

Article

Empty Fruit Bunch Biochar as a Green Additive in Cement Mortar: Engineering Performance and Potential for Biogenic Carbon Retention

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Abstract

Empty fruit bunch (EFB) biochar was investigated as a partial replacement for fine aggregate (sand) in cement mortar, with emphasis on early-age engineering performance and the potential retention of biogenic carbon in a cement-based matrix. EFB was thermally treated at 280, 320, and 360 °C to compare yield, carbon-rich composition, and pore development; 320 °C was subsequently selected as a practical processing condition within the investigated range. Mortars with EFB biochar replacement levels ranging from 0 to 11 wt.% of sand were prepared as 50 × 50 × 50 mm cubes and water-cured for 7 and 28 days. At 28 days, the 3% mixture exhibited the highest measured mean compressive strength of 38.3 MPa, compared with 32.3 MPa for the control. Although the mean strength was generally lower at higher replacement levels, a non-monotonic response was observed, with the 9% mixture reaching 35.6 MPa before decreasing markedly at 11% replacement. Density decreased and bulk accessible porosity increased with increasing biochar content. SEM/EDS observations showed carbon-rich biochar-associated regions within the examined mortar fracture surfaces; however, these localized observations do not by themselves establish specific hydration phases, pozzolanic reactions, uniform dispersion, or long-term durability. The environmental contribution discussed in this study is therefore framed as the potential retention of biogenic carbon rather than quantified net carbon sequestration, which would require dedicated lifecycle carbon accounting.

Keywords: EFB; carbonization; cement mortar; biochar; sustainable cement-based materials



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1. Introduction

Biochar has been investigated as an additive or partial constituent in cementitious materials because it can valorize biomass residues while introducing a carbon-rich solid into a durable matrix [1–20]. Previous studies report that its influence depends strongly on feedstock, carbonization condition, particle characteristics, dosage, replacement basis, and curing regime. Biochar has been used either as a cement-related additive/replacement in some studies or as a fine-aggregate replacement in others. These approaches should not be treated as equivalent because they affect mixture chemistry, water demand, and carbon accounting differently.

The present study uses EFB biochar exclusively as a partial replacement for fine aggregate (sand), not as a cement substitute. Therefore, reductions in clinker-related emissions cannot be inferred directly from the present mixture design. The relevant

sustainability benefit considered here is the potential incorporation of biogenic carbon retained in EFB biochar, together with agricultural-waste valorization. Quantification of net CO₂ removal, avoided emissions, carbonation uptake, permanence, and lifecycle performance requires a dedicated carbon-accounting or LCA framework and is outside the direct experimental scope of this work.

Published work suggests that low biochar dosages can improve or maintain mechanical performance in some cementitious systems, whereas higher dosages may reduce workability or strength because of increased porosity, water demand, and interfacial effects [2,6–9,11,18]. Proposed mechanisms include filler or nucleation effects and water retention by porous biochar; however, such mechanisms depend on biochar properties and should not be regarded as confirmed in a particular system without complementary evidence.

A previous study also discussed the use of biochar as a green additive in cement-based materials in relation to carbon dioxide sequestration [14]. However, the present work examines EFB biochar as a sand replacement and does not directly quantify carbon sequestration; this literature is therefore cited only as broader research context.

A research gap remains in linking relatively mild EFB carbonization conditions with commercial-batch production and systematic evaluation of EFB biochar specifically as a sand replacement over a broad low-to-moderate dosage range. In particular, the balance among biochar yield, carbon-rich composition, pore development, cement mortar density, bulk porosity, and compressive strength requires experimental clarification before broader engineering application can be proposed.

Accordingly, this study aims to (1) characterize the thermal decomposition of EFB and compare biochars produced at 280, 320, and 360 °C; (2) select a practical carbonization condition for commercial-batch production based on the available yield, elemental, and morphological observations; (3) evaluate cement mortar containing EFB biochar over a 0–11 wt.% sand-replacement range through density, porosity, and 7- and 28-day compressive-strength tests; and (4) use SEM/EDS observations to describe, rather than overstate, microstructural features at selected fracture surfaces. The study is limited to early-age physical, mechanical, and localized microstructural observations and does not constitute a lifecycle carbon assessment or durability certification.

2. Experimental Procedure

2.1. Methodology for EFB Biochar

2.1.1. Selection of EFB Biochar

According to previously published literature, during carbonization, increasing temperature promotes progressive thermal decomposition of the organic constituents of EFB and the release of volatile gases. The raw EFB material was supplied by Golden Spring Plantation & Axtrium Sdn Bhd. in Kuala Lumpur, Malaysia and originated from palm-oil processing residues without additional treatment before use. The present study evaluates the conversion of this residue into EFB biochar and its subsequent incorporation into cement mortar as a partial replacement for fine aggregate. The overall processing and inspection procedure is illustrated in Figure 1.

2.1.2. Methodology for EFB Biochar and Cement Mortar

Based on the physical and chemical observations obtained at different laboratory carbonization temperatures, a practical processing condition was selected for commercial-batch production. The selection considered biochar yield, observed pore morphology, carbon-rich elemental characteristics, and processing requirements rather than a quantitatively established optimum. Approximately 100 kg of EFB was processed per batch in a commercial small-batch furnace. The resulting EFB biochar was subsequently incorpo-

rated into cement mortar for physical, mechanical, and microstructural evaluation. The commercial-batch processing and specimen preparation procedures are shown in Figure 2.



Figure 1. The process and inspection procedures for processing raw EFB into EFB biochar.

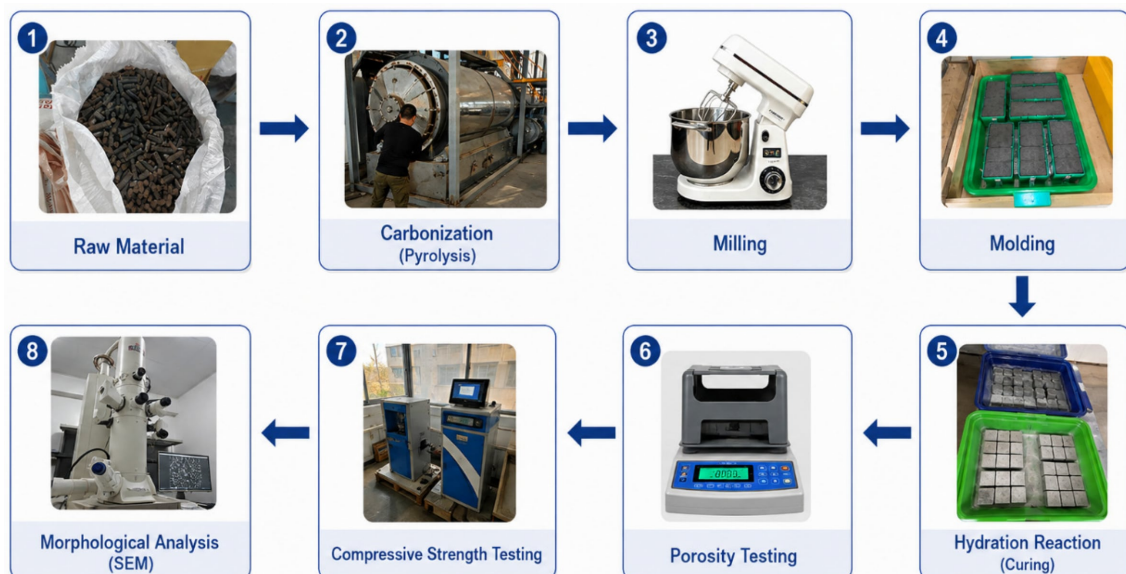


Figure 2. Processing EFB biochar using a commercial small-batch furnace and preparing cement mortar specimens for subsequent physical, mechanical, and microstructural evaluation.

2.2. Materials, Mix Designs and Methods

2.2.1. Materials

Raw EFB was obtained from palm-oil processing operations in Malaysia and was milled before thermal treatment. The EFB was dried at 120 °C for 8 h before subsequent preparation. The cement used for mortar preparation was commercially available Portland Cement Grade I (Xingfu, Lucky Cement, Taipei, Taiwan), and the fine aggregate was Teco Emix DP15 sand (Ruentex Materials Group, Taipei, Taiwan). The present experimen-

tal records do not include a complete XRF composition, particle-size distribution, BET specific surface area, pore-volume distribution, or full proximate/ultimate analysis for all constituents; this incomplete characterization is acknowledged as a limitation when generalizing the observed response.

