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Laboratory investigation of railway-used ballast morphology using 3D imaging data analyses

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A R T I C L E I N F O

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Morphology
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A B S T R A C T

Railway ballast deteriorates over time due to cyclic loading and environmental factors, necessitating its replacement to maintain track stability. However, the potential shortage of fresh ballast has posed challenges in replacing used ballast. One of the challenges in recycling used ballast is determining its useful life. This study proposes a method to characterize fresh and used ballast morphology and shape properties using digital images and advanced data analysis software. The aim is to establish a threshold that distinguishes when ballast can be considered "used.". The study utilizes basic morphology parameters of flatness, elongation, roundness, sphericity, and convexity. Used ballast is generated through the Los Angeles abrasion (LAA) test method, while fresh ballast serves as the control sample. The analysis suggests that specific combinations of shape indices, such as roundness and convexity, offer insights into differentiating between the two types of ballast. Notably, significant differences are observed in the sphericity and convexity indices between fresh and used ballast samples. However, A systematic definition of used ballast based on the basic morphology indices alone was not feasible. Only the combination of sphericity index (> 0.825) and convexity index (> 0.9), by which both indices of used ballast were higher than those of fresh ballast, could roughly classify fresh and used ballast, although a minor overlap persisted. Further exploration of the data using advanced statistical techniques and machine learning could enhance the accuracy of defining used ballast.

1. Introduction

As known, the railway track is one of the critical components of the railway infrastructure, providing efficient and reliable railway transportation of people and goods. The railway track can be classified as a multi-layered structure, with the most important layer of granular material called ballast. The ballast layer is a base for the rail track structure, providing stability and support for the rails and sleepers. However, in reality, the ballast undergoes degradation over time due to repeated loading from train traffic and other associated environmental factors. However, some previous studies showed that the Los Angelis abrasion (LAA) tests at the laboratory scale could reasonably simulate the ballast deterioration [1–3]. This degradation can change the morphology and shape properties of

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the ballast, directly affecting the overall railway track's stability and performance. Besides, the ballast deteriorates over time, becoming "used ballast," and needs replacement with fresh (new) ballast to maintain the safety and efficiency of the tracks. In recent years, a shortage of fresh ballast has made replacing used ballast increasingly difficult, leading to a growing interest in how to reuse such ballast.

One of the major challenges of recycling used ballast is that there needs to be a reasonable definition of used ballast. This lack of scientific definition makes it difficult to determine when ballast has reached the end of its useful life and can be recycled or replaced. This absence leads to unnecessary expenses and compromises the railway system's safety if improperly recycled. To ensure the safety and quality of recycled ballast, a clear and well-accepted definition of used ballast is essential. Therefore, it is necessary to establish standard criteria for systematically defining when the ballast is ineffective, enabling effective recycling and minimizing unnecessary costs and risks.

Laboratory physical tests, such as sieve analysis and shape index tests, have been traditionally used to evaluate ballast degradation. These tests involve the manual measurement and categorization of the shape and size of individual ballast particles, which is a laborious and time-consuming process. Moreover, these physical tests are limited by the number of particles that can be measured and analyzed, which can lead to incomplete or inaccurate results. Recently, variables such as the fouling index (FI) [4] and void contaminant index (VCI) [5,6] expressed through Eqs. (1) and (2) have been utilized to determine whether ballasts need replacement.

$$FI = P_4 + P_{200} \tag{1}$$

The FI is a widely helpful tool for evaluating ballast conditions in the rail industry. It measures the percentage of fine particles in the ballast, which can impact drainage, stability, and track quality. Its widespread use has increased awareness of maintaining clean ballast for safe and efficient train operations [4]. Over the period, the ballast voids become progressively filled with fouled material. According to Selig and Waters [4], more than 75 % of ballast fouling was due to ballast aggregate breakdown. The degree of ballast fouling proposed by Selig and Waters is based on the particle size distribution of numerous ballast samples from track sites in North America. It can be represented quantitatively from the summation by the weight of the percentage of materials passing through No. 4 sieves (P_4) and the percentage of materials passing through No. 200 sieves (P_{200}). Categories of fouling were defined as follows: FI less than 1 for clean ballast, FI between 1 and 10 for moderately clean ballast, FI between 10 and 20 for moderately fouled ballast, FI between 20 and 40 for fouled ballast and FI more than 40 for highly fouled ballast.

