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Characterization of construction and demolition wastes for valorization as raw materials resource

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Abstract: Construction and Demolition Waste (C&DW) comprises a heterogeneous mixture of materials, including concrete, brick, marble, tile, asphalt, mortar, and plaster. Since concrete is the most widely used man-made material, and cement production remains a primary source of global CO_2 emissions, recycling of C&DW as secondary raw materials is essential for advancing the circular economy and preserving natural resources. While C&DW is generally utilized as filler, road base, or aggregate, the sequestration of CO_2 to produce recycled carbonated aggregate (RCA) has gained importance. However, effective valorization depends on comprehensive chemical and mineralogical characterization. In this study, C&DW from an earthquake waste disposal site in Malatya (Türkiye) was characterized by utilizing XRD, XRF, ICP, elemental (CHNS), Mineral Liberation Analysis (MLA), and TGA/DTA analysis techniques. XRF results indicated a complex composition primarily dominated by calcium carbonate (39.87% CaO), with significant concentrations of SiO_2 (17.963%) and considerable amounts of Al2O3 (4.146%). MLA revealed the complexity of the sample, as all the phases are intricately locked together, and the liberation required excessive grinding. The results further indicated that some valuable constituents (e.g., Al and Si) in C&DW can be recovered through metallurgical processing following liberation. Residual materials from hydrometallurgical treatment can subsequently undergo CO_2 sequestration-based carbonation to produce recycled concrete aggregates (RCA) for use in the construction industry.

Keywords: construction and demolition waste, characterization, mineral liberation analysis, concrete

1. Introduction

Construction and Demolition Waste (C&DW), originating mainly from the construction, maintenance, and demolition of infrastructure, represents over a third of global solid waste (Patil et al., 2024). Worldwide C&DW waste reached over 3.2 billion short tons annually in recent years (http1), and the annual growth rate is estimated to be 3–5%, based on the pace of urbanization, infrastructure development, and population growth (Sakthibala et al., 2025). This volume of waste poses significant environmental threats, such as increased landfilling and leaching of harmful substances (e.g., heavy metals, hazardous organic compounds, and asbestos) into soil and water systems. Furthermore, the rising demand for concrete threatens natural resource depletion and environmental degradation. Concrete production is resource-intensive, requiring mineral-based cement and aggregates whose extraction also comes with environmental challenges through mining (Sis et al., 2026).

Cement manufacturing is a major source of CO_2 emissions and particulate emissions that also threaten climate, air quality, public health, and causes high energy consumption (Engelsen et al., 2005; Benhelal et al., 2021; Yang et al., 2024). Furthermore, aggregates constitute about 60-80% of concrete volume, and their production is accompanied by soil and biological degradation, noise and dust pollution, and additional waste generation. Driven by an annual global construction demand exceeding 50 billion short tons, the rapid consumption of natural aggregates (NA) has intensified concerns over natural resource depletion (http1). However, replacing natural quarried stone with reclaimed aggregate

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can reduce extraction activity by 20–30% (http1). Consequently, limiting the usage of natural mineral resources by recycling of C&DW presents a significant opportunity for environmental protection as well as sustainable construction practices and the circular economy (Bianchini et al., 2005; Moschen-Schimek et al., 2023; Tiwari et al., 2024; Sakthibala et al., 2025). As the global volume continues to rise, C&DW market is becoming increasingly important, and global C&DW valuation is expected to grow from USD 32867.75 million in 2026 to USD 34471.69 million in 2027, and further reach USD 50485.23 million by 2035, at a CAGR of 4.88% (http1). Mineral-based materials (e.g., concrete, brick, marble, tile, roof tile) constitute the primary component of C&DW, and there is a potential for them to be reused or recycled at a higher value (Zhang et al., 2020; Zajac et al., 2021; Sakthibala et al., 2025). For instance, Marroccoli et al. (2016) demonstrated that C&DW is worthy of consideration as a new source of reactive calcium, silicon, aluminum, and iron oxides for Portland cement clinker production. However, their technical and economic recycling is challenging due to mixing with several organic, hazardous, or non-inert materials during demolishment, transportation, or dumping in landfills (https1).

