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# Real-Time Sensor-Based Characterization of Recycled Coarse Aggregates (RCA): Advancing Sustainable Construction Through Automated Quality Assessment

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## Abstract

The integration of recycled coarse aggregates (RCA) into construction projects has encountered industry resistance, primarily attributable to apprehensions about variable quality. This paper underscores the imperative need for reliable material quality assessments of RCA to ensure compliance with industry standards. Addressing this concern, we introduce a novel solution: a mobile, containerized sensor-based quality inspection system. This system is furnished with a 3D scanner Gocator, which, through optimized point cloud processing and streamlined segmentation algorithms, ensures rapid extrapolation of particle size distribution (PSD) from the RCA's surface point cloud data, producing outcomes closely aligned with conventional manual sieving techniques. Additionally, the application of laser-induced breakdown spectroscopy (LIBS) within this system has proven effective, consistently producing stable spectral data indicative of the material composition. The effectiveness of LIBS is further enhanced through the adoption of a cluster-based identification algorithm, which provides exceptional accuracy and precision in the spectral analysis. The system also includes conveyor belts capable of processing more than 100 tons of RCA per hour. This synergistic integration of technologies underpins a paradigm shift in RCA assessment, offering a scalable and adaptable model for enhancing the efficiency and reliability of End-of-Life material processing, aligning with global aspirations for sustainable infrastructural development.

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# 1 Introduction

The growing demand for construction materials, along with the need for sustainable waste management, has made the recycling of concrete from End-of-Life (EoL) infrastructure an increasingly practical and environmentally responsible solution (Kabirifar et al., 2020). This approach has gained significant attention in the construction industry, which is shifting towards more sustainable practices. This shift is particularly evident in the rising use of recycled coarse aggregates (RCA) derived from construction and demolition waste, a material that holds promise for reducing the construction industry's environmental footprint (Zong et al., 2025). However, despite the potential benefits, the widespread adoption of RCA presents significant challenges, primarily related to ensuring the quality and purity of RCA (Kim, 2022). These challenges become more complex when RCA is sourced from various types of dismantled infrastructures, which often contain contaminants such as mixed debris, organic materials, and other impurities (Alaejos Pilarand de Juan, 2013). If these contaminants are not effectively identified and managed, they can compromise the structural integrity, durability, and long-term reliability of new construction projects incorporating RCA (Wu et al., 2024). As such, addressing these concerns necessitates the development of standardized quality assessment protocols and stringent regulatory guidelines. Such measures are essential to ensure that RCA consistently meet or exceed the performance criteria of natural coarse aggregates. Without the establishment of these quality standards, the inconsistent quality of RCA may undermine its credibility as a reliable alternative to conventional materials, ultimately hindering its adoption on a larger scale.

Traditionally, RCA quality has been assessed using conventional methods that are labor-intensive, time-consuming, and heavily reliant on manual inspection (Chang, 2025; Marie & Mujalli, 2019). While these approaches have served the industry in the past, their limitations—such as inefficiencies, inconsistencies, and susceptibility to human error—have become increasingly apparent as the sector seeks to enhance productivity and precision (Chang, Di Maio, et al., 2025). With the growing complexity of demolition operations and the need for faster, more reliable results, there is an urgent demand for innovative quality inspection mechanisms that offer greater accuracy, efficiency, and reliability. Recent advancements in sensor technology have emerged as a transformative solution to these challenges (Cabral et al., 2023; Chang, Di Maio, et al., 2025b). These technologies, through innovations in high-speed data acquisition and advanced processing algorithms, enable real-time, on-site characterization of RCA, offering precise assessments without compromising accuracy or reliability (Bonifazi et al., 2018; Chang, Di Maio, et al., 2025a; Nalon et al., 2022). By providing instant feedback during the production process, sensor-based systems facilitate more informed decision-making and allow for immediate adjustments, reducing the likelihood of defects and material wastage. In addition, they optimize resource utilization, thus enhancing the overall efficiency of RCA production. This integration of sensor technology not only contributes to improved material quality but also aligns with broader environmental goals, reinforcing sustainable construction practices and enhancing the operational objectives of the construction industry.

