Quantitative Mineralogy: novel approaches for sorting and recycling Construction and Demolition Waste (CDW)

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INTRODUCTION

Globally, the building and construction sector represents the single most important source of mineral resource consumption. After drinkable water, concrete is the most used material worldwide, with three tons used annually per person on earth (Gagg, 2014). The primary source of angular sand for concrete production is river deposits and quarry mining, accounting for the largest share of globally extracted mineral resources, ranging from 32 to 50 Gt annually, surpassing even fossil fuel extraction (Torres et al., 2017). Additionally, at the end of their life cycle, construction and demolition waste (CDW) continues to represent a burden to the environment, accounting for 35% of global waste disposed of in landfills (Caro et al., 2024). The average CDW composition includes mainly natural sand and rocks, cement and concrete, metal, plastic, wood, ceramic and glass, all materials with high potential recycling rate.

The most common and simplest way to reuse CDW is to convert the inorganic mineral fraction into recycled aggregates, which could replace natural aggregates in the production of concrete, mortars, and plasters. In this recycling process, the first stage is the acceptance and pre-sorting audit, in which the CDW is weighed and visually inspected upon arrival. Only specific waste types are accepted, based on their composition according to the European Waste Code classification (CER). Large and unwanted items, such as hazardous materials or oversized debris, are removed manually to avoid damaging the processing equipment. Afterwards, industrial magnets are commonly adopted together with clamshell buckets in order to separate metal components, mostly resulting from the concrete rebars. The second and most crucial recycling step is the crushing stage using either jaw or impact crushers, which is typically followed by sieving.

The size reduction and sieving are focused on maximizing the yield of the coarse fraction (< 40 mm) to decrease the production of fines (> 4 mm) that are later difficult to valorize (Whittaker et al., 2021). Afterwards, in the Italian framework, each produced batch of secondary raw material (3000 m^3) must undergo leaching tests to evaluate compliance with the "End of Waste" decree no. 127/2024. The UNI 20802 standard and the method specified by the UNI EN 12457-2 are used for the determination of these values.

Nowadays, recycled aggregates are mostly devoted to sub-bases and bases of pavements of roads and highways, employed in unbound layers, often deemed as down-cycling. As a matter of fact, the lack of their recycling in high-grade applications, called up-cycling, comes from the composite and mixed composition that results from poor sorting practices (Wu et al., 2019).

To overcome this challenge, this work, which summarizes the outcomes of a doctoral thesis, introduces a pipeline for the 4.0 green transition of the sector, starting from an automated "End-of-Waste" certification protocol powered by machine learning predictions. Additionally, it explores CDW sorting using optical sensors and computer vision. Then, a novel method for quality control of recycled aggregates using X-ray Powder Diffraction is presented. The aim is to introduce cutting-edge innovations that could be upscale to support the circularity of the construction sector, minimizing its environmental impact.

MATERIALS AND METHODS

The samples of CDW are collected from stockpiles of landfilled materials in authorized recycling facilities in Ferrara (Italy). The procedure follows the guidelines in standard UNI-EN 932–1, 1997. For each material, 20 kg are collected, homogenized and decreased using a quartering process according to UNI-EN 932–2, 1999. Samples are labeled and divided into three main groups: ceramic (CER), which includes samples of brick, porcelain, tile, stoneware and roof tile. Concrete (CON), and lastly, mixed waste (MRA), comprise the CER samples mixed with the CON sample in a 1:1 ratio.

Geochemical analysis

Bulk major and trace (Ba, Co, Cr, Cu, Ga, Ni, Sc, V, and Zn) element concentrations are determined by wavelength-dispersive X-ray fluorescence spectrometry (XRF) on pressed powder pellets using an ARL Advant-XP+ spectrometer. The leaching test follows the protocol modified from UNI EN 12457-Part 2 (2004) and reported in Bianchini et al. (2020).