$$VCI = \frac{V_{f'}}{V_{vb}} \times 100 = \frac{(1+e_f)}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \tag{2}$$

VCI is a parameter that can assess void contamination by considering the significant variation that affects contamination, including specific gravity, void ratio, and ballast and fouling material gradation. Where $V_{f'}$ is the actual volume of fouling material within the ballast voids, V_{vb} is the initial void volume of clean ballast, e_b is the void ratio of clean ballast, e_f is the void ratio of fouling material, G_{sb} is the specific gravity of clean ballast, G_{sf} is the specific gravity of fouling material, M_b is the dry mass of clean ballast, and M_f is the dry mass of fouling material.

Conventional techniques are employed to assess the abrasion durability of ballast, which can resist deterioration or erosion from train traffic. Typically, such methods encompass the Micro-Deval and the LAA test. Several studies to simulate ballast deterioration in an experiment depend on the specific factors studied [7–10]. Commonly, the methods for simulating ballast deterioration with abrasion tests [1,11], applying the ballast in a rotating drum with steel balls with the LAA test [1–3]. Qian et al. [2], propose a methodological approach to investigate ballast fouling. The approach involves using LAA testing and aggregate image analysis to examine the degradation of ballast aggregates caused by factors such as degradation, breakage, and contamination by other fine materials [2]. They used image analysis to evaluate ballast degradation by determining the FI via LAA testing. LAA tests were also used to observe changes in ballast particle size and shape (morphology) [3]. Additionally, 3D image analysis was employed to analyze ballast degradation, emphasizing particle size and shape effects [1]. LAA confirms that it can generate the used ballast in the laboratory. This laboratory method reached a ballast deterioration stage of over 40 % of the FI recommended by Water and Selig [4]. However, previous studies inadequately explored ballast particle morphology, with some studies failing to focus on the characteristics of fresh and used ballast particles.

In recent years, significant advancements have been made in image processing technology, opening new possibilities for characterizing ballast morphology and shape properties [12–19]. High-resolution digital images can provide detailed information about individual ballast particles' size, shape, and texture, allowing for a more accurate and efficient evaluation of ballast degradation [1,16, 20–24]. Moreover, a large number of particles can be analyzed in a relatively short amount of time, providing a more comprehensive understanding of the ballast degradation process [2,3,25–30].

This study presents a relevant method using digital images and an advanced data analysis algorithm to characterize fresh and used ballast morphology and shape properties. The focus is on the so-called used ballast generated through the Los Angeles abrasion (LAA) test method, a widely used test method for simulating the effects of wearing and abrasive resistance on the ballast [31]. The LA abrasion test involves subjecting the ballast to repeated impacts in a rotating drum, which simulates the effects of train traffic on the ballast. The test generates used ballast, which has undergone a degree of degradation. The fresh ballast with the original conditions serves as a control sample.

This study involved capturing digital images of fresh and used ballast samples with a 3D scanner and processing them using image analysis software named "SHape Analyser for Particle Engineering (SHAPE)," developed by Newcastle University, the United Kingdom (UK) [32]. Various image processing algorithms were applied to extract relevant data covering the morphological properties of the individual particles, flatness, elongation, and convexity.

Overall, using morphology analysis from 3D scanner image data can elaborate significant information on material surface textures and shapes of the materials to set up a rational definition of used ballast. By establishing clear definitions for determining the quality of used ballast, the recycling process can become more efficient, reducing the environmental impact of the transportation industry. The use of recycled ballast is becoming increasingly important with the growing interest in sustainability and resource conservation, ensuring the safety and efficiency of railway tracks while reducing environmental impact.