This research investigates the potential of sensor-based quality inspection systems to revolutionize the analysis of RCA. These advanced systems facilitate granular analysis and effective detection of contaminants, offering a flexible and adaptive approach suitable for dynamic demolition environments. Through a series of rigorous experiments and field studies, this study evaluates the operational performance of these sensor-based systems, comparing their results with those obtained from conventional methods. The findings highlight the transformative potential of these technologies in improving the quality assurance process of RCA, emphasizing their role in promoting sustainable construction while maintaining stringent quality standards. Furthermore, this research demonstrates how these systems can be integrated into real-world scenarios, providing insights into their practical applicability, scalability, and long-term impact on the construction industry.

# 2 Method

The sensor-based quality inspection system is housed in a dedicated container, a design that serves several important purposes. This containerization simplifies the transport of the system to various demolition sites, improving mobility and ensuring more efficient use of resources. Additionally, it provides protection against adverse weather conditions, safeguarding the sensor equipment from environmental factors such as humidity, dust, or extreme temperatures that could compromise measurement accuracy. As a result, the integrity and precision of the data are preserved, ensuring consistent and reliable performance. Beyond protecting sensitive instruments, the enclosure also demonstrates the system's flexibility and adaptability in diverse field conditions. The modular nature of the container further facilitates easy deployment and potential upgrades, allowing for the integration of future technological advancements without major system overhauls. This design also supports rapid set-up and tear-down, reducing downtime between deployments and increasing operational efficiency across different demolition sites with varying environmental challenges.

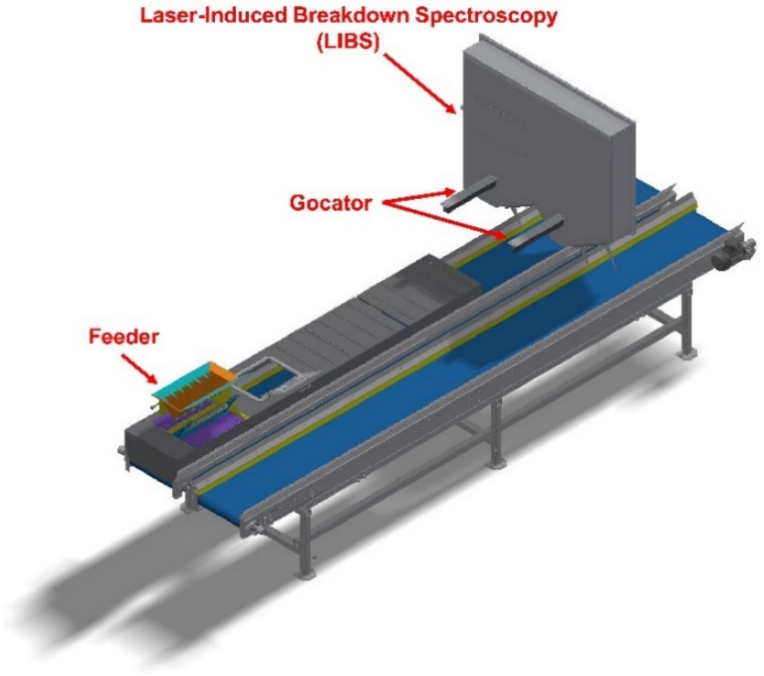


**Figure 1:** Sensor-based quality inspection system

The system (Figure 1) features two main sensors: the 3D scanner Gocator and Laser-Induced Breakdown Spectroscopy (LIBS). Both are positioned above the conveyor belt, ensuring optimal data collection without interference. The Gocator specializes in granulometric analysis of RCA, specifically measuring particle size distribution (PSD). This advanced device generates high-resolution 3D point cloud data, capturing details of the surface topology and granular distribution, which are critical for assessing the quality of RCA for reuse in construction applications. The Gocator's ability to produce accurate PSD measurements enhances the quality assurance process, ensuring that only aggregates with appropriate size distributions are selected for further processing. LIBS, on the other hand, identifies contaminant compositions within the RCA, a crucial step in ensuring that the recycled material meets safety and regulatory standards. A notable feature of the system is the use of reflective mirrors, which allows simultaneous monitoring of RCA on two separate conveyor belts with just one Nd:TAG laser and a single spectrometer. This innovative design reduces operational costs and enhances the system's overall efficiency, offering both cost savings and increased throughput without compromising the quality of inspections.