Despite these advantages, the technical and economic viability of C&DW recycling is hampered by material heterogeneity and contamination. As Macedo et al. (2024) noted, C&DW composition is very variable and depends on its source (e.g., construction, renovation, or demolition site) as well as on the initial sorting process at the site. Cross-contamination with organic, non-inert, or hazardous materials during demolition, transport, and landfilling further complicates processing (https1). Overcoming these barriers requires innovative processing technologies alongside robust material characterization to verify compliance with performance standards. Material characterization is one of the most important steps to understand whether their key properties are suitable for the task. Given the complex structure of C&DW, a straightforward or single analytical method cannot be enough for suitable characterization of such a complex structure, but requires a combination of multiple characterization techniques. To this end, Bianchini et al. (2005) evaluated chemical and mineralogical composition of C&DW through X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) analyses to evaluate their chemical and mineralogical composition to obtain data for correct recycling strategies. Recently, Macedo et al. (2024) applied a combination of XRD, XRF, Scanning Electron Microscopy–Image Analysis (SEM-IA) and Thermogravimetric Analysis (TGA) techniques for proper structural and compositional characterization of C&DW materials.

Even though significant recycling studies were performed in the last decades, a comprehensive characterization of C&DW remains scarce (Bianchini et al., 2005; Bianchini et al., 2020; Macedo et al., 2024). This study addresses this gap by employing multiple characterization techniques to determine the chemical and mineralogical properties of C&DW from the Malatya (Türkiye) region. The content and key properties of C&DW material were determined by utilizing XRD, XRF, ICP, Mineral Liberation Analysis (MLA), and TGA/DTA analysis techniques. These properties, in turn, were correlated with their possible valorization area.

2. Materials and methods

2.1. Materials

The representative samples were collected from the C&DW landfill in Malatya (Türkiye). The collection of a representative sample was challenging because of the significant waste volume, covering a very large area. To address this, prior to sampling, a comprehensive site survey and visual inspection were conducted, resulting in the marking of 20 sampling locations. Certain constituents, including metals, plastics, wood, and packaging materials, were excluded as they possess established secondary markets and are infrequently landfilled (HaitherAli and Anjali, 2024). Furthermore, textiles, asphalt, and other complex organic or inorganic-organic mixtures were also excluded from the study.

The collected samples were transported to the mineral processing laboratory and laid out for drying for three days. The dried samples were weighed, and a total of 2216.17 kg of materials was recorded. All collected samples were then mixed and prepared for detailed characterization. As illustrated in the flowsheet (Fig. 1), the samples underwent successive comminution utilizing jaw, roll, and hammer crushers. Finally, the crushed samples were classified using a 38 μm laboratory sieve to avoid over-grinding, and the coarser fraction was ground below 38 μm using a rod mill. The ground ore was divided into 400-g representative samples by a rotary sample divider and stored in sealed plastic bags

until the characterization test. The comminution and sieving processes were performed dry to avoid particle agglomeration caused by the hydration of cementitious fractions.

The particle size distributions (PSD) of the ground samples were determined using a Malvern Mastersizer 2000 Particle Size Analyzer (Malvern Instruments Ltd., UK), which utilizes a laser diffraction technique. As seen in Fig. 2, the ground sample exhibited a unimodal distribution with D10, D50, and D90 values of 2.05 µm, 12.94 µm, and 48.96 µm, respectively.

