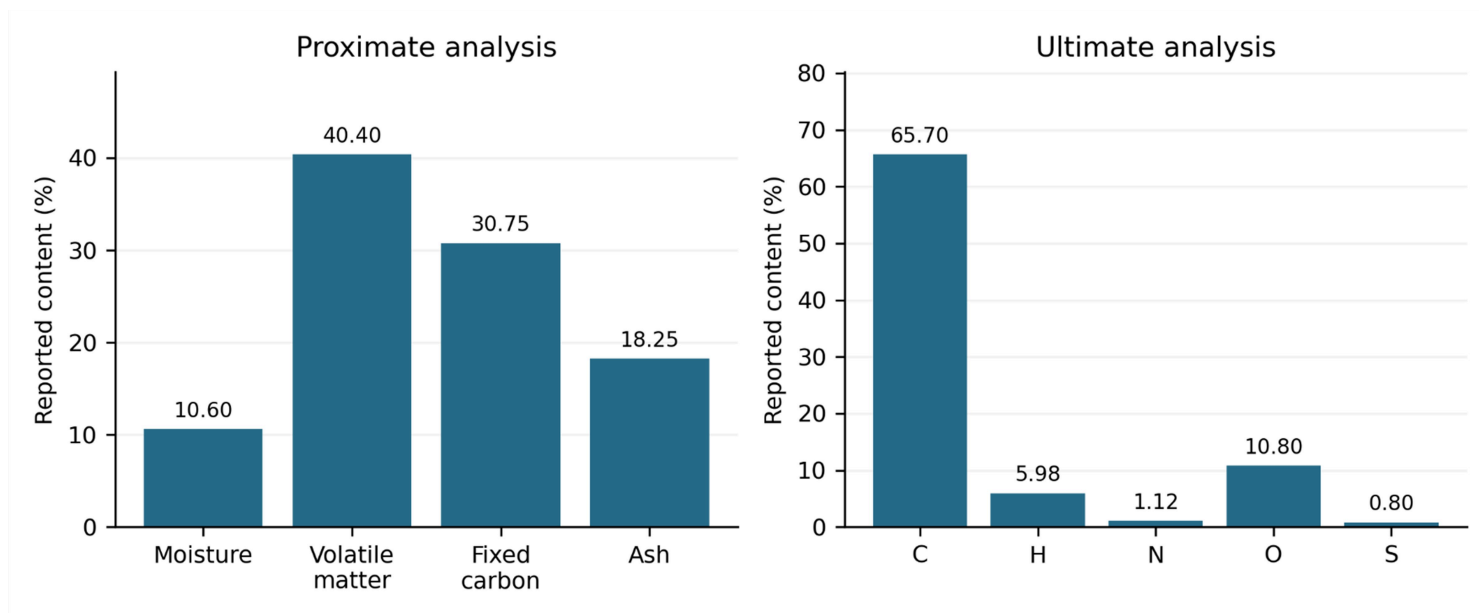


Figure 3

Charcoal composition and calorific value

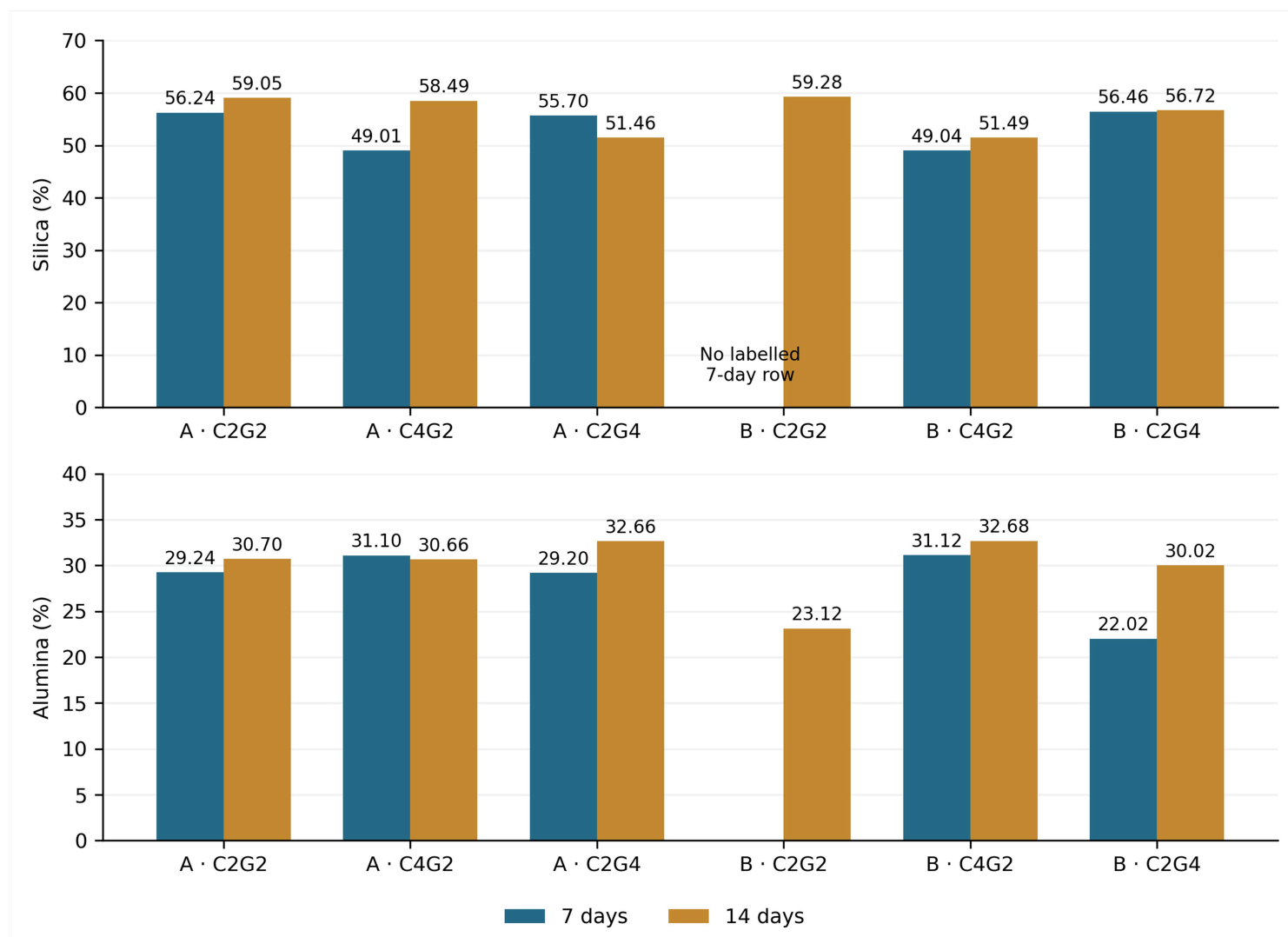


Figure 4