2.2.2. Preparation of EFB Biochar

Preparation of EFB Biochar in Laboratory for TGA and SEM

For laboratory-scale characterization, EFB was rinsed with 95% ethanol, filtered, dried at 120 °C for 2 h, ground, and passed through a 40-mesh sieve. Approximately 100 g was treated per batch at a heating rate of 10 °C/min to target temperatures of 280, 320, and 360 °C, followed by a 30 min holding period. Nitrogen was supplied during cooling to limit oxidation. The resulting materials were designated 280EBC, 320EBC, and 360EBC. These temperatures bracket the principal decomposition region identified by TGA/DTG and were selected to compare relatively mild thermal-treatment conditions while retaining sufficient biochar yield. For mortar mixtures, EFB biochar replaced sand by mass at 0, 1, 3, 5, 7, 9, 10, and 11%. The broad dosage range was selected to identify the transition from potentially beneficial low additions to performance losses at higher additions, consistent with dosage-dependent behavior reported in the biochar-cement literature [2,6–9,11,18].

Preparation of EFB Biochar in Pilot Plant for Cement Mortar

Previous studies have shown that the thermal-treatment condition of biochar can influence its pore structure and subsequent performance in cementitious materials. On this basis, the present pilot-scale production adopted a relatively mild carbonization condition. The 320 °C condition was treated as an operational compromise based on yield, observed morphology, and processing considerations, rather than as a quantitatively demonstrated optimum or as evidence of superior carbon characteristics.

EFB pellets from the continuous dryer were processed in an MJ-12 batch furnace. Approximately 100 kg of EFB was loaded into the carbonization chamber for each batch. The furnace was operated under negative pressure, and the temperature was increased at approximately 100 °C/h. After the chamber temperature exceeded approximately 120 °C, moisture removal became evident. The carbonization temperature was controlled within the investigated range, followed by a holding period of approximately 1–2 h and cooling for approximately 3–4 h. The commercial-batch trials produced approximately 22–25 kg of EFB biochar per 100 kg of feedstock. These operating conditions are reported as practical processing parameters for the present study and should not be interpreted as a universally optimized carbonization protocol.

2.3. Mix Designs

Cement mortar mixtures were prepared with EFB biochar replacing fine aggregate (sand) by mass, with replacement levels ranging from 0 to 11 wt.% of the sand fraction. Cement (Portland Cement Grade I), sand (Teco Emix DP15), and the required EFB biochar were weighed and dry-mixed before water was introduced. This study was conducted as a pre-commercial pilot investigation linked to ongoing industrial scale-up. Detailed water-adjustment and batching procedures form part of the collaborating company's proprietary process know-how and ongoing patent-related development in Southeast Asia and therefore cannot be disclosed in full. We acknowledge that mixing water is a critical parameter and that the absence of complete batch proportions, effective water-to-cement ratio, biochar absorption, and workability data limits reproducibility and mechanistic interpretation. Accordingly, the results and conclusions are restricted to observations from the specific cement mortar system tested here and should not be interpreted as universal mixture-design recommendations.

2.4. Casting and Curing

Mortar was cast into 50 × 50 × 50 mm molds following the laboratory casting procedure. Cement, sand, and EFB biochar were premixed, water was then introduced, and the mixture was mechanically mixed for approximately 3 min. The fresh mortar was placed in molds treated with release agent and consolidated using rodding and vibration to reduce entrapped air. Specimens were kept at room temperature for 24 h, demolded, and water-cured at approximately 25 °C until testing at 7 or 28 days. At least ten specimens were prepared for each formulation and divided between the two curing ages. Because workability and effective water-to-cement ratio were not systematically measured, interpretations involving internal curing are treated only as plausible mechanisms and not as experimentally confirmed effects.

2.5. Testing Procedures

2.5.1. Density of EFB Biochar-Based Cement Mortar Cubes

The density of the cement mortar containing EFB biochar was determined in accordance with ASTM C642-13 [21]. The mass (M) and volume (V) of each cube were measured, and density was calculated using the following equation:

$$\text{Density} = \frac{M}{V}$$

To ensure the credibility of the experimental data, the MH-300 electronic density meter (Hangzhou Jingfei Instrument Technology Co., Ltd., Hangzhou, China) was used for double check, with its design based on the ASTM D792, ISO1183, C188, and GB/T 208 standard methods.

2.5.2. Porosity

After the compressive-strength test, crushed cement mortar samples were immersed in water for 24 h and then covered with commercially available plastic wrap to determine the wet mass (A). The samples were subsequently immersed in a 1:1 acetone/alcohol solvent mixture for 24 h, removed, and oven-dried at 150 °C for 8 h to determine the dry mass (B) [21]. The porosity of the EFB biochar-based cement mortar cubes was calculated using the following equation:

$$\text{Porosity \%} = \left(\frac{(A - B)}{A} \right) \times 100\%$$

To ensure the credibility of the experimental data, the MH-300 electronic density meter was used for comparison, with its design based on the ASTM D792, ISO1183, C188, and GB/T 208 standard methods.

2.5.3. Compressive Strength Test of Cement Mortar

The cement mortar specimens were tested for compressive strength in accordance with the AS 1012.9 (2014) testing standard using an ELE International (Milton Keynes, United Kingdom) material testing system (model 36-5125/02). The same loading conditions were applied to each specimen, with a loading rate of 4.90 MPa/s.

Compressive strength was determined using 50 × 50 × 50 mm cement mortar cubes containing EFB biochar as a partial sand replacement. Replacement levels ranging from 0 to 11 wt.% were investigated in the experimental program. Compressive strength was calculated from the applied failure load divided by the loaded cross-sectional area, as follows:

$$\text{Compressive strength} = \text{Load} / \text{Cross sectional area}$$

2.5.4. SEM Analysis

SEM observations were performed using an FEI Quanta 200E instrument. EFB biochars produced at different temperatures were examined at representative magnifications to compare surface morphology. For mortar, fragments were collected from fracture regions after 7- and 28-day compressive-strength testing and examined to describe observable matrix, pore, and biochar-associated features. The available experimental record does not document all operating parameters (e.g., accelerating voltage and working distance) for every image; therefore, only recorded instrument and specimen-preparation information is reported.

2.5.5. EDS Analysis

EDS was used together with SEM for localized elemental analysis of EFB biochar and selected mortar fracture regions. For the 320EBC mortar observations, spectra were obtained at selected spots and elemental maps were used qualitatively to identify carbon-rich and cementitious regions. Because EDS is spatially local and only a limited number of mortar locations were examined, the results are not used to claim representative bulk dispersion or to quantify hydration reactions throughout the specimen.

3. Experimental Results and Discussion

3.1. Material Properties

3.1.1. Thermo-Gravimetric Analysis of EFB Raw Material

Thermo-gravimetric analysis of EFB raw material was carried out using Perkin Elmer STA8000 equipment in a N₂ environment at N₂ flow rate of 20 mL/min. The TGA and differential thermogravimetric (DTG) mass loss curves of EFB are shown in Figure 3.

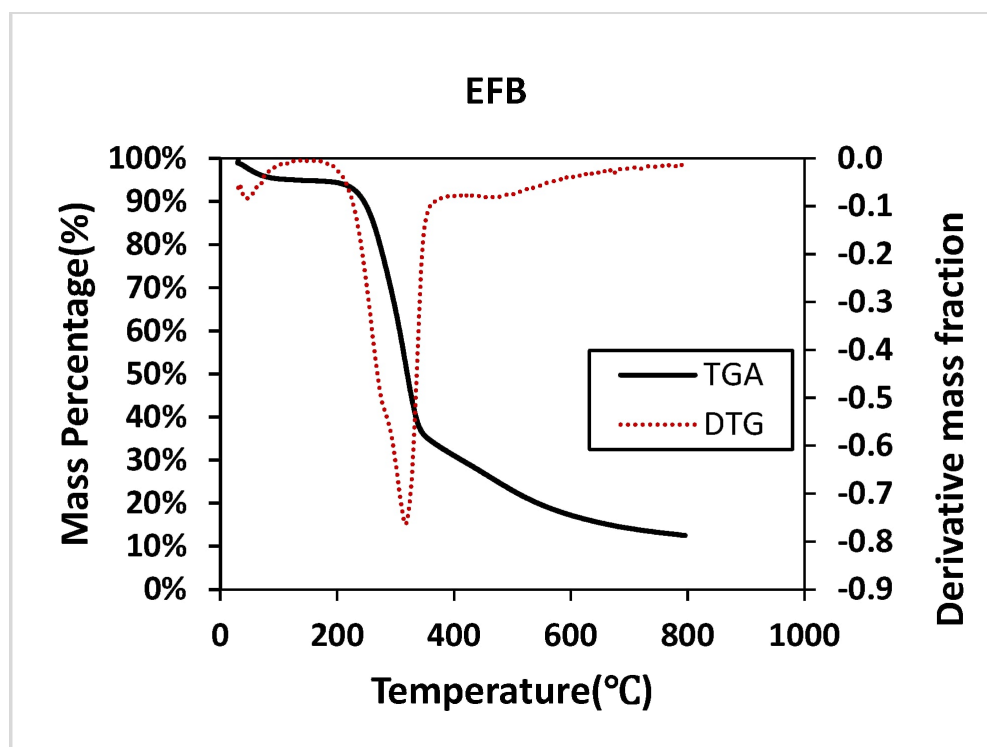


Figure 3. TGA & DTG analysis of EFB raw material.