Mineralogical analysis

The X-ray Powder Diffraction (XRPD) are collected in the 2θ range of 3-90° at room temperature at each 0.02 step (θ) for a time of 2 or 3 seconds, depending on the expected resolution. The setting used is a fixed irradiated length mode, where the slit width is automatically adjusted to maintain a constant irradiated length of 15 mm. The instrument used within the present thesis is a Bruker D8 Advance Da Vinci. Phase identification was carried out with DIFFRACT.EVA v. 6.0 suite utilizing the Powder Diffraction File (PDF-2) database maintained by the International Centre for Diffraction Data (ICDD).

Machine learning

The leaching prediction modeling is executed using the PyTorch library (version 2.0.0) in the Python environment (version 3.10.10). The pipeline follows those of previous neural network-based studies (Song et al., 2020). A simple neural network architecture with a single hidden layer of four neurons is adopted for modeling. Functional layers—batch normalization followed by rectified linear unit nonlinear activation are added before and after the hidden layer (Bisciotti et al., 2025).

The advanced-sorting of CDW based on optical sensors and computer vision instead relies on convolutional neural networks using ResNet-18. The model training is driven by minimizing the mean squared error (MSE) loss between the predicted values and measured ones. A transfer learning approach is then followed (Bisciotti et al., 2024).

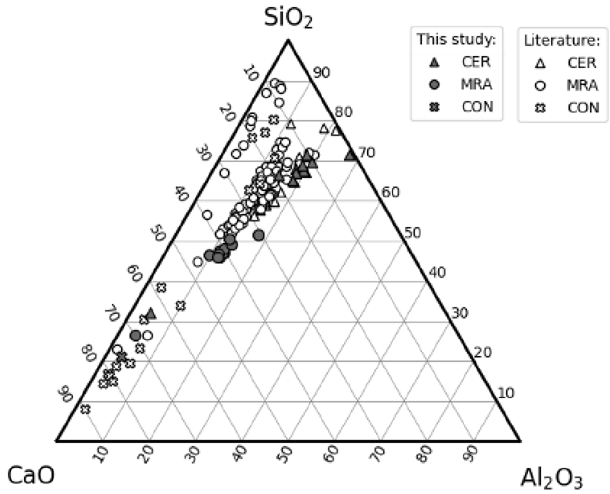

Figure 1 *Triplot for the XRF major oxides composition (reproduced from Bisciotti et al., 2025).*

RESULTS

Automated Prediction of Leaching Concentrations

The XRF analysis of the CDW of this study displays a considerable degree of variability in major oxides composition. Positive or negative correlations between oxides in binary diagrams indicate the dominant mineralogy of the CDW materials (Bisciotti et al., 2023). The CER samples are primarily silicate-based (SiO_2: 50–70 wt.%), whereas the CON samples have a calcium-based chemical structure (CaO: 35–50 wt.%), resulting from Portland cement binders, lime, and gypsum. The MRA samples are clustered between these two end-members (Fig. 1).

It is known that the release of potential contaminant elements is inversely proportional to the granulometry of materials. Therefore, the worst-case scenario is taken to assess the maximum potential release of chemical species. Fine powder (< 100 μm) of CDW samples is subjected to 24-h leaching tests while pH and temperature are monitored.

The results for CER samples show the highest levels of V and SO_4, whereas CON samples have high Cr. A different scenario occurs in the MRA compared to the pure CER environment. Due to higher alkaline pH (from CON interaction), the mobility of the leachates is influenced and the actual release of these elements is lower.