2. Material and methods

In this study, fresh and used ballast were used to investigate the morphology characteristics. The research process is demonstrated in Fig. 1. Firstly, fresh ballast undergoes simulated deterioration using the LA abrasion testing schemes to produce the used ballast. The FI and VCI indices were applied to assess ballast deterioration in the laboratory. Secondly, determine the basic properties of fresh and used ballast, such as particle size distribution, particle density, bulk-specific gravity, and water absorption. Thirdly, take the ballast sample acquired from the quartering process to be scanned and created into ballast particles. Finally, the ballast particle was further analyzed for morphology by SHAPE software using MATLAB algorithms [32].

2.1. Ballast sample

The ballast materials studied in the laboratory were crushed granite aggregate, which was supplied from the ballast resource of the Chiang Mai State Railway of Thailand (SRT). It would be noted that this study is limited only to the use of the granite aggregate collected, not covering other aggregate types. The gradation test sample is collected by the quartering method, dividing all ballasts into four quarters after discarding two diagonally opposed quarters; the remaining ballasts are cycled through the quartering process until a suitable sample remains. Then, the clean aggregate was blended, cleaned, oven-dried, and air-cooled at room temperature. Their properties are bulk specific gravity of 2.92, oven-dried particle density of 2912 mg/m^{3,} and water absorption of 0.18 %. In this case, 100 kg of ballast represents the distribution associated with the State Railway of Thailand's requirement [33], as shown in Fig. 2.

2.2. Los Angeles Abrasion (LAA) accelerated deterioration

The LAA test is commonly used to evaluate ballast abrasion resistance by measuring mass loss after subjecting the sample to mechanical stress. It was observed that the ballast subjected to the repeatedly wearing and abrasive loads of the LAA test deteriorated with more fine generations. This behavior was similar to the ballast under repeated train loads [3,34].

As a result of abrasion and breakage, the gradation of the ballast is changed. Thus, Selig and Waters [4] suggested the FI as the deteriorated ballast levels. This parameter determined the degree of ballast fouling along the ballast gradation and suggested that the

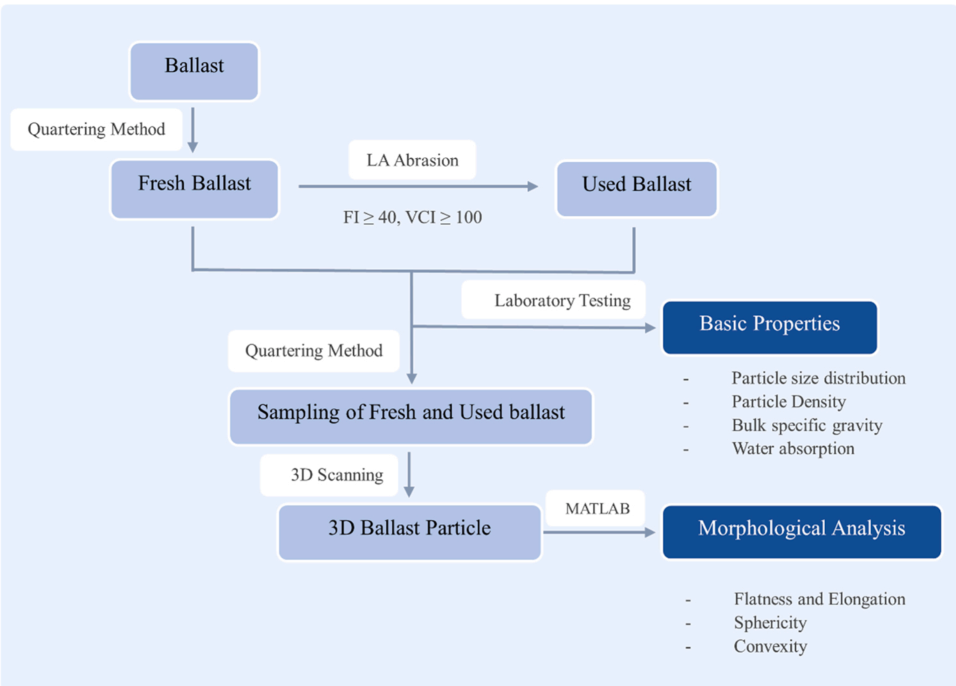

Fig. 1. Research methodology.