The inspection process begins when RCA are introduced into the system via a feeder and deposited onto the conveyor belt, forming a triangular pile. This configuration ensures an even distribution of RCA from the center to the outer edges (Figure 2). It optimizes the Gocator's ability to inspect the surface and assess RCA properties accurately. As the RCA move along the conveyor, they are sequentially analyzed by both the Gocator and LIBS. The data from these inspections are instantly recorded in a computer system and uploaded to a secure cloud platform for long-term storage and retrieval, ensuring that inspection results are accessible for future reference and analysis. The conveyor belt runs at a constant speed of 0.529 m/s, enabling it to transport over 50 tons of RCA per hour, ensuring high throughput and efficiency.

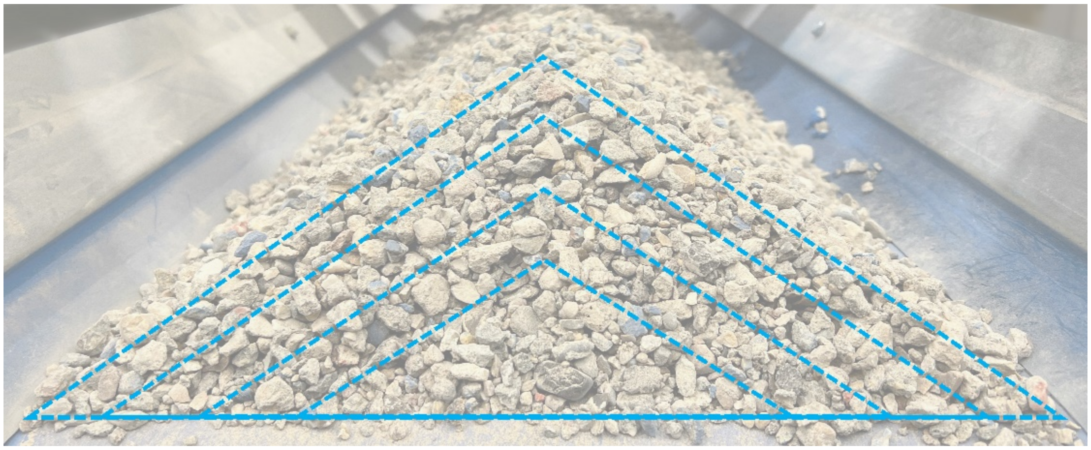


**Figure 2:** Layered formation of RCA piles

# 3 Results and Discussion

## 3.1 Particle Size Distribution (PSD)

(1) Resolution of Point Cloud Data

Given the uniform distribution pattern of constituents within the RCA piles, it is possible to extrapolate the PSD characteristics of the entire pile by analyzing only the outer surface layer. This approach provides an effective means to obtain a representative understanding of the overall PSD of the RCA piles. To facilitate this, a 3D scan of the RCA pile's external surface was conducted using the Gocator, which generated point cloud data (Figure 3(a)). The spatial resolution of the point cloud data plays a critical role in determining the accuracy and detail of the RCA particle analysis. Notably, the resolution varied depending on the spatial orientation, which has important implications for the granulometric assessment.