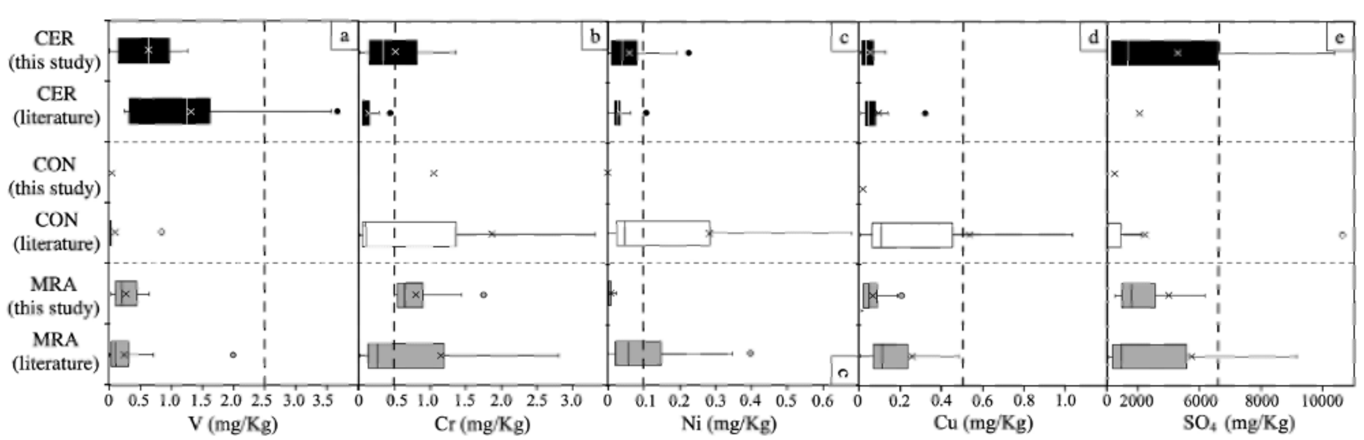

Figure 2 *Leaching values (mg/Kg) of selected chemical elements and species (reproduced from Bisciotti et al., 2025).*

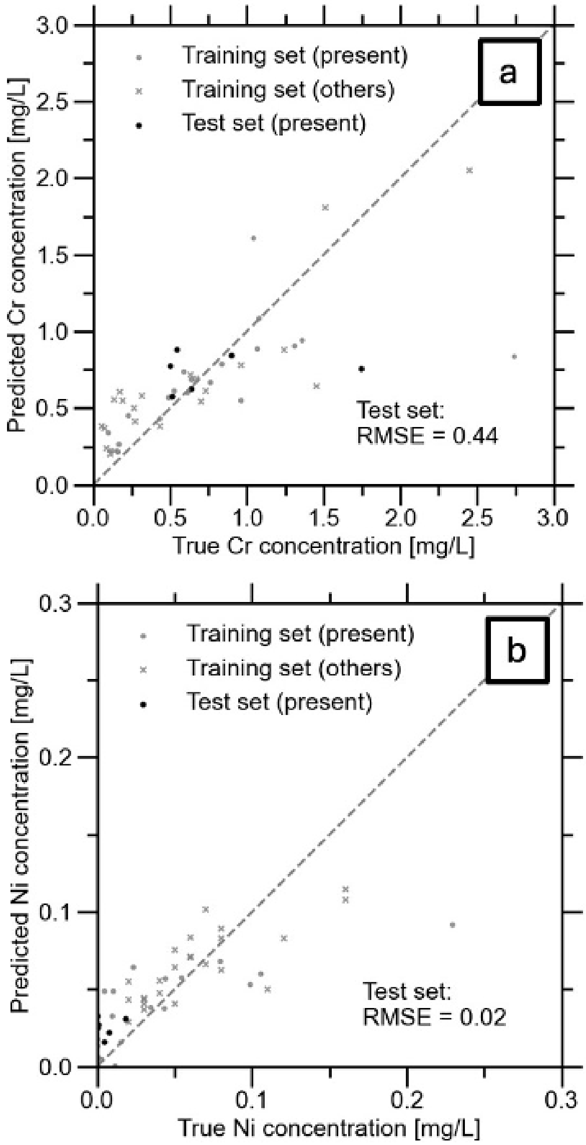

Figure 3 Machine Learning model prediction accuracy (reproduced from Bisciotti et al., 2025).

However, most of the concentrations are below the limits established by the Italian "End-of-Waste" criteria (D.M. n. 127/2024) thresholds.

With the aim of providing a faster approach for assessing the release of contaminants from CDW, a prediction of the same values is conducted directly from the bulk XRF composition using machine learning (Bisciotti et al., 2025).

The results obtained reflect varying levels of model accuracy based on their respective Root Mean Square Errors (RMSEs). The highest RMSE (0.44) is observed for Cr, indicating that the model struggles to accurately predict leaching. Indeed, Cr mobility is linked to the pH of the environment, making it hard to predict. In contrast, Ni shows the highest predictive levels (RMSE ~0.02), indicating that the model effectively captures the variables influencing Ni leaching (Fig. 3).