Silica and alumina contents at 7 and 14 days

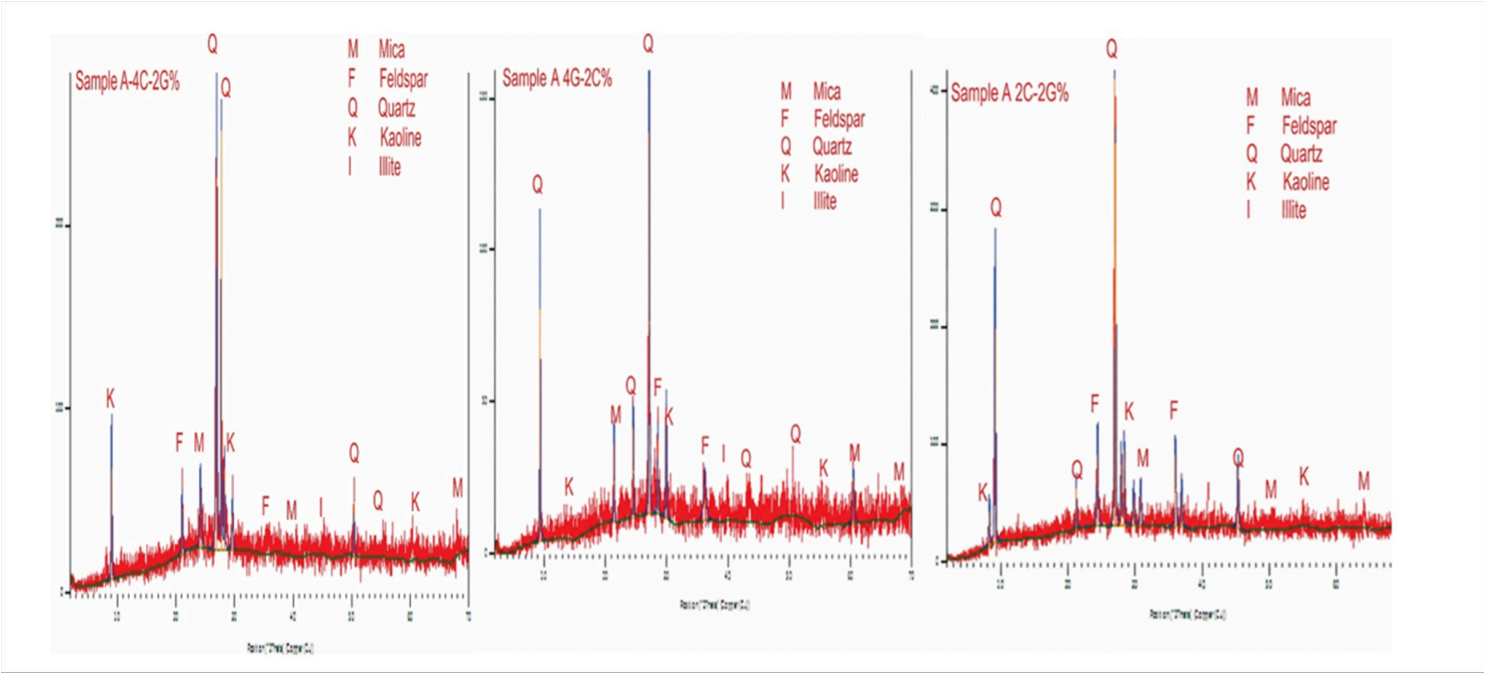


Figure 5

X-ray diffraction patterns of Sample A at 14 days

Treatments from left to right: C4G2, C2G4 and C2G2.