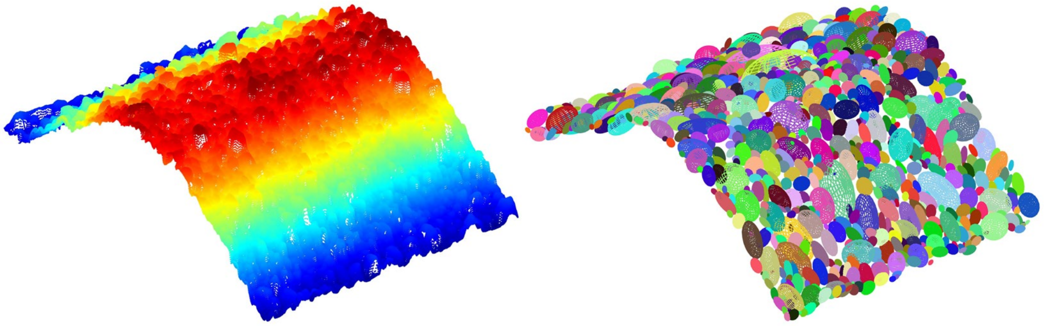

(a) 3D view of the point cloud data (b) Ellipsoids fitted to each particle

**Figure 3:** Point cloud processing

Along the direction parallel to the conveyor belt's motion, two key factors influenced the point cloud resolution. First, the velocity of the conveyor belt, which was carefully controlled by adjusting the rotational speed of the motor drive. This speed was governed by two interrelated parameters: the output frequency and the number of poles. In this study, the motor drive was configured to operate at an output frequency of 50 Hz and a 4-pole design, resulting in a rotational speed of exactly 1500 rpm. Additionally, the gearbox ratio was set to 19, and the wheel perimeter was 402.116 mm, leading to a conveyor belt speed of 0.529 m/s. The second factor was the encoder resolution of the Gocator, which was calibrated to register 1024 ticks per full revolution. This calibration resulted in a point cloud resolution of 0.393 mm in the direction of the conveyor belt's motion.

However, when measurements were taken perpendicularly to the conveyor (across its width), the resolution varied between 0.375 mm and 1.100 mm. This variation is attributed to the scanner's field of view at different points. To maintain data consistency, the transverse resolution was standardized at 0.375 mm.

Vertical resolution, which refers to the height of the RCA piles, is another important consideration. The Gocator's internal mechanisms provide a resolution range from 0.092 mm to 0.488 mm. This variability demonstrates the scanner's flexibility, allowing it to adapt to different granulometric conditions, making it an effective tool for detailed analysis of RCA piles. For this study, the vertical resolution was set at 0.092 mm.

### (2) Point Cloud Segmentation

The segmentation of the acquired point cloud data was performed using the Fastscape algorithm (Braun & Willett, 2013). This algorithm, originally developed for terrain analysis, facilitates watershed segmentation (Steer et al., 2022). The point clouds were divided into distinct regions, each representing an individual RCA particle. To optimize processing speed, the algorithm was adapted to support parallel processing, enabling real-time operation.

To analyze the morphology of RCA particles, each segmented region was enclosed within an ellipsoidal envelope (Figure 3 (b)). This ellipsoidal shape approximated the form of the RCA particles and provided a means for detailed analysis of their structure, orientation, and morphology within the sample. A key feature of this representation was the selection of the second shortest axis as the primary gradation parameter. This axis was chosen because it effectively correlates with particle size and, by extension, the PSD.

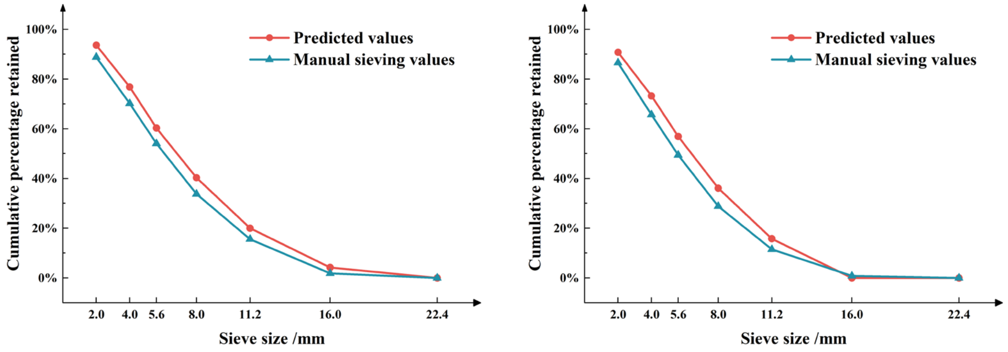
To address the concern regarding the time-consuming nature of 3D scanning and point cloud segmentation, the proposed system incorporates several strategies to ensure real-time performance and practical processing speed, even in field conditions.