The development of non-supervised real-time risk-assessment tools for CDW management is supported by machine learning tools that can be effectively implemented to predict the concentrations of key leachates directly from the bulk chemical composition of the input waste. In such a way, if the predictions don't exceed the threshold values set by the D.M. 127/2024, the process of "End-of-Waste" declaration could be completed without any significant concern. Instead, if the predictions show signs of risk of exceeding such threshold values, an accurate analysis must be conducted according to the protocol defined by the UNI-EN 1245-7.

Machine learning algorithms and computer vision systems can automate waste classification, predict contaminant leaching behavior, and optimize recycling processes. By analyzing large datasets of waste composition, leaching test results, and regulatory thresholds, AI models support decision-making for safe material reuse, hazard assessment, and compliance with circular economy targets. This integration accelerates sustainable practices in the construction sector while reducing landfill dependency.

Eventually, by speeding up this procedure, a higher volume of materials can be recycled in a circular economy, achieving a more effective recycling of CDW (Bisciotti et al., 2025).

Automated Sorting based on the Leftover Cement content

In the Italian framework, following "End-of-Waste" acceptance (D.M. n. 127/2024), the recycled aggregates produced can be formally re-introduced in the circular pathways of new building materials. However, especially when obtained from CDW crushed concrete (CON samples), these materials are typically composed of the original natural sand and gravel and of a variable amount of leftover cement paste (LCP), clinging to their surface (Fig. 4).

It is known that the quality of recycled aggregates is directly influenced by the total amount of LCP (Dinh et al., 2022). Therefore, implementing an industrial separation based on this characteristic could significantly advance the circular economy within the sector. Ultimately, it would enable the sorting of high-quality raw materials from lower-quality fractions.

To this aim, an extensive database of more than 300 individual images of CON samples has been collected. An image analysis procedure is then performed based

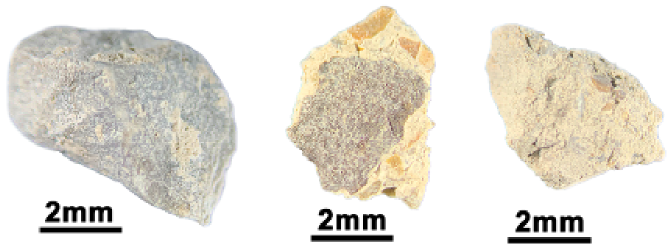

Figure 4 Recycled aggregates with variable amounts of LCP (reproduced from Bisciotti et al., 2024).

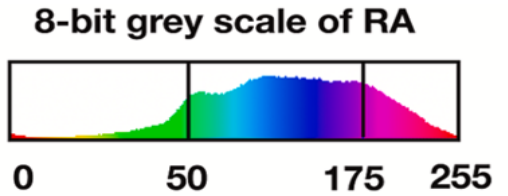

Figure 5 8-bit grayscale values used for segmentation.

on the grayscale 8-bit transformation of the original RGB database. The grayscale values have been therefore divided into three selected intervals (0–50, 50–175, and 175–255) that cover the characteristic pixel values associated with the background, aggregates, and LCP, respectively (Fig. 5).

To overcome the bottleneck associated with the manual image analysis procedure, a deep learning model is further incorporated to automate the determination of the LCP, which enables high-throughput screening of CDW in real production.

The Convolution Neural Network approach is selected because it is well-recognized for visual imagery with its dominant superiority in accuracy and efficiency among all algorithms for computer vision developing (Song et al., 2020).

Following common practice, 80% of the images are used (i.e., training set) to train the model, while the remaining 20% of images (i.e., test set) are kept hidden for testing the prediction accuracy of the model trained. The model accuracy is again evaluated by the MSE loss. The results show that as the training proceeds, the model loss decreases exponentially and plateaus at around 60 epochs. After that, model performance gradually converges to a steady stage where a small divergence between training and test sets is observed.