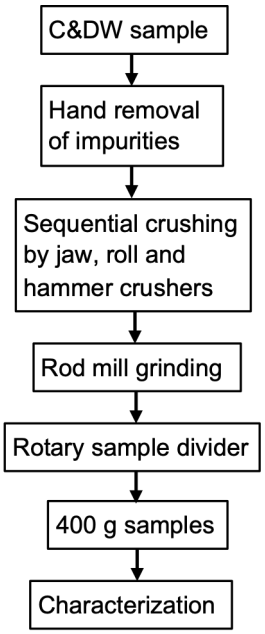

Fig. 1. Simplified sample preparation flowsheet for characterization

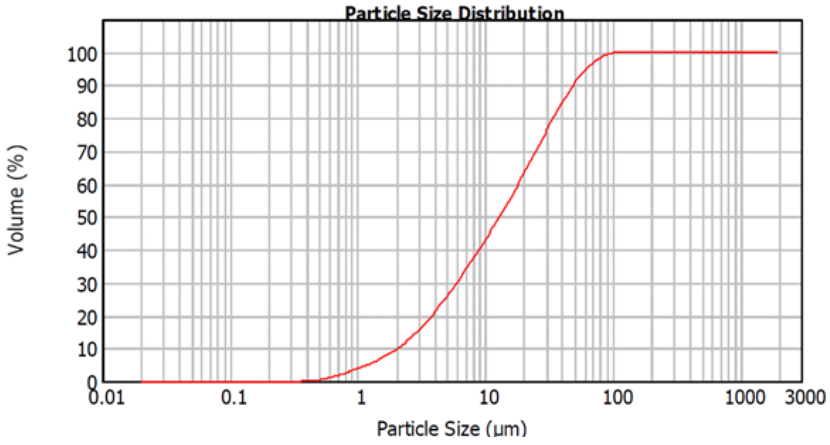

Fig. 2. Particle size distribution of the ground C&DW sample

2.2. Methods

Comprehensive characterization of the C&DW samples was performed using elemental, MLA, XRD, XRF, TGA/DTA, and ICP-OES analyses. All analyses were conducted in duplicate or triplicate to evaluate experimental reproducibility. Elemental concentrations of C, H, N, and S were determined using a Leco CHNS-932 analyzer (LECO Corp., MI, USA). Mineralogical and petrographic phases were identified via MLA (ThermoFisher Scientific Scios 2) and XRD (Rigaku Miniflex 600, Cu-Kα radiation, λ = 1.5405 Å). A narrow size fraction of -106+75 µm was prepared to meet MLA instrument specifications.

Chemical composition of the samples was determined by an XRF instrument (Malvern-Pananalytical, Epsilon 4) at the Mining Engineering Department of İnönü University and an ICP-OES instrument at Central Laboratories of Middle East Technical University. Thermal behaviour of the

samples was evaluated by a Shimadzu TGA/DTA 50 instrument at the chemistry laboratories of İnönü University. The measurements were performed in an O_2 atmosphere from room temperature to 1000 °C at a heating rate of 10 °C/min.

3. Results and discussion

XRD analysis was employed to identify the crystalline phases present in the sample. As illustrated in the diffractogram (Fig. 3), the material is predominantly composed of calcite and quartz. Several minor, unidentified reflections at 2θ = 11.2°, 18.01°, 27.9°, and 31.0° were also observed. These peaks likely correspond to sintering products such as larnite (Ca_2SiO_4), wollastonite ($CaSiO_3$), or mullite ($3Al_2O_3.2SiO_2$), which typically form during the manufacture of cement, ceramics, bricks, and tiles. The challenges in categorical phase matching may be attributed to sample polycrystallinity, lattice imperfections, or peak suppression resulting from the low concentration of these secondary phases.

Elemental analysis yielded average concentrations of approximately 7.269% C, 0.238% S, and 0.319% H, while nitrogen remained below detection limits (Table 1). The high carbon content corroborates the XRD findings and confirms a carbonate-rich composition. Furthermore, the detected sulfur is attributed to gypsum ($CaSO_4.2H_2O$) derived from wall plaster and cementitious components.