General plant materials, primarily composed of cellulose, hemicellulose, and lignin, exhibit typical multistage behavior during thermal decomposition. At approximately 50–200 °C, moisture removal and mild volatile release occur. Between approximately 200

and 400 °C, substantial decomposition of hemicellulose and cellulose occurs and the major mass-loss region is observed. Above approximately 400 °C, slower decomposition and carbonization of lignin continue.

From the TGA curve, it was determined that the sample experienced mild weight loss before 200 °C; the main weight loss stage between 200–350 °C; and continued slow weight loss after 350 °C, with about 28% residual at 500 °C and around 12% at 800 °C.

From the DTG curve, the principal decomposition peak occurred at approximately 330–350 °C, with a distinct shoulder near 250 °C indicating the onset of substantial hemicellulose decomposition. These observations show that EFB begins to undergo pronounced thermal decomposition at relatively low temperatures. The selected 280–360 °C carbonization range therefore spans the main low-to-moderate temperature transformation region identified by TGA/DTG.

3.1.2. SEM Analysis of EFB Biochar Produced at 280, 320 and 360 °C

SEM analysis was performed on EFB biochar produced by carbonization at 280, 320, and 360 °C (280EBC, 320EBC, and 360EBC) using an FEI Quanta 200E SEM at 250×, 500×, and 1000× magnifications to compare surface morphology. Increasing carbonization temperature was accompanied by progressively more developed porous features in the examined particles. Representative SEM images at the three carbonization temperatures are shown in Figure 4.

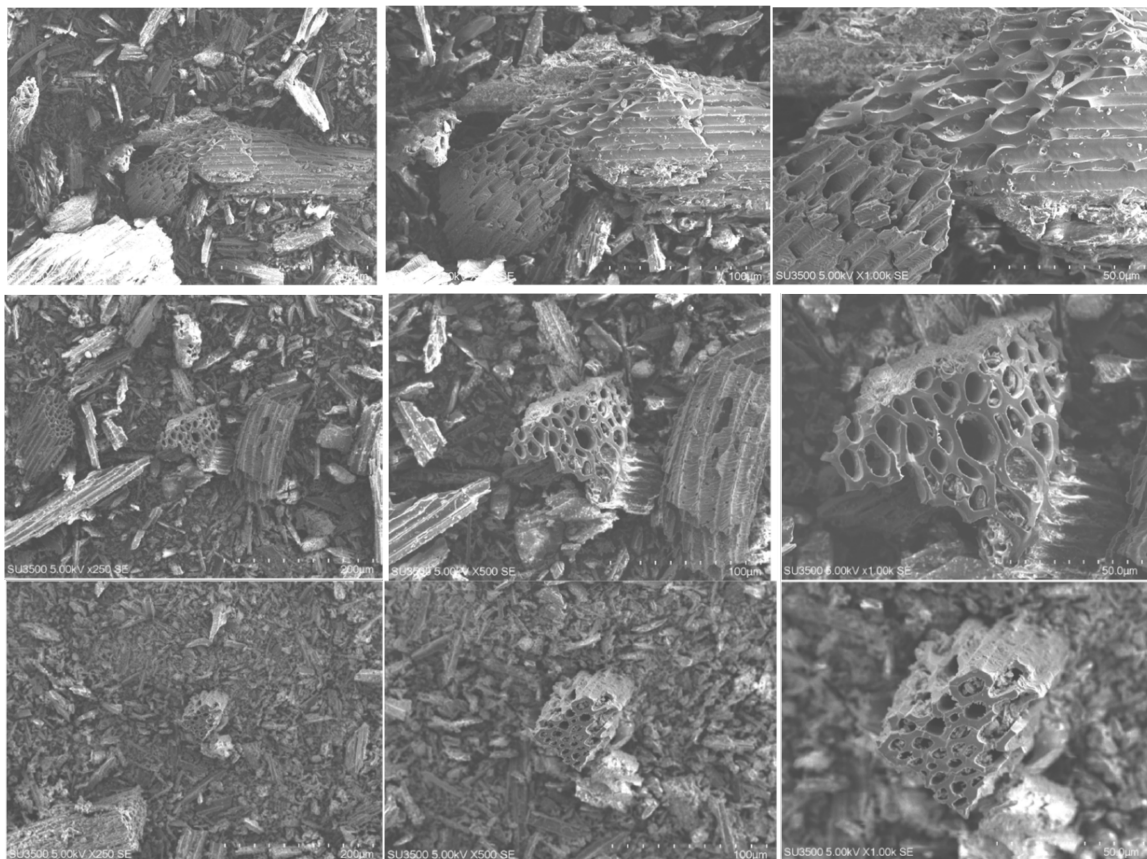


Figure 4. SEM images of EFB biochar for 280EBC, 320EBC and 360EBC (from **up** to **down**) at 250×, 500× and 1000× (from **left** to **right**) magnification levels.

The EFB raw materials were calcined at temperatures of 280 °C, 320 °C, and 360 °C, respectively, resulting in a decrease in biochar yield as the temperature rose, with yields of 31.3%, 27.8%, and 18.9%, respectively.

280EBC retained comparatively high structural integrity. At 250 $\times$, a distinct fibrous tissue structure remained visible, preserving much of the macroscopic morphology of the original EFB. The fiber surface showed limited cracking or collapse, while at 1000 $\times$ a wrinkled texture associated with dehydration and shrinkage could be observed. The pore structure appeared less developed than in the higher-temperature samples. These observations are consistent with relatively mild carbonization and partial preservation of the original plant tissue structure.

320EBC showed more pronounced structural transformation. At 250 $\times$, the fiber edges became irregular, with visible shrinkage, increased surface roughness, fine cracks, and depressions. At 1000 $\times$, additional pores and localized cell-wall disruption were observed. These morphological changes are consistent with increased volatile release within the principal thermal-decomposition region. The observations support the use of 320 °C as a practical intermediate carbonization condition, but SEM alone does not quantify specific surface area or adsorption performance.

360EBC showed the greatest morphological disruption among the examined conditions. The original fibrous structure was less distinct, while a more developed three-dimensional porous skeleton and fragmented features were observed. These changes are consistent with more extensive thermal decomposition and volatile release at the higher carbonization temperature. The SEM observations describe morphology only and do not independently establish changes in specific surface area or adsorption capacity.

3.1.3. EDS Analysis of 280EBC, 320EBC and 360EBC

While detecting SEM (FEI Quanta 200E), the electron beam illuminates the sample and emits characteristic X-rays. The EDS detector measures the energy of these X-rays using either a silicon drift detector (SDD) or a lithium drift silicon detector (LSD), identifying the types of elements and quantitatively analyzing their content. It can quickly identify the elements contained in sample micro zones, calculate the weight percentages of each element relative to their atomic percentages, display the distribution of specific elements in two-dimensional space, and analyze changes in element concentrations along specific paths. Representative EDS results for the three biochar samples are presented in Figure 5.

EDS measurements were collected from multiple surface locations of biochars produced at the three temperatures. The measured carbon ranges for 280EBC, 320EBC, and 360EBC were approximately 75.8–80.7, 74.4–79.6, and 74.3–79.8 wt.%, respectively, while oxygen varied correspondingly across the examined locations. Because these ranges overlap and EDS is a localized surface technique, the data do not establish a monotonic bulk-carbon trend with carbonization temperature. Instead, they confirm that all three products contained carbon-rich regions together with oxygen and minor mineral elements.

The EDS overlay for 280EBC showed carbon- and oxygen-bearing regions across the examined fibrous surface. The localized oxygen signal was relatively prominent at some measured locations. These observations are consistent with a comparatively mild carbonization condition; however, EDS alone cannot identify specific oxygen-containing functional groups or establish adsorption behavior. The preserved fibrous morphology is consistent with partial retention of the original EFB structure.