Eventually, the model reached an impressive 90% recall rate in correctly predicting the clean materials and LCP cover aggregates, distinguishing the two categories

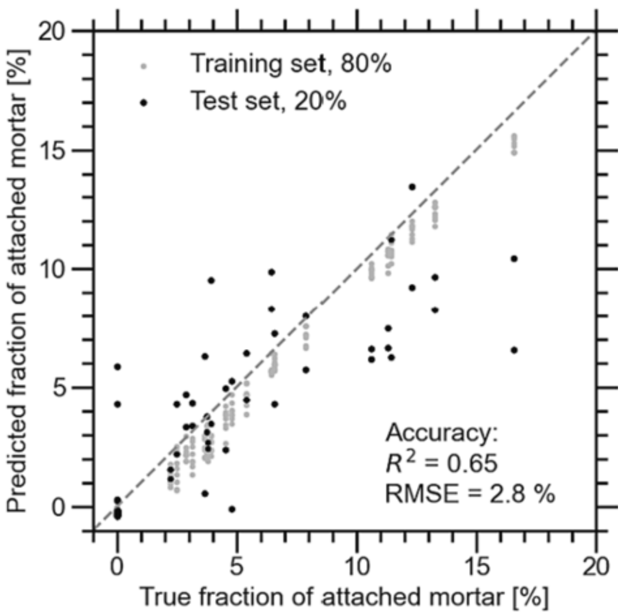

Figure 6 Machine Learning prediction accuracy (reproduced from Bisciotti et al., 2024).

from the predicted values (Fig. 6). This result shows that a portion of high-quality secondary raw materials can be exploited from the CDW unsorted waste stream using an optical-based sorting facility that employs machine learning.

These recycled aggregates, free from LCP, can be fully reused in the production of concrete without compromising the overall engineering properties of building materials, making them perfectly comparable to those derived from mineral resources extraction, like river sand and quarry mining (Bisciotti et al., 2024).

Upcycling of CDW based on the amount of Leftover Cement content

The introduction of advanced optical sorting equipment is not always feasible, and still some time will be needed to achieve a full-scale development of similar technologies. However, the proportion of LCP to natural sand and gravel remains the most significant parameter to establish the quality of recycled aggregates, prior to their reuse.

Different studies propose multiple approaches to measure LCP ranging from wet chemical tests to more advanced spectroscopy, microscopy, and image analysis. However, many of these methods are time-consuming, unsuitable for laboratory routine quality control, or prone to inaccuracies (Ulsen et al., 2022). For example, wet methods may overestimate LCP in aggregates containing acid-soluble minerals, absorption tests are influenced by cement porosity, physical methods lack reproducibility, and microscopy is operator-dependent. At the same time, an estimation based on the chemical composition, such as X-ray fluorescence, cannot distinguish LCP from limestone. In this scenario, XRPD coupled with Rietveld quantitative phase analysis may provide a valuable solution. XRPD opens enormous possibilities for in-situ monitoring of process and quality control, even in the field of continuous in-line measurements during industrial production, like CDW sorting and recycling. This method has grown beyond its roots in the world of laboratory research and is regarded as one of the most powerful industrial process-control tools in the field of building materials and minerals.

To test this approach, CON samples are collected and ground into a fine powder using a jaw crusher, followed by compaction with a mechanical press. The obr powder obtained is directly analyzed through XRPD. An accurate quantitative phase analysis is then performed by the Rietveld profile fitting using the Bruker TOPAS 5.0 software. The results provide a direct weighted (wt.%) quantification of the crystalline assemblage of the natural sand and gravel and of the LCP's minerals (*i.e.*, clinker constituents, hydration phases and carbonation products).