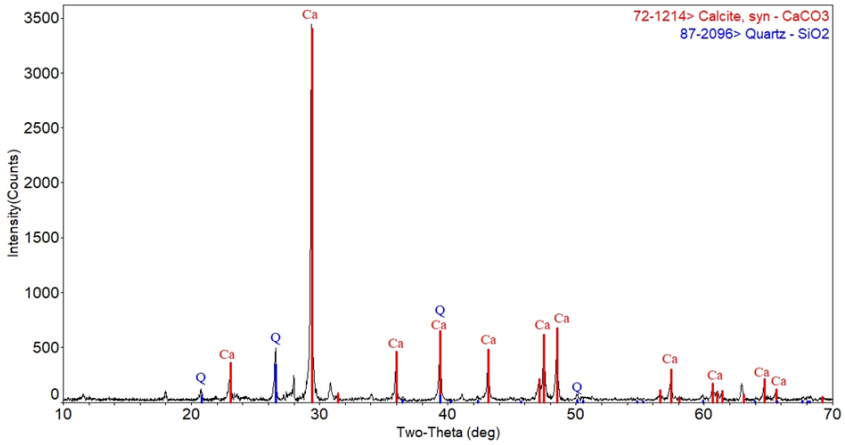

Fig. 3. XRD analysis of the sample

Table 1. Elemental analysis of C&DW sample

	C (%)	S (%)	N (%)	H (%)
Sample 1	7.232	0.261	-	0.319
Sample 2	7.306	0.215	-	0.319
Average	7.269	0.238	-	0.319

XRF analysis was conducted in triplicate, and Table 2 presents the raw and averaged elemental composition of the sample. The results indicate a significant concentration of calcium carbonate, evidenced by 39.874% CaO and a corresponding loss on ignition (LOI) of 31.34%. This high carbonate content is typical for C&DW and originates from both the cementitious matrix and the calcareous natural aggregates used in concrete production. The analysis also identified substantial levels of SiO_2 (17.963%) and Al_2O_3 (4.146%), along with minor concentrations of Fe_2O_3 (2.553%) and MgO (2.088%). All other constituents remained below 1.0%. The presence of 0.963% SO_3 further corroborates the inclusion of gypsum from wall plasters and cement manufacturing.

TGA/DTA analysis was performed on the sample to correlate the thermal degradation with temperature, and the results are given in Fig. 4. A total mass loss of 30.79% was recorded between 25 and 1000 °C. Initial mass losses of 1.25% (45–150 °C) and 1.44% (218–486 °C) are attributed to the removal of moisture and the decomposition of hydrated phases, such as gypsum, respectively. A sharp mass loss initiated at 650 °C and concluded at about 800 °C indicated the decomposition of carbonates (mainly calcium carbonate) by the release of CO_2. This high carbonate content is consistent with the mineralogical findings from XRD (Fig. 2) and chemical data from XRF (Table 2). The DTA profile

exhibited exclusively endothermic peaks, confirming the absence of carbon-rich organic combustible matter, which would otherwise appear as exothermic reactions.

Table 2. XRF analysis of the samples

Component	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Average (%)
Al_2O_3	4.154	4.132	4.152	4.146
Fe_2O_3	2.567	2.516	2.577	2.553
SiO_2	18.015	17.909	17.966	17.963
CaO	40.158	39.611	39.853	39.874
TiO_2	0.328	0.332	0.343	0.334
MgO	2.090	2.083	2.091	2.088
SO_3	0.981	0.947	0.963	0.963
K_2O	0.603	0.605	0.618	0.609
ZnO	0.123	0.125	0.128	0.125
LOI	30.98	31.74	31.31	31.34