The EDS overlay for 320EBC showed carbon-rich regions together with oxygen and minor inorganic elements such as Si, Mg, K, and P. Potassium appeared locally in a point-like distribution and may be associated with mineral constituents of the original biomass. Because the measured carbon ranges overlapped among the three carbonization temperatures, the 320 °C condition should not be interpreted as having quantitatively superior carbon characteristics. The condition was instead selected as a practical intermediate treatment based on the combined yield, morphology, and processing observations.

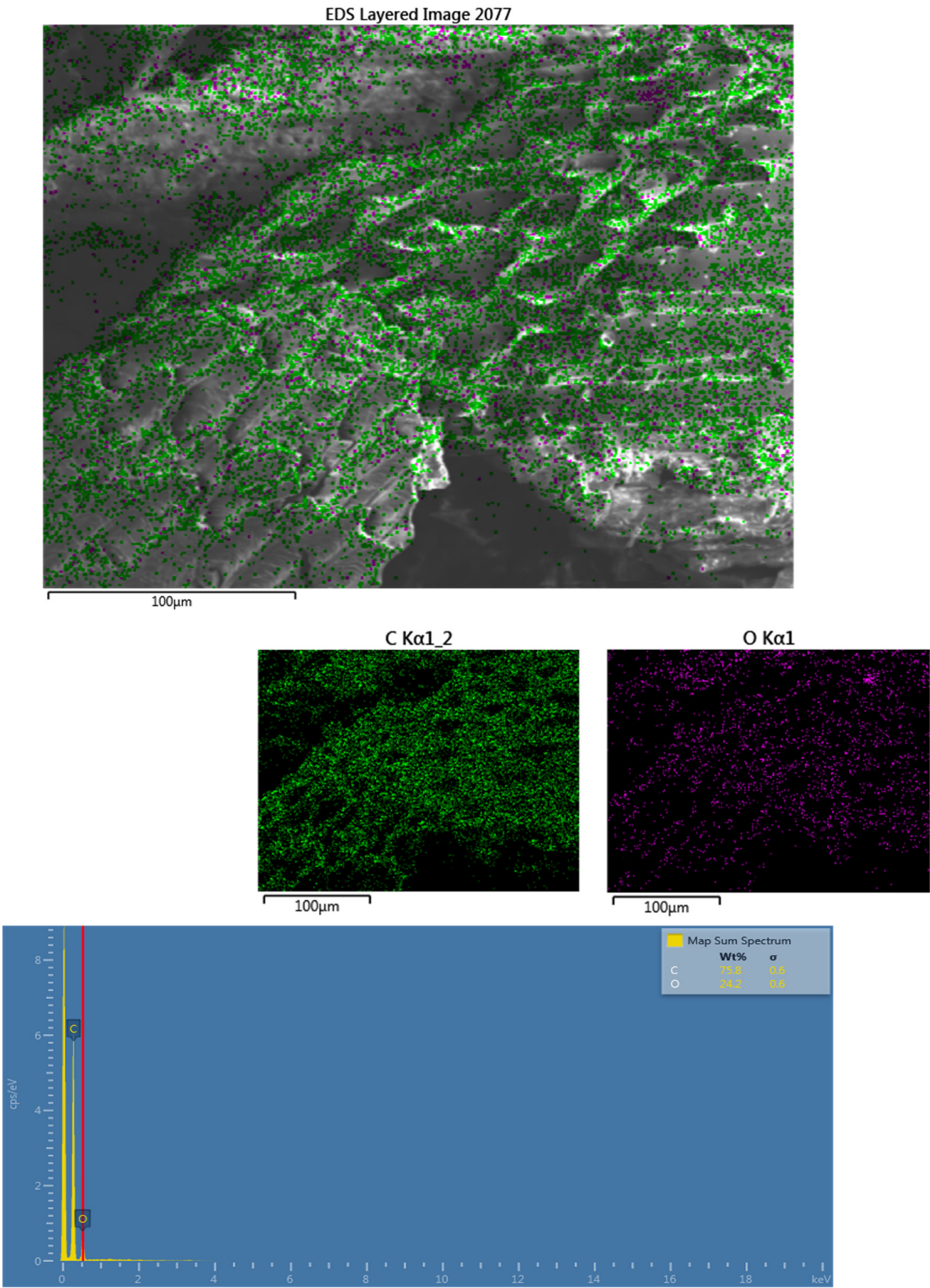


Figure 5. Cont.

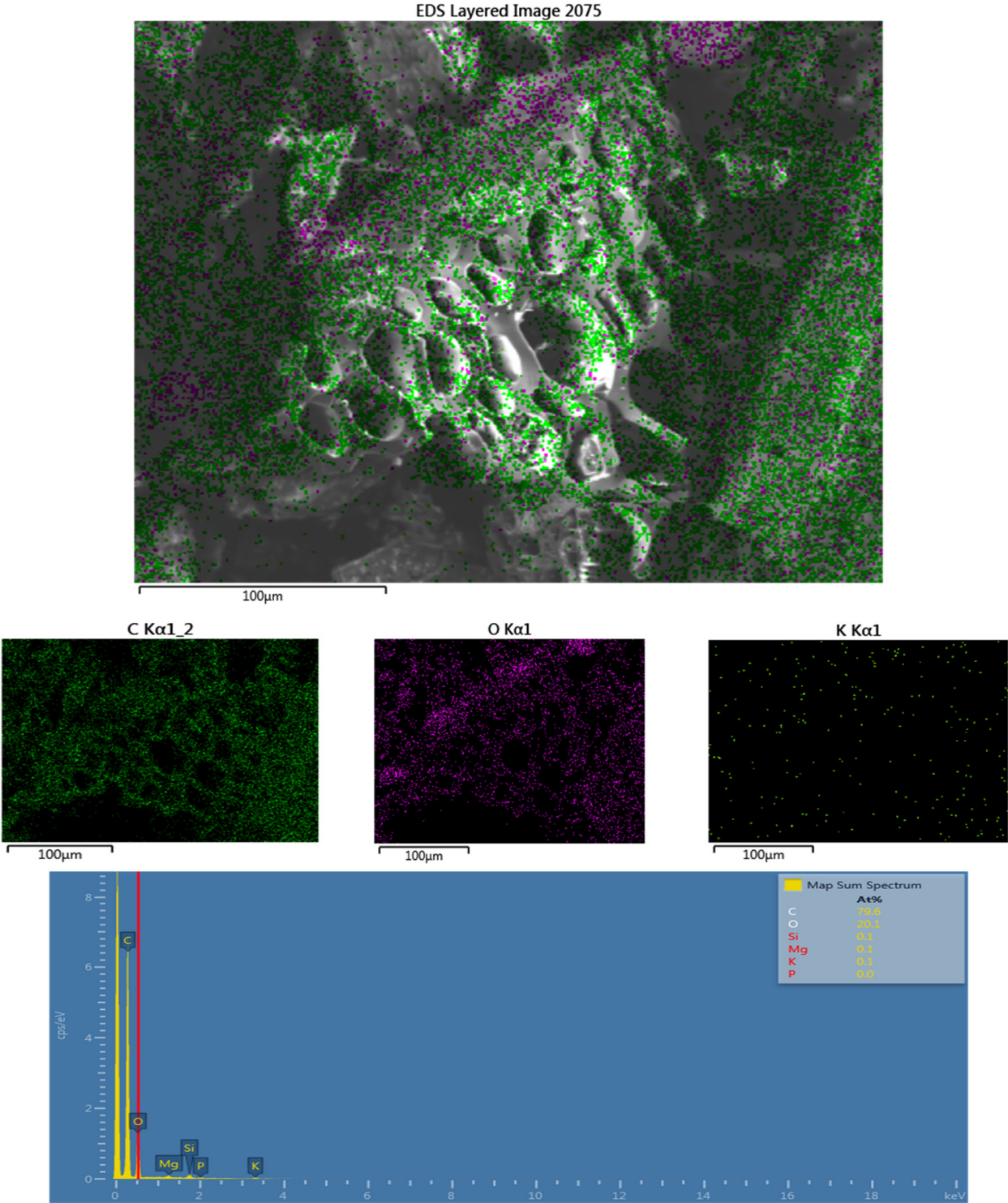


Figure 5. Cont.