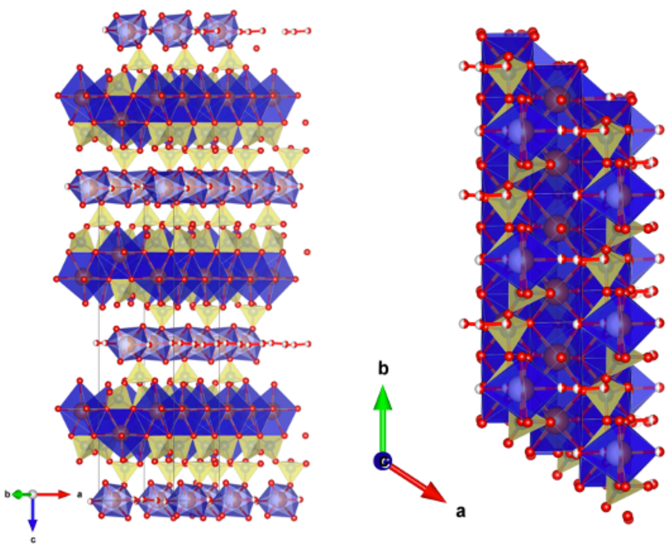

Figure 7 Tobermorite structure (natural analogues of C-S-H).

The majority of the LCP is composed of cement hydration products (namely C-S-H, ettringite, portlandite and hydrated calcium aluminates). For the C-S-H gel component, a tobermorite-like structure can be used to mimic C-S-H chemical and semi-crystalline composition (Fig. 7). To this aim, the crystallite size was fixed at 1.5 nm to achieve a profile fitting that follows the LCP amorphous content.

During the Rietveld calculation, the individual peak shape functions of the crystalline constituents are summed and combined with a background function. The background is modeled using a three-term Chebyshev polynomial equation over the entire 2θ range to maintain an almost linear profile. This approach allows for the visualization and quantification of the semi-amorphous C-S-H peak, which overlaps with the background and lies beneath the bases of the more crystalline peaks. The goodness of fit is evaluated using the Residual Weighted Profile (Rwp) value and by visually assessing the difference between the observed and calculated profiles on the same scale.

The same batch of recycled aggregates tested is afterwards used in the manufacturing of concrete specimens. The mix-design of the concrete is done according to the British Department of the Environment (DOE) standard method. Cement type, water-to-cement ratio, and mixing and curing procedures are kept constant. This consistency helps highlight the effects of the LCP itself on the concrete microstructure.

The investigation of the concrete microstructure is conducted by adopting lab-based X-ray computed tomography (X-ray micro-CT). The analyses are done using a Zeiss XRadia MicroXCT-400 at ZAG's Materials Department (Slovenia) with an 80 kV voltage, 10 W power, and LE2 filtering. Each sample underwent 1600 projections over 360°, with a 3-second exposure per projection and a 17.6 μm pixel size. Tomographic reconstruction was performed using Zeiss XRM software, which includes beam hardening correction. The resulting 16-bit TIFF axial slices were processed and analyzed using DragonFly software.

The pore characteristics in the concrete specimens are strongly influenced by the usage of recycled aggregates and specifically by the LCP content (Fig. 8). Therefore, various statistical attributes were computed for each specimen, including pore volume, pore sphericity and connected pores skeletonization (Skeleton Euclidean Length).

When natural aggregates are replaced with recycled aggregates, the average pore volume decreases by 75%, from 0.08 mm^3 to 0.002 mm^3. Sphericity index shows minor variations, whereas the highest impact is seen in pore network connectivity. When recycled fines replace natural aggregates, the number of connected pores increases tenfold and the skeleton Euclidean length decreases.