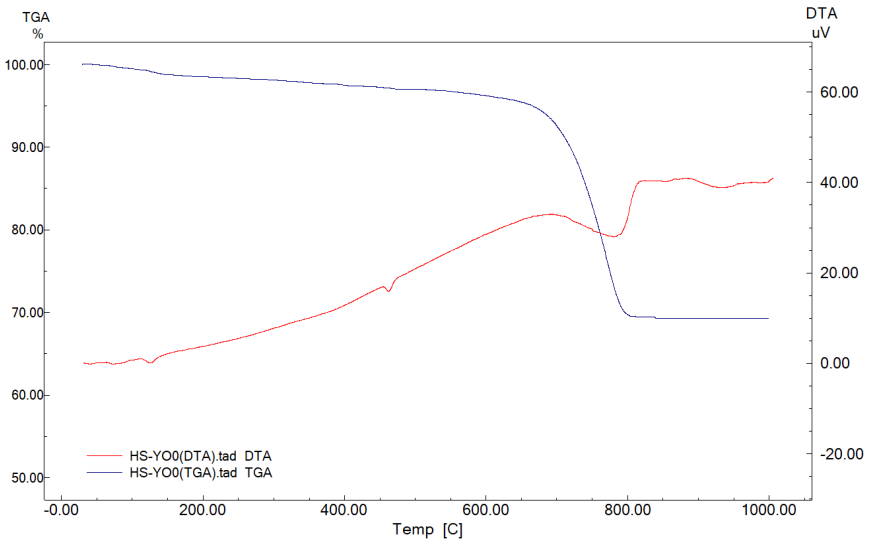

Fig. 4. TGA/DTA analysis of the samples

Table 3 summarizes the ICP-OES results for the duplicate samples and their corresponding mean values, indicating a high calcium content (27% Ca) originating mainly from calcite. The Si and Al contents were found to be significant, as 7.35% and 2.3%, respectively. The sample also contains 1.525% Fe, 1.37% Mg, 0.555% Na, and 0.15% Ti. Concentrations of Ni, Cu, Pb, and P elements remained below the detection limit of the instrument. Although the elemental trends from XRF and ICP-OES are largely consistent, a notable discrepancy was observed in sulfur content. ICP-OES yielded 0.965% S, which is considerably higher than the values determined by elemental analysis (0.238% S) and XRF (0.963% SO_3, equivalent to ~0.385% S). Considering that the ICP-OES analysis could not provide very reliable results for sulfur analysis and high amounts of sulfur are not expected in these samples, XRF and elemental analysis results should be more representative.

The MLA is an automated quantitative mineralogy technique that enables rapid, high-throughput identification and quantification of minerals (Petruk, 2000). The MLA instrument can create digital images of particles and also provide precise measurements of mineral liberation as well as data on mineral grain size, association, and textures. The colored-mapping presented in Fig. 5 illustrates the high degree of sample complexity, characterized by multi-phase particles with irregular shapes. All MLA images showed no fully liberated phases. Even at higher magnification (Fig. 6), no evidence of

liberation was observed, indicating that partial liberation is only achievable at finer particle sizes through additional grinding.

Table 3. ICP-OES analysis of waste samples

Element	Sample 1	Sample 2	Average
Ca (%)	27	27	27
Si (%)	7.3	7.4	7.35
Al (%)	2.3	2.3	2.3
Fe (%)	1.52	1.53	1.525
Mg (%)	1.36	1.38	1.37
S (%)	0.95	0.98	0.965
Na (%)	0.56	0.55	0.555
K (%)	0.48	0.48	0.48
Ti (%)	0.15	0.15	0.15
Zn (ppm)	746	763	754.5
Ba (ppm)	503	514	508.5
Mn (ppm)	342	347	344.5
Cr (ppm)	283	302	292.5
Ni (ppm)	-	-	-
Cu (ppm)	-	-	-
Pb (ppm)		-	-
P (ppm)	-	-	-

Although the technique identified calcite, quartz, albite, iron oxide, lime, and zincite, several phases remained unclassified (Table 4). This lack of definitive classification is attributable to exposure of the raw materials to elevated temperatures and intensive processing, which distorts original crystal structures and facilitates the formation of complex phases that the software may not categorically identify. Among the classified phases, calcite was the predominant phase, accounting for 96.02% of the area, followed by quartz at 0.78%, albite (0.22%), iron oxide (0.14%), lime (0.04%), and zincite (0.02%). Because of the extreme phase complexity and limitations in categorical classification, the software could not generate liberation statistics. Nevertheless, the mineralogical trends observed via MLA are highly consistent with the results obtained from XRD and XRF analyses.