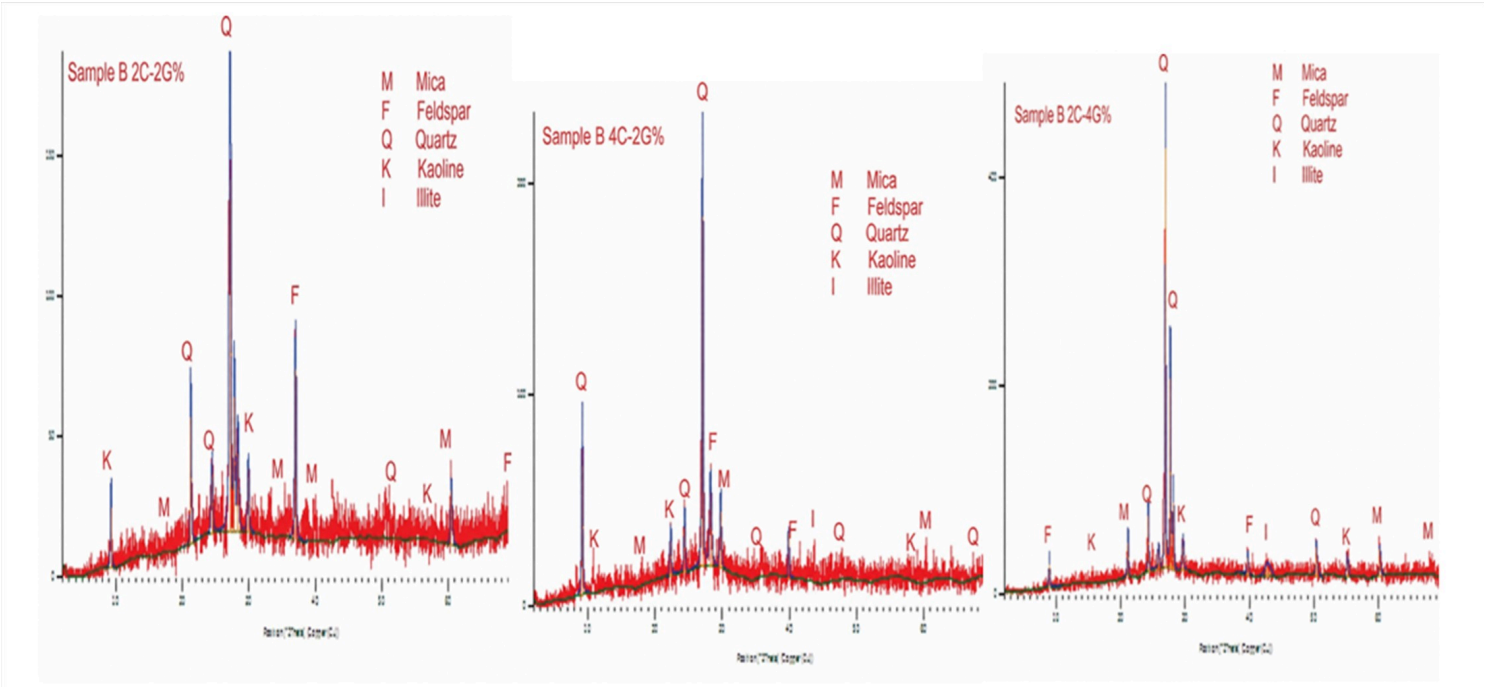


Figure 6

X-ray diffraction patterns of Sample B at 14 days

Treatments from left to right: C2G2, C4G2 and C2G4.