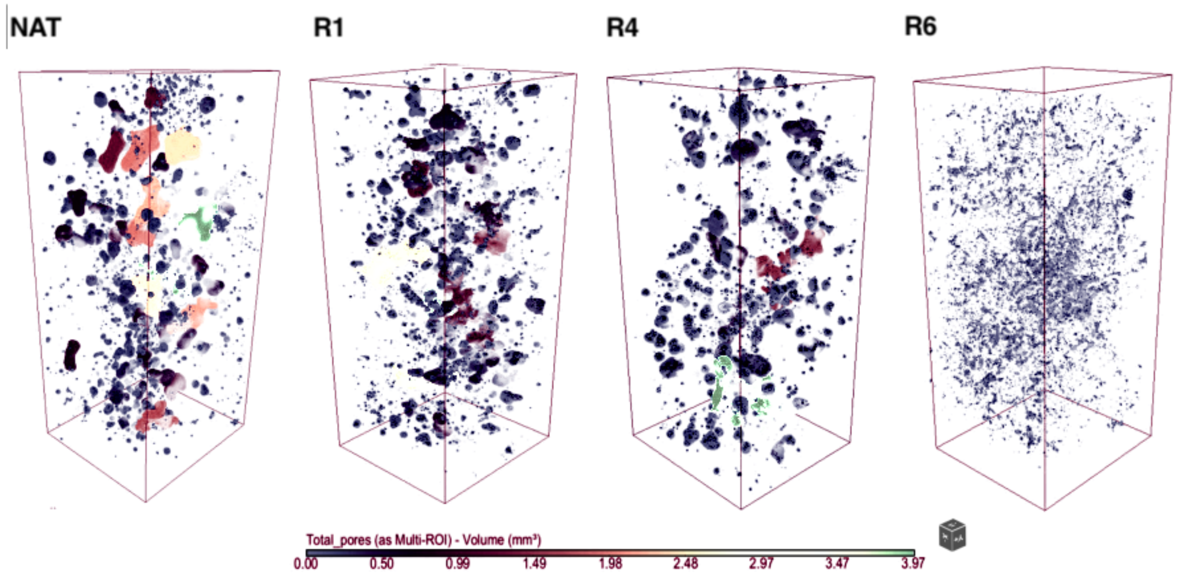

Figure 8 3D rendering of concrete specimens produced with recycled aggregates highlighting their internal porosity, NAT is concrete made with natural aggregates R1 with 10-4 mm recycled agg., R4 with 4-0.6 mm and R6 with 0.6-0 mm.

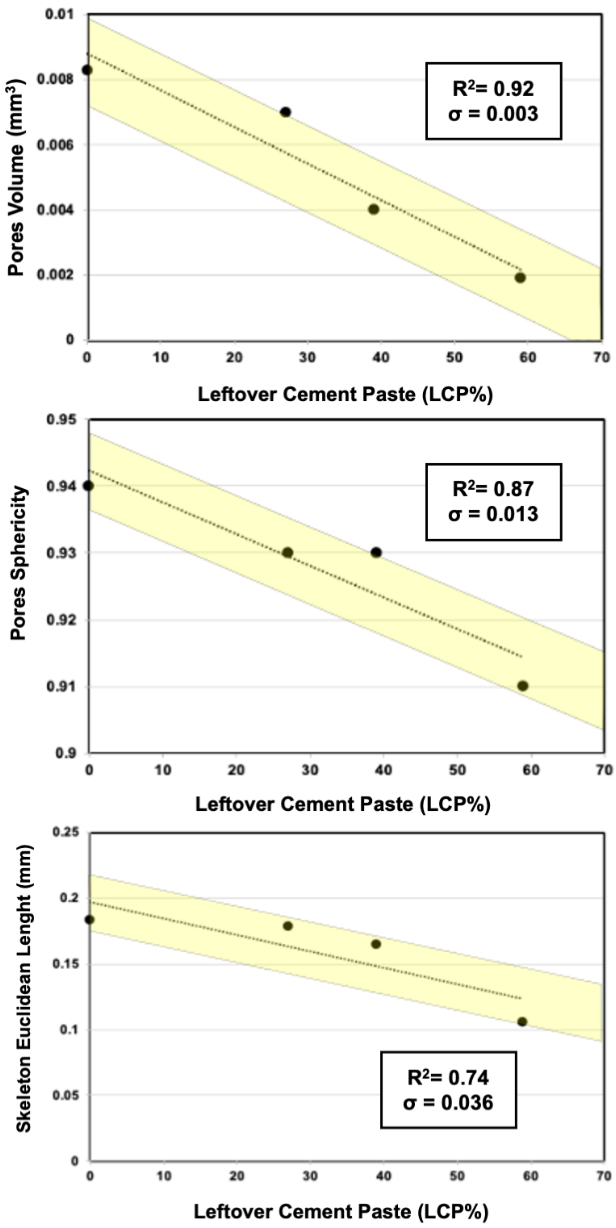

Figure 9 *Comparison of LCP% and concrete microstructure.*

All these features of the concrete porosity appear to be linked with the LCP values obtained from XRPD, which span from 0% (for natural aggregates) to 59% (recycled aggregates fines) with intermediate values for coarse and medium size aggregates (Fig. 9).