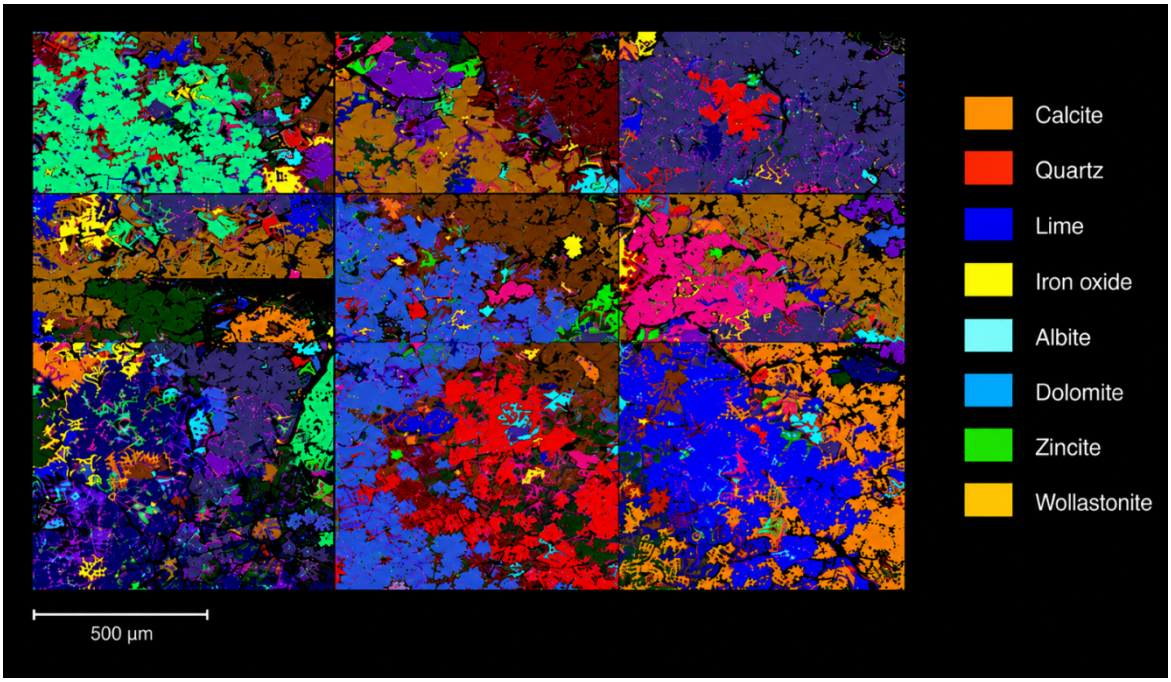

Fig. 5. MLA results of the ground sample

Table 4. The MLA results of the ground C&DW sample

Category	Features	Total Features (%)	Class Features Area (sq. nm)	Features Area (%)
All features	2434	100	$1.82.10^{12}$	100
Classified	1959	80.48	$1.77.10^{12}$	97.23
No Classification	475	19.52	$5.05.10^{10}$	2.77
Marked	0	0	0	0
Class	**Features**	**Total Features (%)**	**Class Features Area (sq. nm)**	**Features Area (%)**
Calcite	1547	63.56	$1.75.10^{12}$	96.02
Quartz	325	13.35	$1.42.10^{10}$	0.78
Albite	35	1.44	4.08.109	0.22
Iron oxide	29	1.19	2.52.109	0.14
Lime	15	0.62	7.9.108	0.04
Zincite	8	0.33	3.24.108	0.02