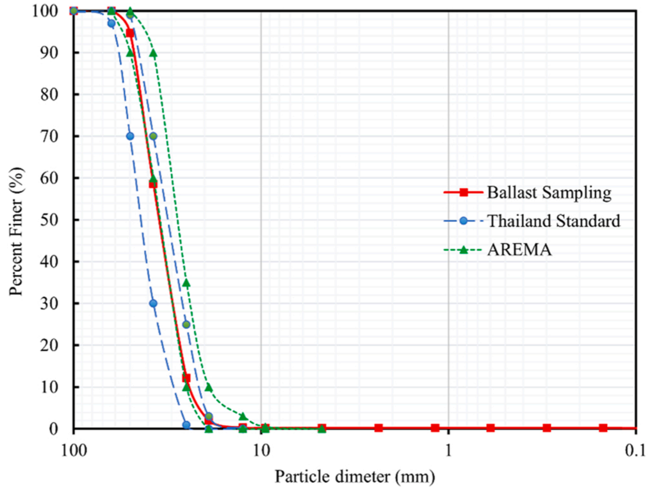

Fig. 2. Particle size distribution curves for ballast materials in Thailand.

fouling index value be greater than 40 %, indicating a high level of fouling that could impact the tracks' performance [4]. Indraratna et al. [5] publish the VCI, integrating the impacts of void ratios, specific gravities, and gradations of both fouling material and ballast. It is demonstrated that VCI may be used as a more realistic fouling index, particularly when the fouling material has a specific gravity significantly different from the rock aggregates [6].

As described above, to recreate the deteriorated ballast, the 10 kg of fresh ballast material was repeatedly processed through the LAA tests until the fouling index value was more than 40 % and the VCI was more than 100 %. This process produced what is known as used ballast. Fig. 3 demonstrates that after 3500 rounds of the LAA test, the deteriorated ballast was above 40 % of the FI and 100 % of the VCI.

2.3. 3D ballast scanning

In accelerating ballast deterioration, 10 kg of used ballast was produced, which contained degraded ballast particles and fouling material (particles passing a 9.5 mm sieve) [35]. In this study, the morphological analysis of the ballast focused on the ballast particle, excluding any fouling material. A quartering method was performed to scale down the ballasts to select a statistically representative sample of the ballast particles. One hundred ten ballast particles, including 54 fresh and 56 used ballasts, were selected and scanned by the EINSCAN-SE (see Fig. 4). To begin the process, the 3D image processing machine must be installed and calibrated with the EINSCAN-SE scanning software. The particle should be fixed to the reference point system, and the three-dimensional coordinate values of the particle's point cloud should be obtained. The camera should be set to capture the scanning process using turntable steps of 8 and a speed of 10 for one turn at 0–360° with an accuracy of 0.1 mm. More captured points will generally lead to a more precise 3D