Efficient Data Acquisition and Preprocessing: The system employs a high-speed 3D scanning module capable of capturing point cloud data with minimal latency. Additionally, preprocessing steps, such as noise filtering and down-sampling, are implemented directly on the hardware to reduce the volume of data transferred for segmentation. These hardware-accelerated techniques significantly reduce processing overhead while preserving critical structural information.

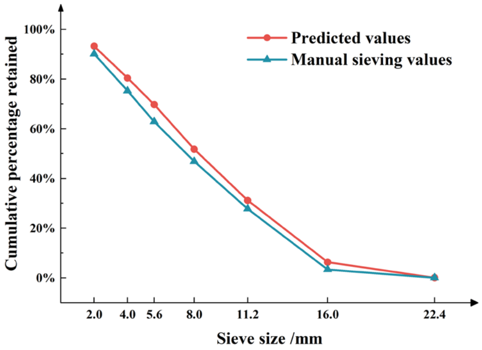
Optimized Segmentation Algorithms: The segmentation algorithms focus on extracting essential features rather than performing exhaustive analyses, which helps to maintain a balance between accuracy and speed. Furthermore, the segmentation process is accelerated through the use of parallel processing and hardware acceleration, such as multi-threading and GPU-based computation, to handle large datasets efficiently.

By incorporating these strategies, the proposed system effectively addresses the typical bottlenecks in 3D scanning and point cloud segmentation. This ensures both practical usability and real-time operability in field applications, making it suitable for dynamic environments where speed and accuracy are crucial.

(3) PSD Calculation



(a) Test 1 (b) Test 2



(c) Test 3

**Figure 4:** Cumulative percentage retained graphs

The PSD derived from the analysis was clearly represented by the cumulative percentage retained graph (Figure 4). This graphical representation, based on calculations of ellipsoidal volume and the apparent density of the RCA, effectively illustrated the PSD characteristics of the RCA piles. Additionally, it provided valuable insights into the aggregate structure and its potential influence on concrete performance.

To validate the accuracy and reliability of this non-intrusive, surface-based method for determining PSD, a comparative analysis was conducted. The PSD results obtained from the 3D point cloud data were compared with those derived using the traditional, more invasive manual sieving method. This comparison aimed to evaluate the correlation and consistency between the surface PSD measurements and the overall PSD of the entire pile. Figure 4 shows the results of this comparison, where the cumulative percentage retained curves derived from the point cloud data are compared with those obtained from manual sieving, based on pilot scanning trials. To assess the precision of this method, the Root Mean Square Error (RMSE) was calculated between the predicted and manually obtained values. The RMSE values of 4.93%, 5.38%, and 4.27% across three experiments indicate minimal deviations, demonstrating the robustness and accuracy of the predictive methodology in estimating the PSD of RCA piles on a conveyor belt. Preliminary findings suggest a strong agreement between the two methods, indicating that the 3D scanning approach can reliably estimate the full PSD, significantly reducing manual effort and time.