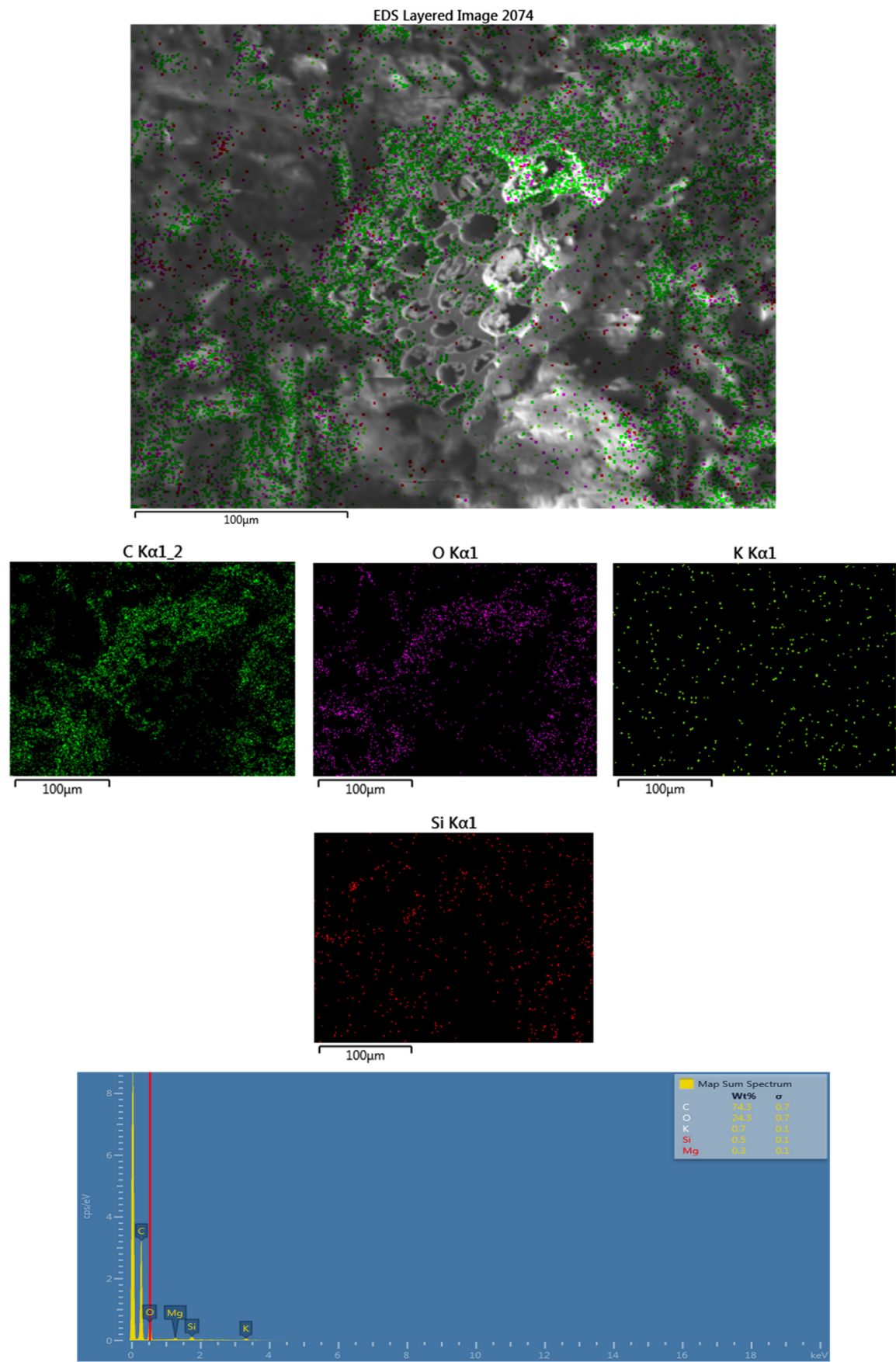


Figure 5. Typical EDS images of EFB biochar for 280EBC, 320EBC and 360EBC at 1000× magnification levels.

The EDS overlay for 360EBC showed carbon-rich regions together with oxygen and localized mineral-element signals, including potassium and silicon. The examined surface also exhibited more developed pore morphology than the lower-temperature samples. These localized EDS observations do not establish a monotonic change in bulk carbon content with carbonization temperature, nor do they uniquely identify specific mineral phases. They are therefore interpreted together with the yield and SEM observations rather than as proof of superior carbonization.

Considering the laboratory yield, carbon-rich EDS observations, pore morphology, and the objective of using a relatively mild processing temperature, 320 °C was selected for subsequent commercial-batch production as a balanced operational compromise within the investigated range. This selection does not represent a quantitatively proven optimum or evidence of superior bulk carbon content. The commercial batch furnace processed approximately 100 kg EFB per batch and produced approximately 22–25 kg biochar in the reported trials.

3.2. Cement Mortar Properties

3.2.1. Density Results of EFB Biochar-Based Cement Mortar Cubes

The 320EBC condition was selected for subsequent cement mortar experiments as a practical compromise based on biochar yield, observed pore morphology, carbon-rich elemental characteristics, and commercial-batch processing considerations. Because laboratory-scale production was insufficient to provide the quantity required for the mortar program, a commercial small-batch furnace was used, with approximately 100 kg EFB feed per batch and approximately 22–25 kg EFB biochar produced.

The 320EBC biochar was incorporated into cement mortar as a partial replacement for sand. Replacement levels ranging from 0 to 11 wt.% were investigated in the experimental program, and the specimen codes followed the corresponding EFB biochar replacement level.

The density of the cement mortar containing 320EBC biochar was determined in accordance with ASTM C642-13 after 28 days, as shown in Figure 6.

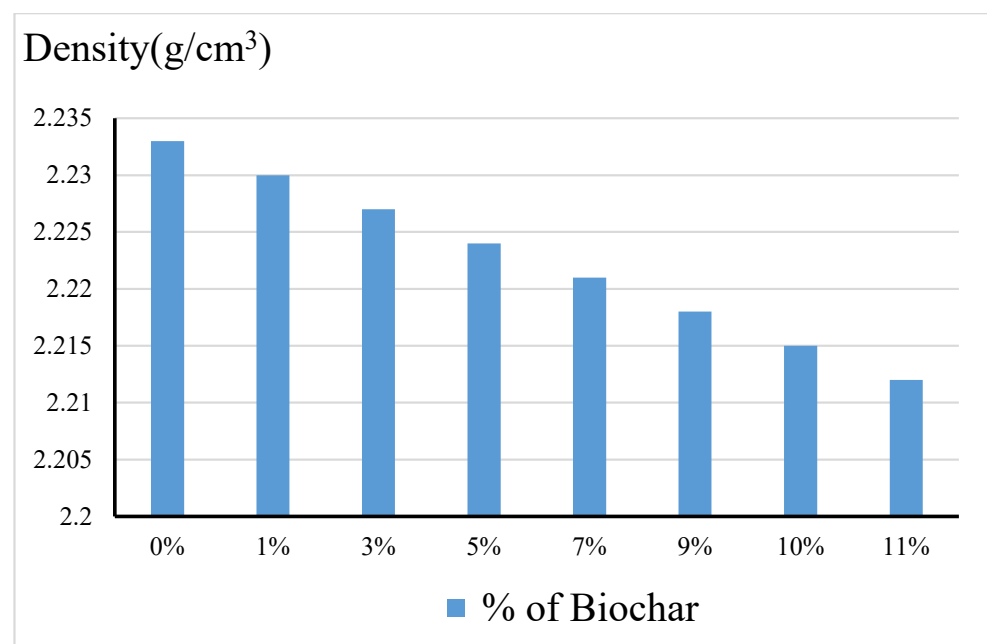


Figure 6. Density of biochar-based cement mortar cubes.

At 28 days, cement mortar density generally decreased as EFB biochar content increased. The reported mean values available in the retained dataset were approximately 2.229 g/cm³ for the control and 2.227, 2.224, 2.221, 2.218, 2.215, and 2.212 g/cm³ for the reported biochar-containing groups. Each reported mean was based on five specimens, with a relative standard deviation below 0.4%. Because the retained dataset does not provide a separately traceable numerical density value for every nominal replacement level in the 0–11 wt.% experimental range, no missing value was reconstructed. The observed trend is specific to the tested cement mortar system.

3.2.2. Porosity of EFB Biochar-Based Cement Mortar Cubes

The porosity of the hardened cement mortar was evaluated with reference to ASTM C642-13 and ISO 5017 procedures. The results are presented in Figure 7.