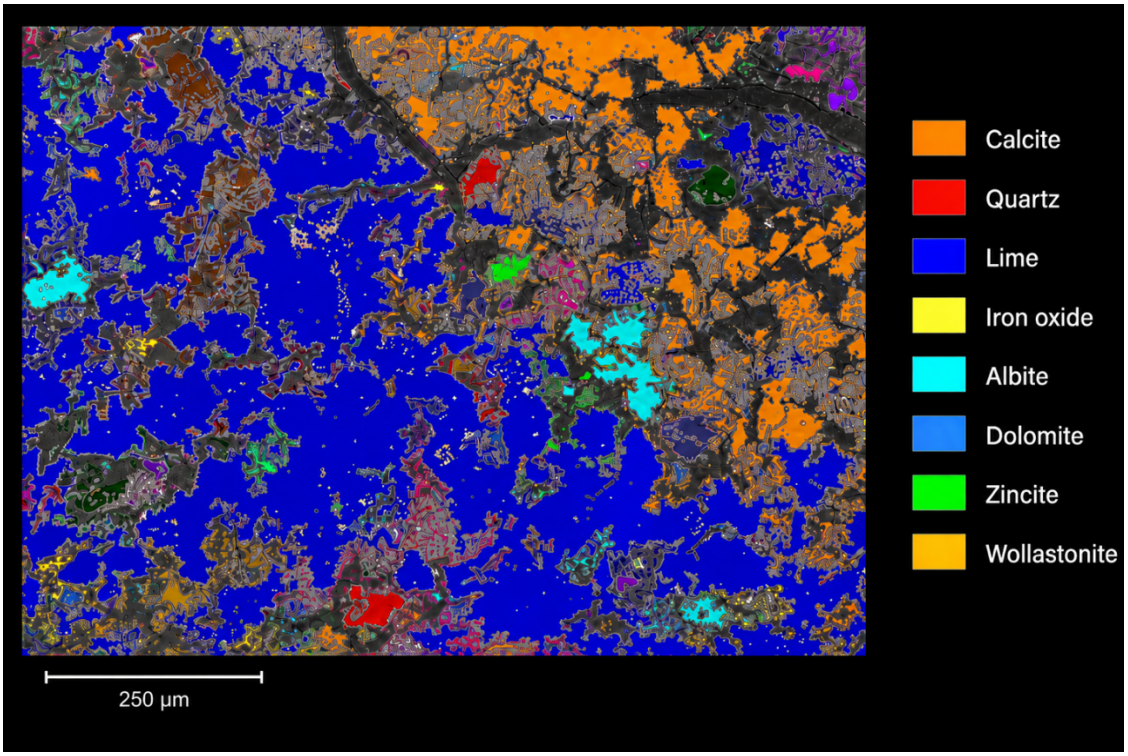

Fig. 6. MLA results of the ground sample

4. Conclusions

This study provided a comprehensive chemical and mineralogical characterization of C&DW material collected from the earthquake waste disposal area in Malatya (Türkiye). The utilized techniques, namely, XRD, XRF, ICP, elemental, MLA, and TGA/DTA, were found to be very useful for identifying the sample well. Despite minor discrepancies, the data from different techniques were complementary. MLA, in particular, was confirmed as a robust tool for identifying most mineralogical phases and determining composition. It revealed that the sample was very complicated, and the phase liberation level was quite low. The characterization confirmed that carbonates, specifically calcium carbonate, are the predominant constituents, alongside significant concentrations of SiO_2 (17.963%) and a fair amount of Al_2O_3 (4.146%). Based on these characterization insights, a synergistic pyro-hydrometallurgical flowsheet integrated with mineral carbonation was proposed to recover valuable silicon and aluminum components and produce recycled concrete aggregates (RCA) from the C&DW matrix. In the first step,

a finely ground C&DW sample can be subjected to alkaline leaching (e.g., NaOH) to selectively solubilize the aluminum and silicon fractions, yielding a pregnant leach solution (PLS). Then, the heterogeneous slurry can undergo quantitative solid-liquid separation via filtration to obtain a purified, silicon- and aluminum-bearing PLS and a chemically altered, carbonate-rich solid leach residue. The separation of silicon and aluminum species from the alkaline PLS can be achieved by pH-controlled sequential precipitation as a hydrated silica gel ($SiO_2.nH_2O$) and aluminum chloride ($AlCl_2.6H_2O$), respectively. Later, separate high-temperature oxidative roasting (calcination) of $SiO_2.nH_2O$ and $AlCl_2.6H_2O$ solids can yield high-purity silica (SiO_2) and alumina (Al_2O_3), respectively. In contrast, the solid residue from the primary alkaline leaching stage, enriched in alkaline earth carbonates and oxides, can be used as a substrate for mineral carbonation with CO_2 gas. This process promotes permanent carbon sequestration, converting reactive phases into stable carbonated minerals to produce RCA.

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