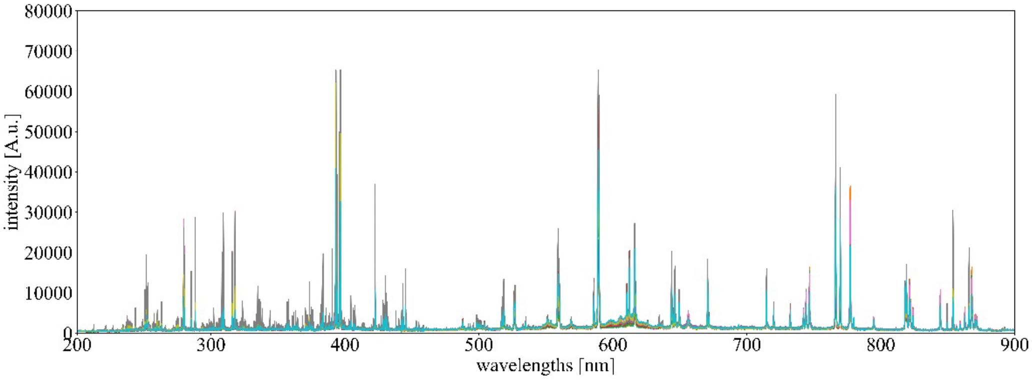
In Figure 4, the predicted values of PSD are consistently higher than those obtained through manual sieving. This systematic discrepancy can be attributed to two primary factors. First, the ellipsoid approximation used to model particle shapes may overestimate the dimensions of irregularly shaped or angular particles. In the proposed method, particles are modeled as ellipsoids to approximate their shapes for computational efficiency. However, this simplification tends to overestimate particle sizes, especially for non-spherical particles. The ellipsoid fitting algorithm calculates the semi-principal axes of each particle by determining the minimum-volume bounding ellipsoid based on the point cloud data. The optimal fit is achieved by minimizing the sum of squared distances from the points to the ellipsoid's surface, subject to constraints that ensure the surface represents an ellipsoid. This process prioritizes enclosing the particle's volume, which may result in slightly inflated size predictions compared to physical sieving, where particles are forced through sieve meshes. Second, the resolution of the 3D point cloud data can affect accuracy. Lower resolutions may smooth out fine details, further contributing to an overestimation of particle sizes. In this study, the resolution of the 3D scanner varied in each direction, which balances computational load and measurement accuracy but may still introduce minor deviations.

The accuracy of PSD estimation from the 3D point cloud data is influenced by several factors, including the speed of the conveyor belt. The spatial resolution of the point cloud, which directly impacts the accuracy of the PSD calculation, can be affected by the speed at which the RCA move along the conveyor. In this study, the conveyor belt was set to a constant speed of 0.529 m/s, which provided a balance between high-resolution data capture and real-time operation. However, variations in belt speed can influence the resolution of the 3D scan data. Specifically, a faster conveyor belt speed may reduce the time available for scanning, leading to a lower point cloud resolution, which could negatively affect the accuracy of the PSD calculation. Conversely, reducing the belt speed can enhance the resolution of the point cloud data, thereby improving the precision of the PSD estimation. Further studies could explore the potential for increasing conveyor belt speed while maintaining accuracy by optimizing the synchronization between the scanner's resolution and conveyor motion. Such optimization may allow for higher throughput without compromising PSD estimation quality.

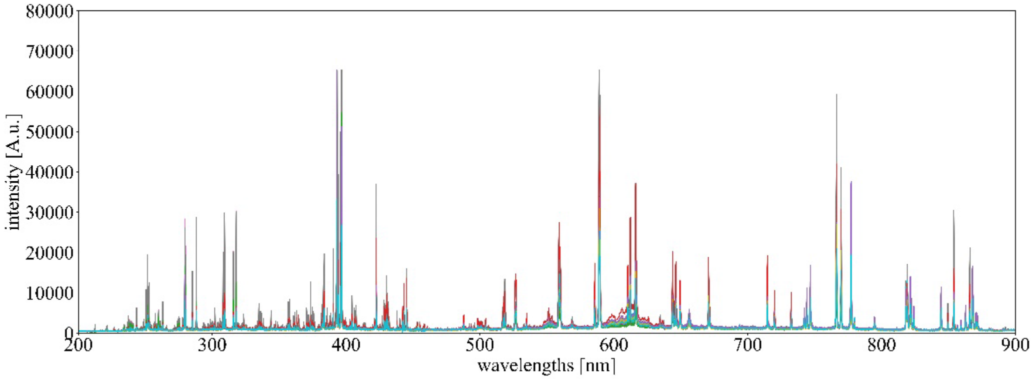
## 3.2 Contaminant Detection

To thoroughly evaluate the performance of LIBS in capturing spectra at a conveyor belt speed of 0.529 m/s, and to assess the potential influence of conveyor belt movement on the efficacy of the reflective mirrors within the system, a systematic study was conducted. In this study, spectral measurements were obtained for a variety of materials under two distinct conditions: when the conveyor belt was moving and when it was stationary.