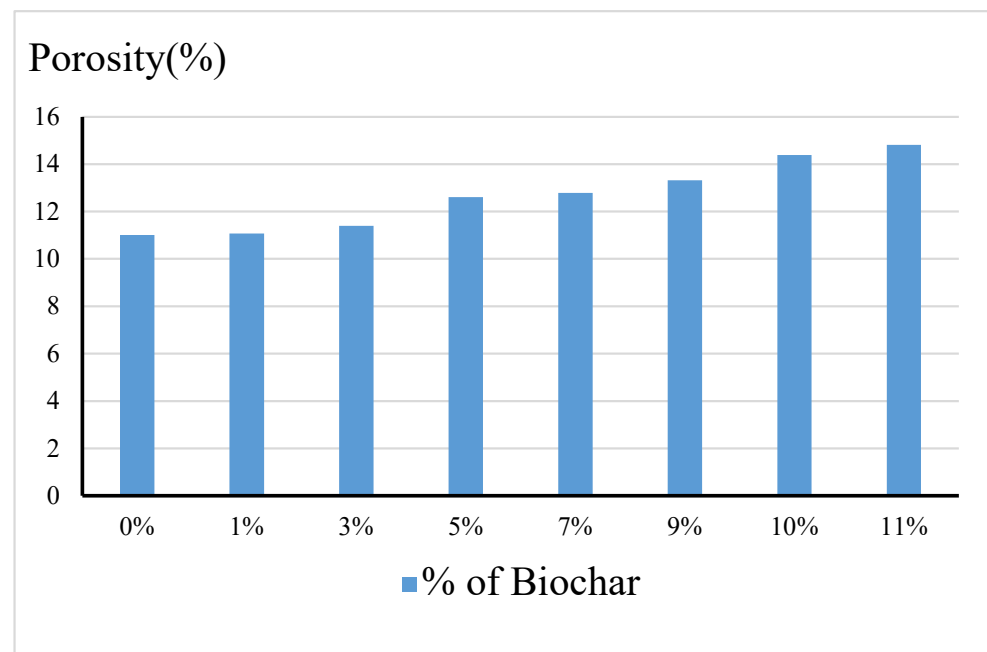


Figure 7. Porosity of biochar-based cement mortar cubes.

After 28 days, bulk accessible porosity increased with increasing EFB biochar dosage. The measured values reported for the biochar-containing groups were approximately 11.71, 11.74, 12.76, 13.42, 14.53, 14.92, and 16.30%, compared with approximately 11.66% for the control. Each mean was based on five specimens, with the reported relative standard deviation below 0.4%. This result is consistent with the porous nature of EFB biochar and directly contradicts any general claim that increasing biochar reduces the bulk porosity of the mortar. Localized densification at a particular biochar–matrix interface, if present, should therefore be distinguished from the measured bulk accessible porosity.

3.3. Effect of 320EBC on Cement Mortar Properties

3.3.1. Mechanical Strength of EFB Biochar-Based Cement Mortar Cubes

Compressive strength was evaluated at 7 and 28 days for cement mortar containing 320EBC as a sand replacement. The overall experimental replacement range was 0–11 wt.%; Figure 8 presents the retained compressive-strength results for 0, 1, 3, 5, 7, 9, and 11% replacement. The corresponding 28-day mean strengths were 32.3, 36.6, 38.3, 37.0, 32.2, 35.6, and 19.9 MPa, respectively. The previously reported value of 25.6 MPa for the 9% mixture was a transcription error; the original experimental value is 35.6 MPa, consistent with Figure 8. The 3% mixture therefore had the highest measured mean 28-day compressive

strength among the reported groups. Because specimen-level data sufficient for formal statistical testing were not retained, this result is described as the highest observed mean rather than a statistically established optimum. A separately traceable compressive-strength result for the 10% formulation was not available in the retained dataset, and no value was reconstructed or interpolated.

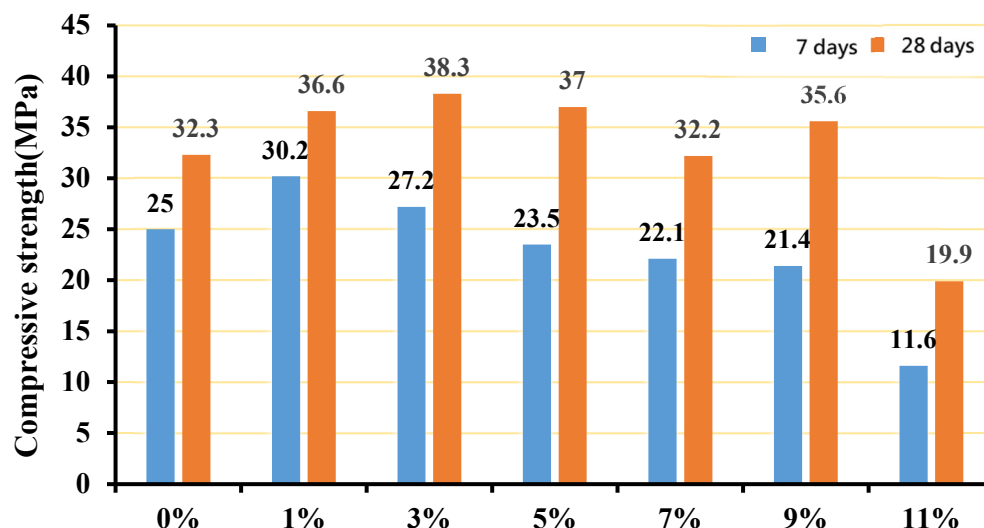


Figure 8. Compressive strength results of 320EBCs.

At 7 days, the available mean strengths for 0, 1, 3, 5, 7, 9, and 11% replacement were approximately 25.0, 30.2, 27.2, 23.5, 22.1, 21.4, and 11.6 MPa, respectively. At 28 days, the highest observed mean occurred at 3% replacement. Although the mean strength was generally lower at higher replacement levels, the response was non-monotonic: the 9% mixture reached 35.6 MPa before the strength decreased markedly to 19.9 MPa at 11%. The 7% result (32.2 MPa) was close in magnitude to the control (32.3 MPa), but statistical equivalence was not established. Accordingly, the results are interpreted only as observed differences in group means for the tested cement mortar system.

Porous biochar can retain water, and previous studies have proposed water release/internal curing as one possible explanation for changes in cementitious performance [2,21–23]. In the present work, however, biochar absorption, effective water-to-cement ratio, and workability were not systematically measured. Internal curing is therefore discussed only as a plausible literature-supported mechanism. Replicate specimens were prepared for each formulation, but the available manuscript dataset does not provide specimen-level compressive-strength values sufficient for a defensible ANOVA/post hoc analysis. Accordingly, the revised interpretation emphasizes measured group means and avoids claims of statistical optimality.

3.3.2. SEM Analysis of 320EBC7 Cement Mortar

Figure 8 shows that the 3% mixture had the highest measured mean 28-day compressive strength. SEM/EDS observations were nevertheless performed on a 320EBC7 cement mortar fracture specimen as a representative higher-dosage mixture whose 28-day mean strength was close to the control. These localized observations are used only to describe visible microstructural features and should not be interpreted as proof of the mechanisms responsible for the 3% strength maximum.

At the examined fracture surface, SEM revealed a heterogeneous cement mortar matrix containing pores, plate-like and irregular morphologies, and porous particles attributable to EFB biochar. Morphology alone cannot uniquely identify C-S-H, portlandite, CaCO_3 , or other hydration products. The SEM images are therefore interpreted descriptively.

Any phase-specific interpretation or reaction mechanism would require complementary characterization such as XRD and TGA/DTG of hydrated specimens. Representative fracture-surface morphology at 1000 $\times$ magnification is shown in Figure 9.