The impact of the LCP content in concrete microstructure is shown, highlighting the importance of monitoring such features prior to their reuse, while supporting the validity of the protocol described based on XRPD and Rietveld quantitative phase analysis

DISCUSSION

Selective demolition of old constructions remains the most effective practice for maximizing the recycling potential of Construction and Demolition Waste (CDW) into high-grade applications. However, this approach is often deemed excessively time-consuming and cost-inefficient, leading to its limited adoption. As a result, CDW is frequently found in a mixed, unsorted state after demolition and prior to its recycling.

The findings of this research indicate that the bulk chemical composition of CDW reflects its mineralogical and material composition. Significant variations arise due to the fluctuating content of concrete (CON) in relation to ceramics (CER) and other minor constituents. These variations directly impact the leaching behavior of CDW, as different constituent ratios lead to varying pH levels, influencing pollutant release.

By integrating machine learning methods, leaching values can be predicted solely on the bulk chemical composition of CDW. This capability presents significant potential for environmental hazard monitoring and the development of rapid, accurate auditing technologies preceding the final End-of-Waste declaration. If this declaration serves as the passport for recycled CDW, the adoption of such predictive models could function as a digital tracking system, enabling rapid screening to immediately identify potentially hazardous compositions.

It is clear that achieving a circular construction sector presents considerable challenges. Even when homogenous CON-based CDW is available, its upcycling may be hindered by various factors, with the presence of leftover cement paste (LCP) being a primary concern. The LCP content significantly affects the quality of recycled aggregates, limiting their applications in high-grade structural concrete. One potential solution is the implementation of advanced sorting machines equipped with optical sensors. The development of such facilities is becoming increasingly common, particularly in Europe, where they are being introduced for sorting CDW based on the material composition and also adopting robotic arms. These optical sensors for waste separation range from standard RGB cameras to more complex Hyperspectral Imaging (HSI) devices.

This research demonstrates that accurate sorting of CDW can be achieved using standard RGB cameras. Deep learning techniques enable robust and high-speed image analysis of screened materials. LCP can be distinguished from natural clasts through differences in grayscale values, as well as other distinguishing characteristics such as roughness, texture, and morphology, which are recognized through computer vision. While these features may seem negligible to the human eye, they are crucial for computer-based analysis in determining whether a recycled aggregate is coated with LCP or is comparable to newly extracted quarry materials. Efficient separation of high-quality recycled aggregates from mixed CDW streams can result in the recovery of substantial quantities of valuable minerals.

Nevertheless, additional laboratory-based quality evaluation protocols are essential for determining LCP content, especially in a batch of materials that might come from standard sorting facilities. The LCP presence in recycled aggregates significantly affects the mechanical properties of concrete, raising concerns about structural safety, durability, and sustainability. Therefore, prior to precasting and on-site concrete production, the assessment of this feature must be verified. However, currently available methods often have limitations and may yield low-accuracy measurements.

To address this issue, X-ray Powder Diffraction (XRPD) has been tested as a rapid and efficient tool for monitoring the quality of recycled aggregates. Using Rietveld refinement and quantitative phase analysis, LCP content can be accurately measured, providing a volume reconstruction. However, this method may be unfamiliar or complex for laboratory technicians who are not specialized in XRPD applications. To mitigate this challenge, machine learning can be integrated to develop automated software capable of estimating LCP content from XRPD patterns. While this advancement is still in development, it represents one of the most critical future directions for this research.

CONCLUSIONS

The construction sector must transition towards sustainability, as traditional building materials production remains highly polluting despite 200 years of technological progress. This research presents a focus on circular economy approaches in Construction and Demolition Waste (CDW) management, emphasizing recycling, sorting, and environmental risk assessment using AI-driven models. Key advancements include predicting contaminant leaching, improving recycled aggregates for high-value applications, and implementing automated material characterization with XRPD and AI. Standardized methods and advanced sorting technologies are needed to enhance CDW recycling, reduce environmental impact, and achieve End-of-Waste certification. The circular economy in construction is essential for sustainability, resource efficiency, and climate change mitigation.

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