Figure 5 presents a comparison of LIBS spectra for brick materials under two conveyor belt conditions: (a) operational state (belt in motion) and (b) stationary state (belt at rest). The spectra cover a broad wavelength range of 200–900 nm, providing insights into the elemental composition of the brick samples. Several characteristic emission peaks can be identified in both conditions, such as those at approximately 280 nm, 393–397 nm, and 589 nm. These peaks correspond to the primary chemical elements found in brick and serve as markers for compositional analysis.



(a) Conveyor belt in the operational state



(b) Conveyor belt in the stationary state

**Figure 5:** Comparison of spectra of Brick in the operation and stationary states of the conveyor belt

In the operational state (Figure 5(a)): The spectra exhibit slight variations in intensity, particularly in the 200–400 nm region, where weaker peaks experience minor shifts or noise. This phenomenon likely results from movement-induced disturbances, such as changes in the laser focus or micro-vibrations of the brick surface on the moving conveyor. However, the positions of the primary emission lines remain consistent, and their relative intensities are preserved. This suggests that the system is capable of compensating for dynamic conditions, ensuring that the material composition is reliably detected even during high-speed operations.

In the stationary state (Figure 5(b)): The spectra show smoother and more uniform peaks with reduced noise levels. This is due to the absence of mechanical disturbances, allowing the laser-material interaction to remain stable. The stationary condition serves as a baseline, providing a reference for assessing the robustness of the LIBS system under real-time operational conditions.

A detailed comparison of the two spectra highlights that the primary spectral features, such as peak positions and relative intensities, remain nearly identical between the two states. This consistency demonstrates the robustness of the LIBS system in maintaining accuracy and reliability regardless of conveyor motion. Although slight variations in peak intensity are observed in the operational state, they are negligible in terms of analytical performance. Such findings validate the system's suitability for industrial applications, such as real-time quality monitoring and contaminant detection in recycling processes, where the conveyor belt is in constant motion.

The influence of conveyor belt speed on the spectral data collected by the LIBS sensor was also assessed. While the conveyor belt was in motion (0.529 m/s), the stability and reliability of the spectral readings remained high, as shown in Figure 5. This suggests that even at relatively high speeds, the system can maintain accurate contaminant detection. Future experiments may examine the feasibility of increasing conveyor belt speeds while ensuring the spectral data's integrity, exploring whether faster belt speeds can be accommodated without sacrificing analysis quality.

Following the spectral data collection, a classification analysis was performed using the Cluster-based Identification Algorithm (Chang et al., 2022). This algorithm, recognized for its ability to group data based on inherent similarities, was effectively applied to identify patterns in the spectral data. This algorithm integrates chemometric methods, including Principal Component Analysis (PCA) and Chi-square distribution, to classify single-shot spectral data efficiently. The approach follows these key steps:

Dimensionality Reduction via PCA: Initially, the high-dimensional spectral data undergoes dimensionality reduction through PCA, which helps reduce data redundancy and noise, retaining only the most significant features of the spectra.

Transformation to a New Coordinate System: The PCA transforms the original spectral data into a new coordinate system where the components become independent normal distributions. This transformation simplifies the classification process by focusing on the principal components.

Chi-square Distribution for Classification: After standardizing the data using z-scores, the transformed spectral data is subjected to a chi-square test to assess whether the data fits the distribution of the material in question. A high chi-square value indicates a higher likelihood that the spectrum belongs to the identified material.

The model’s performance was rigorously evaluated to ensure its suitability for real-world applications. Remarkably, the model achieved strong performance metrics: an accuracy rate of 0.92, a weighted average precision of 0.93, a weighted average recall of 0.93, and a weighted average F1-score of 0.94 on the validation dataset.