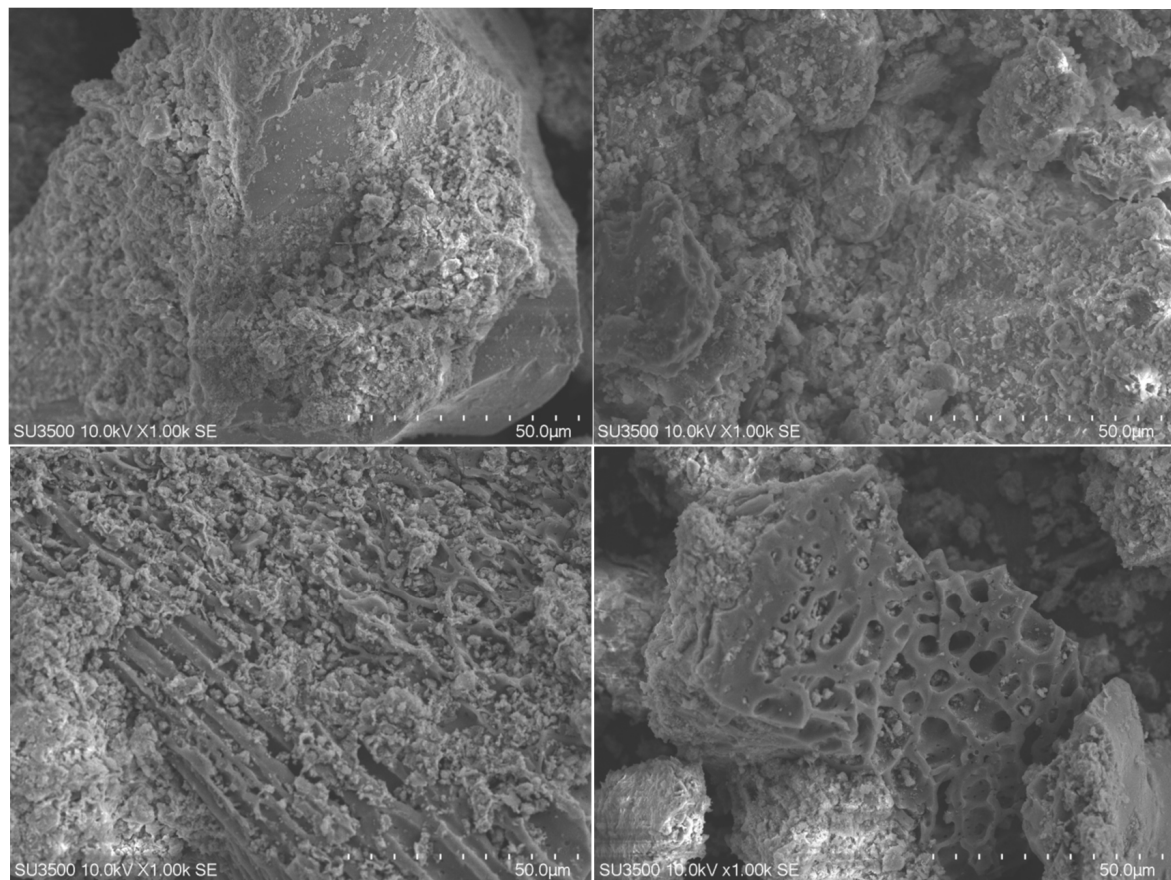


Figure 9. Typical SEM of 320EBC7 at 1000 $\times$ magnification levels.

Some examined regions contained blocky or plate-like features together with porous EFB biochar particles that were embedded in, or partially exposed from, the cement mortar matrix. These features are described only in terms of morphology. Their chemical or mineralogical identity cannot be confirmed from the SEM images alone.

At higher magnification, the fracture surface showed locally compact and porous regions around the cement mortar matrix and EFB biochar. Such morphology may be consistent with physical filling, heterogeneous nucleation, or localized interfacial effects reported in previous studies; however, the present SEM images do not demonstrate pozzolanic activity, portlandite consumption, additional C-S-H formation, or carbonate formation. These possible mechanisms therefore remain hypotheses for future verification rather than confirmed reactions in the present study. Additional SEM observations at 2000 $\times$ magnification are shown in Figure 10.

Plate-like, angular, and irregular features were observed locally at higher magnification. Because SEM morphology is not phase-specific, these features are not assigned to portlandite, C-S-H, CaCO_3 , or other individual phases in the present study. Complementary XRD and hydrated-specimen TGA/DTG would be required to verify phase identity and any associated reaction mechanisms.

The SEM observations indicate that EFB biochar can be embedded within the cement mortar matrix and that local morphology varies around the examined fracture regions. These local features should not be generalized as a reduction in overall porosity because the bulk porosity measurements increased with biochar dosage. More detailed characterization

of the biochar–matrix interfacial transition zone using higher-resolution imaging, systematic mapping, XRD, and hydrated-specimen TGA/DTG would be needed to establish any underlying reaction mechanisms.

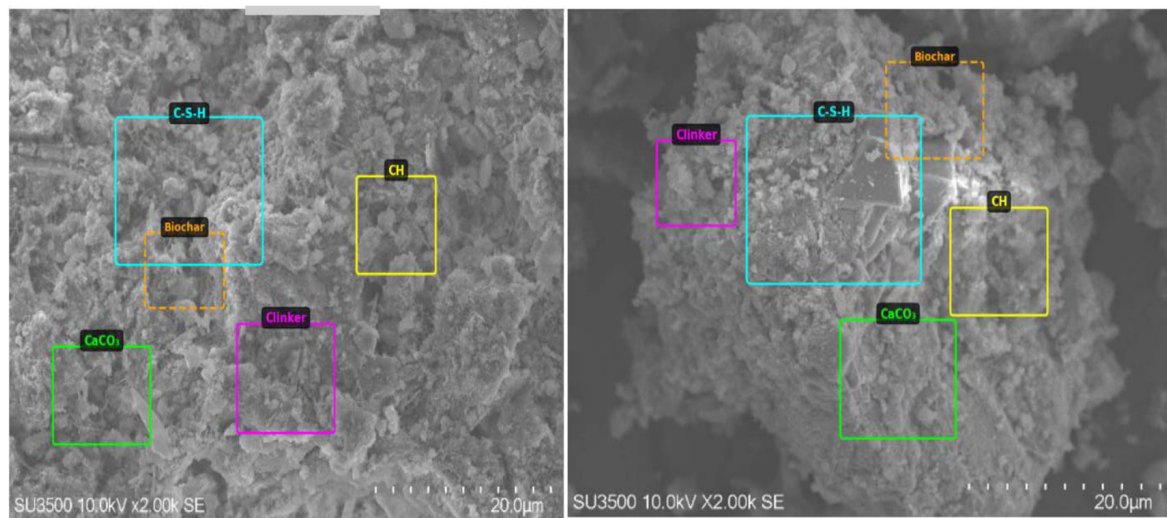


Figure 10. Typical SEM of 320EBC7 at 2000× magnification levels.

3.3.3. EDS Analysis of 320EBC7 Cement Mortar

Energy-dispersive X-ray spectroscopy (EDS) was conducted at two selected sampling spots (Spot 1 and Spot 2) within a fracture region of 320EBC7 cement mortar after compressive-strength testing at 1000× magnification.

The two examined spots contained O, C, Ca, Si, and minor K, Al, Fe, Mg, and S signals. These measurements describe local elemental composition only. Oxygen, calcium, and silicon are common constituents of hydrated cementitious regions, but EDS alone cannot uniquely identify C-S-H, portlandite, unhydrated calcium silicates, or other mineral phases. The carbon signal is consistent with the presence of carbon-rich EFB biochar at the examined fracture locations. Minor K, Al, Fe, Mg, and S signals may originate from cementitious constituents and/or biochar ash. Platinum peaks resulted from the conductive coating used for SEM-EDS preparation and were excluded from interpretation of the specimen composition.

Elemental mapping showed Ca- and O-bearing regions across the examined field, heterogeneous carbon distribution, localized Si-rich regions, and scattered K- and S-bearing points. These maps are interpreted as spatial distributions of elements only; they are not used to assign specific hydration products or mineral phases. The heterogeneous carbon signal is consistent with localized biochar-containing regions within the examined cement mortar fracture surface. The corresponding EDS spectra and elemental maps are presented in Figure 11.

The EDS results show that the two examined fracture locations contained oxygen, calcium, silicon and carbon-bearing regions consistent with a cement mortar matrix containing EFB biochar. The carbon signal supports the presence of biochar at those locations. However, EDS alone cannot uniquely identify specific hydration products, and observations from only two spots cannot establish uniform biochar dispersion throughout the cement mortar. Representative dispersion and phase identification would require systematic elemental mapping over multiple fields and independent specimens together with complementary analytical techniques.