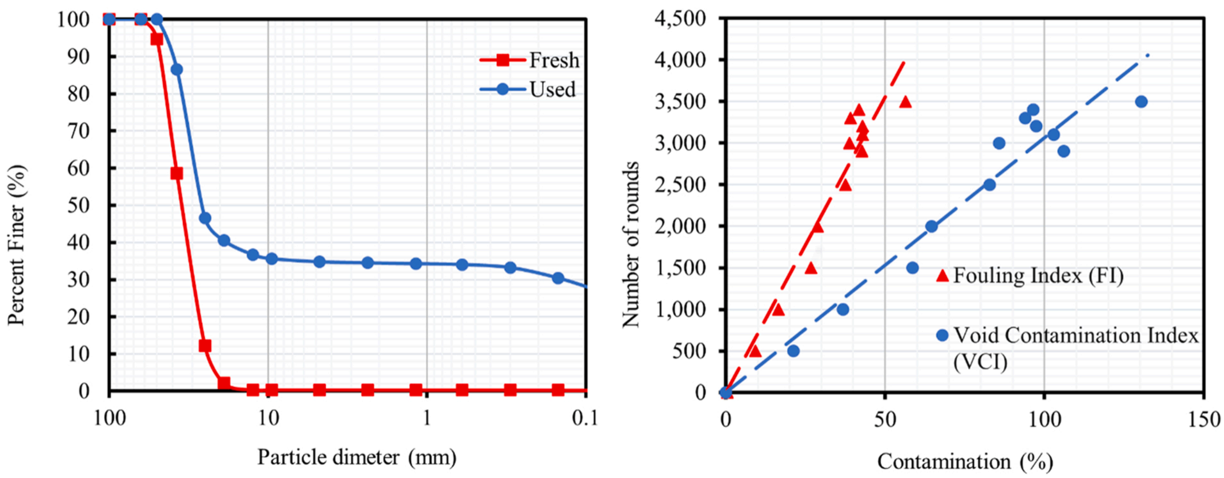

Fig. 3. (a) Particle size distribution curve of fresh and used ballast. (b) Percent of contamination response to the number of the LAA abrasion rounds.

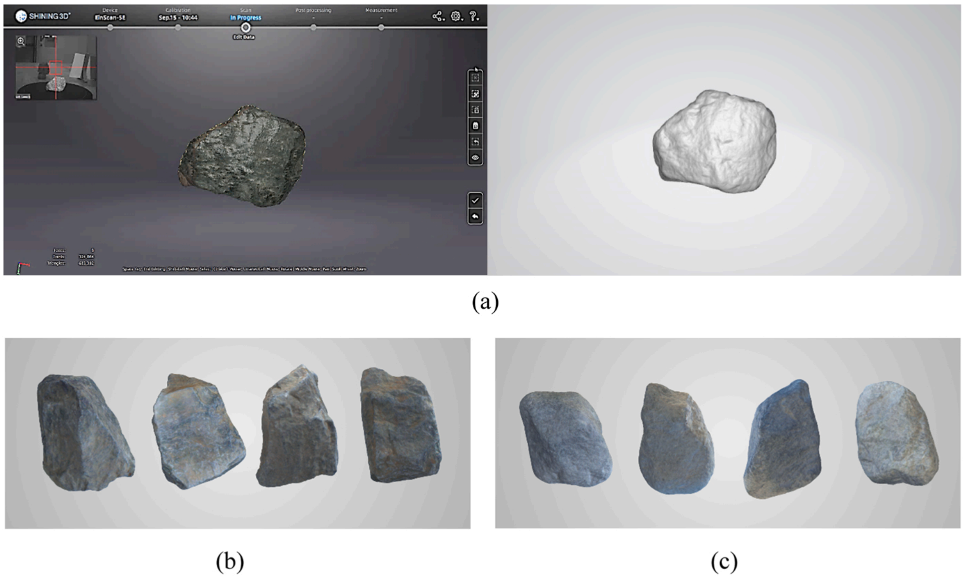

Fig. 4. (a) Scanning ballast by the EINSCAN-SE. (b) Fresh ballast (c) Used ballast.

model, obtaining an STL mesh file whose output is later processed using MATLAB.