These performance metrics underscore the effectiveness of LIBS as a powerful analytical tool, particularly in the context of recycled concrete aggregates in industrial settings. The high accuracy and precision demonstrate that LIBS not only enables rapid analysis but also maintains high-quality results. These capabilities have the potential to transform quality assessment processes in the industry, improving both efficiency and reliability in recycled concrete aggregate processing. By leveraging such advanced analytical techniques, industries can optimize the use of recycled materials while ensuring stringent quality control.

## 3.3 Comparison with Other Methods

To assess the effectiveness of the proposed system, we compared its performance with existing techniques such as computer vision-based methods for particle detection and size estimation. Computer vision algorithms, such as traditional edge detection and more recent convolutional neural networks (CNNs), have been widely used for particle analysis in industrial settings. However, these methods often face challenges related to lighting conditions, occlusions, and texture variations on the surface of materials.

In comparison, the proposed method using the 3D scanning and LIBS system offers several advantages. Firstly, the 3D scanning technique provides a more accurate reconstruction of particle surfaces, which reduces errors caused by shadows and lighting variations. The LIBS system, on the other hand, allows for real-time elemental analysis, which enhances the detection of contaminants that may not be visible to traditional vision-based methods.

While both methods achieve similar accuracy in particle size detection, the proposed 3D and LIBS-based method stands out in terms of robustness and ability to detect hidden contaminants, making it more suitable for complex industrial environments. Further comparisons with more advanced machine learning-based image processing techniques, such as deep learning models, could provide additional insights into the potential advantages and limitations of our method.

# 4 Conclusions

The global focus on sustainable infrastructure development has placed increasing importance on the efficient use of EoL materials, especially in the construction and demolition sectors. As demand for recycled materials grows, ensuring that these materials meet strict quality standards for safe and effective reuse is becoming more urgent. This research evaluates the potential of advanced technologies to assess the quality of RCA sourced from demolition sites. It emphasizes the need for real-time, on-site inspection systems that provide immediate feedback during construction processes.

A sensor-based quality inspection system, housed in a durable container, exemplifies the integration of mobility, resilience, and accuracy—key features for field applications. This system, with its high-speed data acquisition and processing capabilities, not only ensures real-time performance but also offers scalability and flexibility. These qualities make it suitable for diverse demolition environments where quick decision-making is essential. Furthermore, automating the quality assessment process reduces human error, enhancing the consistency and reliability of evaluations.

The detailed granulometric analysis enabled by the Gocator 3D sensor, along with contaminant detection through LIBS, provides a comprehensive understanding of RCA quality. This dual approach addresses key concerns, including PSD and contaminant content—factors critical to the suitability of RCA for reuse in construction. By evaluating these parameters, the system ensures compliance with industry standards while optimizing RCA for applications such as concrete mixes or road construction. Additionally, the system’s real-time data capture, integrated with cloud-based storage platforms, represents a significant advancement in data management and accessibility. These features streamline decision-making, allowing quality control teams to remotely monitor and adjust parameters to consistently meet quality benchmarks.

The ability to monitor two conveyor belts simultaneously with a single laser and spectrometer demonstrates the system's efficiency. This feature enhances cost-effectiveness by reducing the need for additional hardware and operators, significantly lowering operational costs without sacrificing precision. This solution, with its reduced complexity, presents a compelling case for industry-wide adoption.

In conclusion, this research highlights the potential of integrating advanced technologies into the processing of RCA. By combining innovation with precision, the study promotes a future where the quality of recycled materials is established through objective, real-time data. The findings demonstrate that, with the right technological tools, industries can achieve a balance between operational efficiency and material quality. These advancements have practical implications for reducing waste, lowering carbon footprints, and supporting sustainability goals in the construction sector. As the world shifts toward sustainability, studies like this lay the foundation for a new approach to quality and efficiency in material reuse. This will be crucial in the transition to a circular economy, where materials retain value throughout their lifecycle.

# Acknowledgments

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