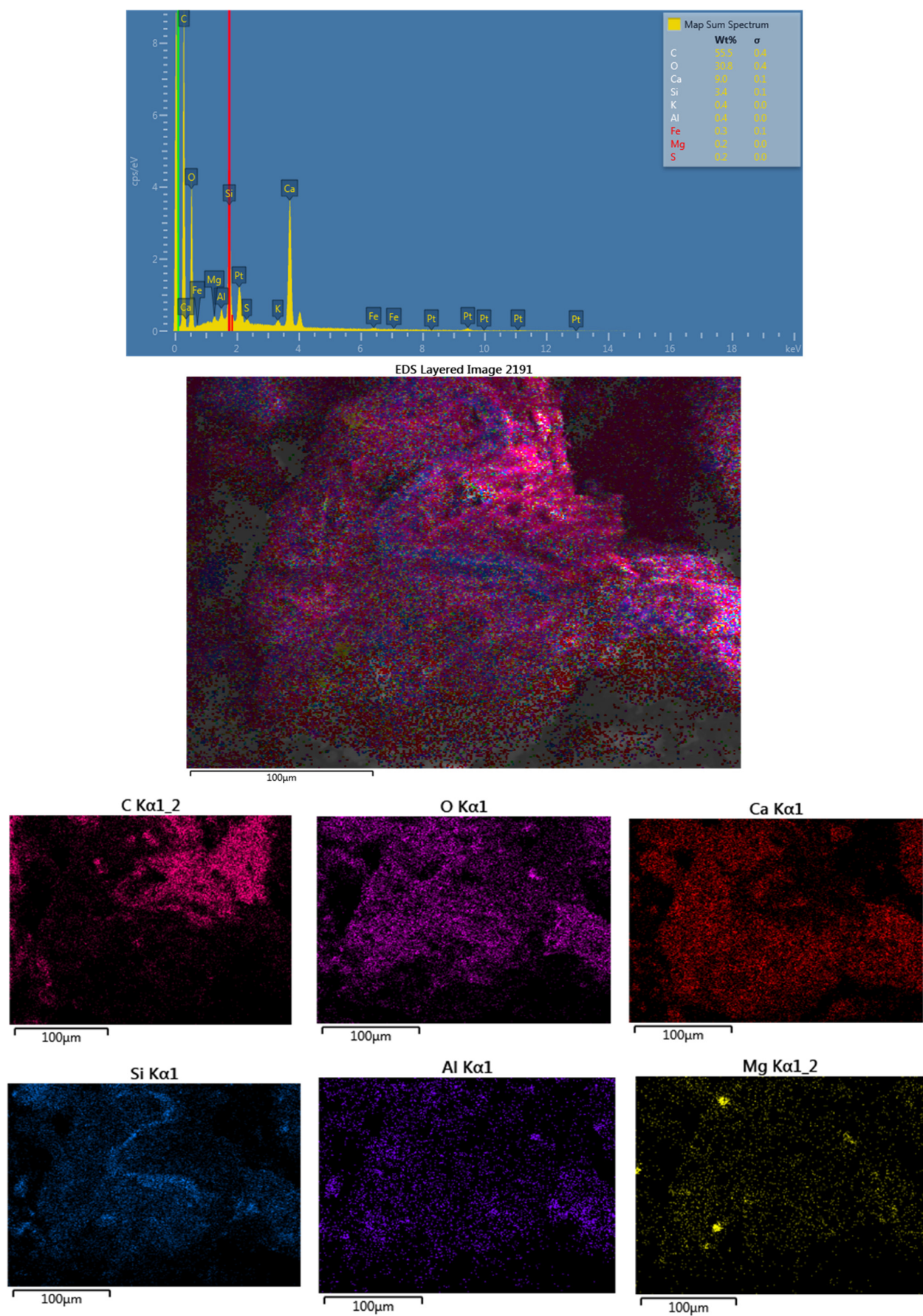


Figure 11. Cont.

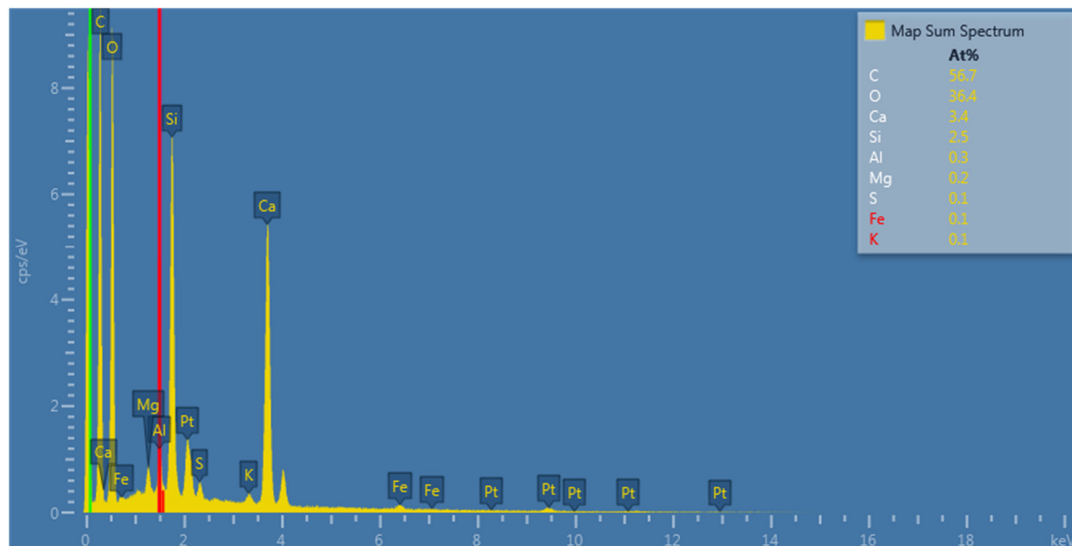


Figure 11. Typical EDS images of 320EBC7 at 1000× magnification levels.

4. EFB Biochar for Southeast Asian Construction: Scenario-Based Outlook

EFB biochar offers a potentially useful pathway for coupling agricultural-residue valorization with lower-density cement mortar materials in Southeast Asia. The present experiments demonstrate only the engineering response of cement mortar containing EFB biochar as a sand replacement; they do not directly quantify net CO₂ removal, avoided clinker emissions, carbonation uptake, carbon-credit eligibility, or lifecycle greenhouse-gas performance. Consequently, regional decarbonization implications should be interpreted as a scenario-based outlook grounded in prior literature rather than as a direct experimental outcome of this study. Future scale-up should combine standardized biochar characterization, moisture/workability control, long-term durability testing, and a transparent carbon-accounting framework that separately considers biogenic carbon storage, carbonization energy and emissions, transport, carbonation, and end-of-life behavior. Compliance with standards such as ASTM C595 or EN 197-1 cannot be inferred from the present cement mortar tests and would require dedicated standard-specific validation. Within these limitations, commercial-batch conversion of EFB to biochar and its use as a fine-aggregate replacement merits further investigation as a circular-economy strategy for construction materials.

5. Conclusions

The main conclusions are as follows: (1) EFB carbonization at 280, 320, and 360 °C produced biochar yields of 31.3, 27.8, and 18.9%, respectively; 320 °C was selected as a balanced operational compromise within the investigated range rather than as a quantitatively demonstrated optimum. (2) EFB biochar was used as a partial replacement for sand in cement mortar, not as a cement substitute. (3) At 28 days, the 3% mixture produced the highest observed mean compressive strength of 38.3 MPa, compared with 32.3 MPa for the control. The higher-dosage response was non-monotonic, with the 9% mixture reaching 35.6 MPa before a marked decrease at 11% replacement. Because specimen-level data sufficient for formal statistical testing were not retained, these results represent observed mean differences rather than statistically demonstrated improvement. (4) Density generally decreased and bulk accessible porosity increased with increasing biochar dosage in the tested system. (5) SEM/EDS identified biochar-associated morphology and carbon-bearing regions at selected fracture surfaces, but the available observations do not uniquely identify hydration phases, prove pozzolanic reactions, or establish uniform dispersion. (6) The carbon-related contribution of this study is therefore described as the potential for biogenic

carbon retention; verified net carbon sequestration would require dedicated lifecycle carbon accounting and permanence assessment.

The study is limited by the absence of complete constituent characterization (e.g., XRF, BET surface area, pore-volume distribution, and full proximate/ultimate analysis), publicly disclosed batch-by-batch water-adjustment information, biochar water absorption, workability, effective water-to-cement ratio, specimen-level compressive-strength data for formal significance testing, and long-term durability measurements. Detailed batching and water-adjustment procedures are associated with the collaborating company's proprietary process development and are not disclosed in full. Future work should include systematic ITZ/elemental mapping, XRD and hydrated-specimen TGA/DTG, sorptivity/permeability, carbonation and chloride resistance, long-term strength, and study-specific lifecycle carbon assessment. These limitations restrict generalization beyond the tested early-age cement mortar system.

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Conflicts of Interest: Author S.-J.L. was employed by the company Berachah Trading Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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