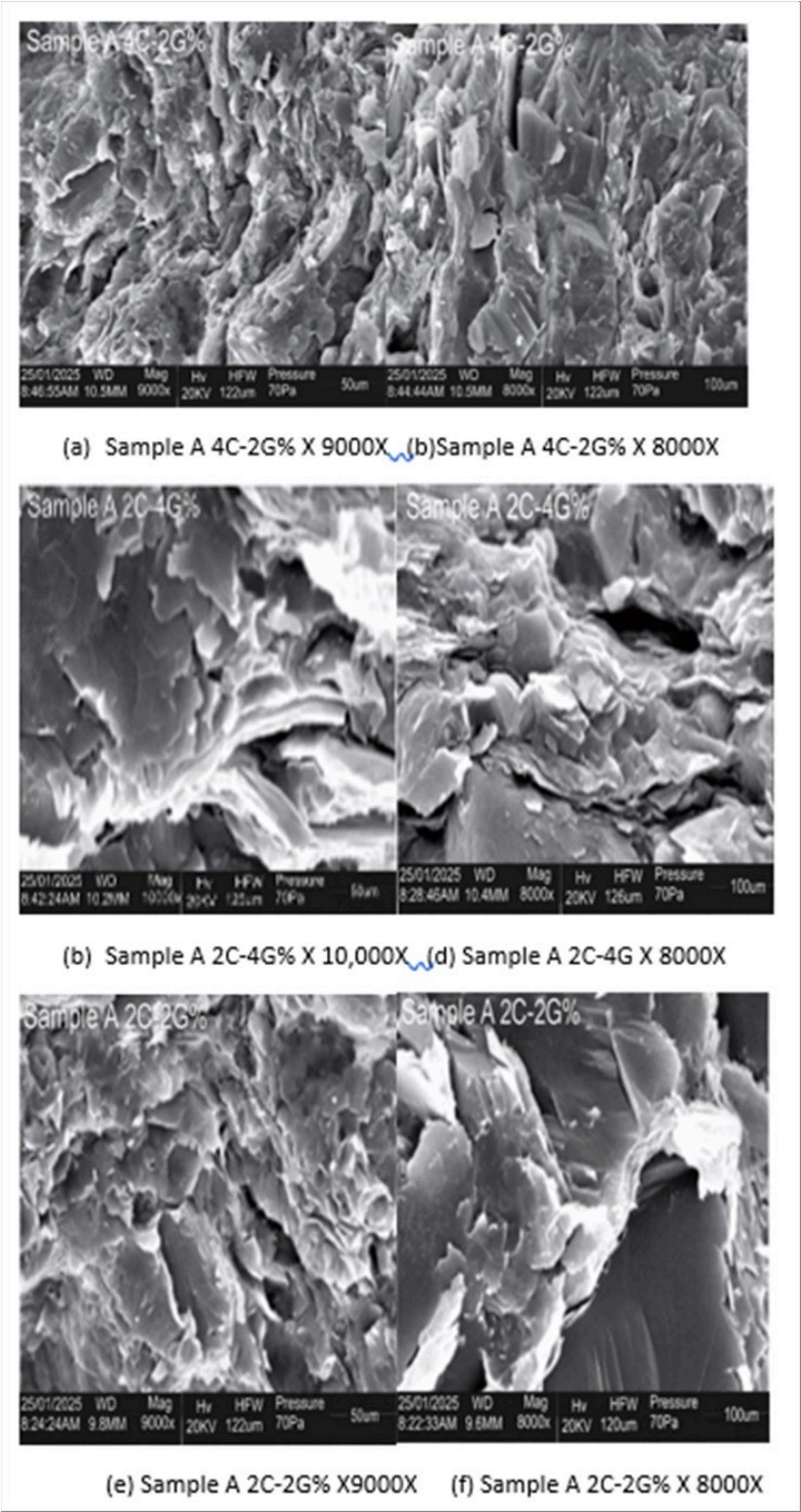


Figure 7

Scanning electron micrographs of treated Sample A

Panels (a–b): C4G2; (c–d): C2G4; (e–f): C2G2. Panels (a), (c) and (e): 7 days; panels (b), (d) and (f): 14 days.

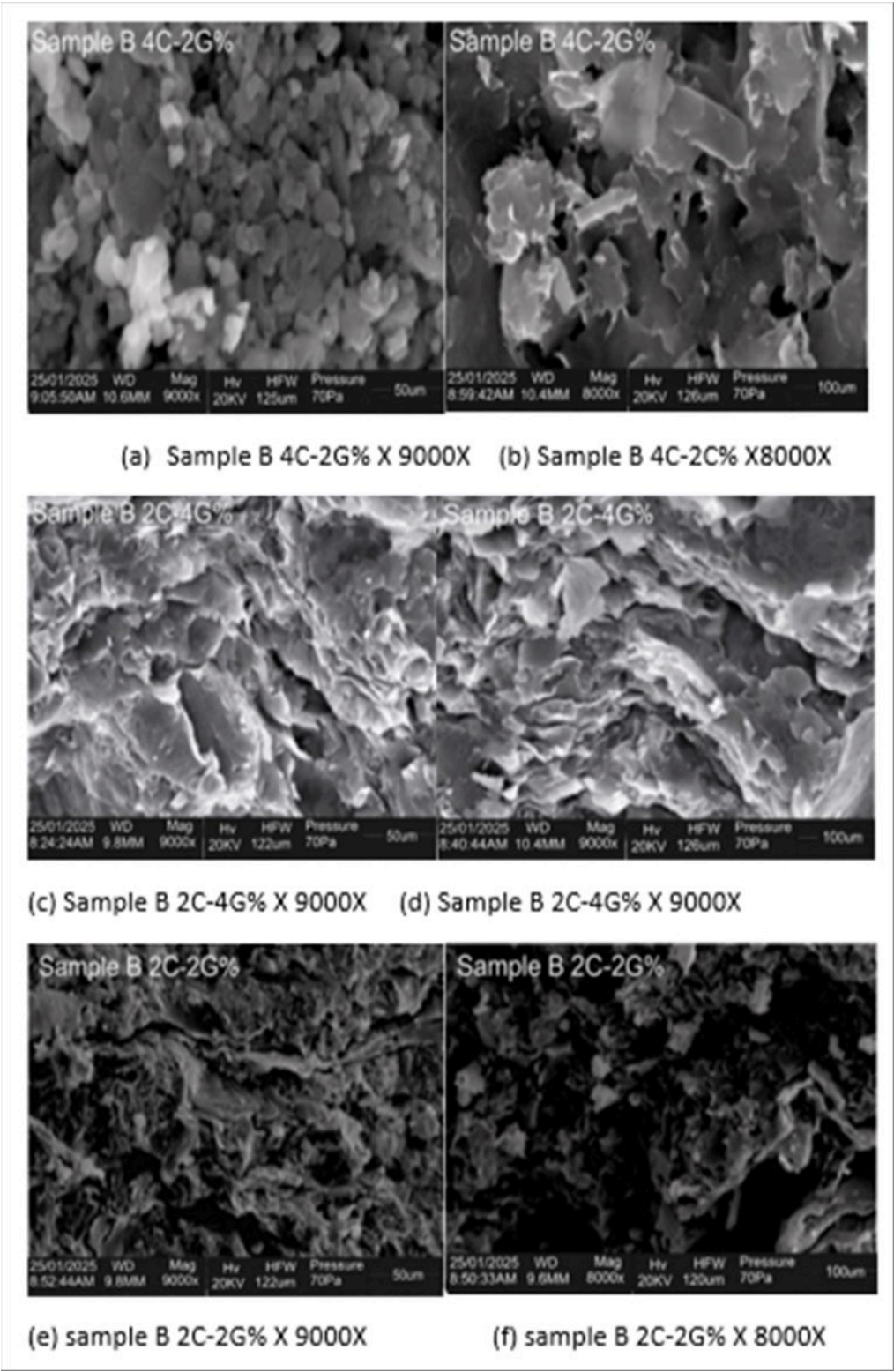


Figure 8

Scanning electron micrographs of treated Sample B

Panels (a–b): C4G2; (c–d): C2G4; (e–f): C2G2. Panels (a), (c) and (e): 7 days; panels (b), (d) and (f): 14 days.