3. Analysis approach

The ballast degradation process increases the fouled material. It affects the morphology of the ballast particle, which was considered in this study to explore the differences between fresh ballast and used ballast. For determining the morphological characteristics, several variables are used in the description. Mitchell and Soga [36] classified parameters based on the detailing of the scale into three scales, as shown in Fig. 5. Generally, the macroscale or form-level parameters are flatness, elongation, sphericity, and convexity. The roundness and angularity indices are referred to as mesoscale indices. Lastly, this analysis did not consider the microscale, which comprises the surface texture index or roughness.

The morphology parameters were obtained using MATLAB, some of which were derived from the SHAPE platform [32] and Mvelase et al. [20]; the details of each parameter are described as follows.

3.1. Flatness and elongation

The simplest approach to characterizing the general shape of grain is to inscribe it into a rectangular prism and define three lengths: short (S), intermediate (I), and long (L). as illustrated in Fig. 6. Zingg [37] classified the form of pebbles into four distinct categories: flat, spherical, flat&elongated and elongated, by setting an arbitrary threshold at 2/3 for flatness and elongation ratio.

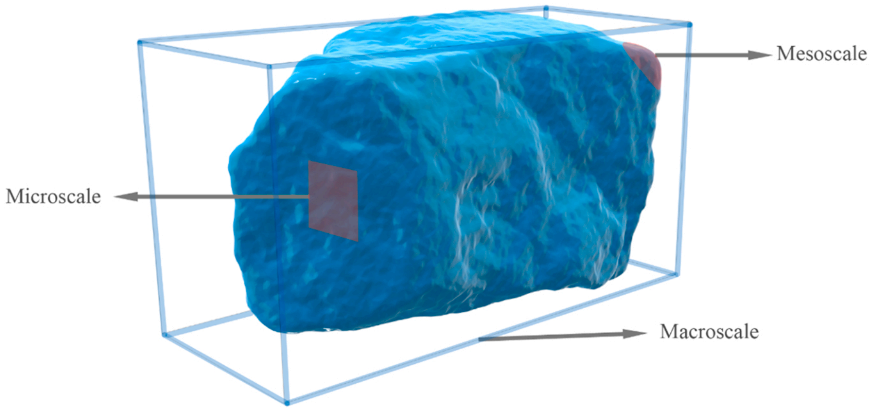

Fig. 5. Leveling of morphology detail.

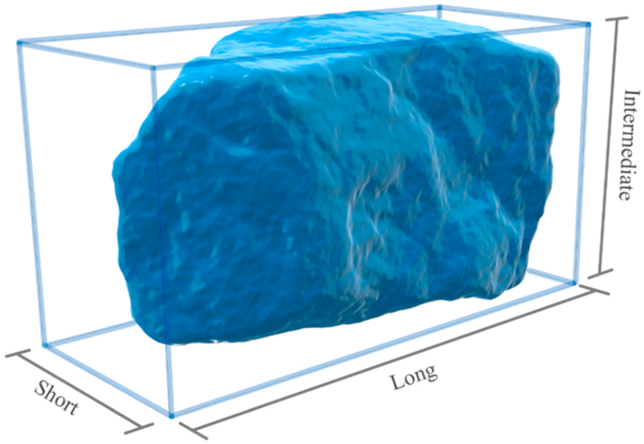

Fig. 6. Dimension of ballast particle.

$$\text{Flatness(F)} = \frac{S}{I} \tag{3}$$

$$\text{Elongation(E)} = \frac{I}{L} \tag{4}$$

3.2. Sphericity

Wadell [38] assessed an object's form approaches a perfect sphere is determined by its sphericity, the proportion between the particle's actual surface area (A_s), and the surface area of a sphere with the same volume (A_e). The maximum value of sphericity is 1, indicating a particle that is perfectly spherical shape, any particle which is not a sphere is always less than 1.

$$\text{Sphericity} = \frac{A_e}{A_S} \tag{5}$$

3.3. Convexity

The convexity index is the concavity of a particle by the ratio of the particle (V) volume to the minimum convex hull circumscribing the particle (V_{CH}) [32]. When the convexity index approaches 1, indicating a decreased severity of concavity. The highest possible level of convexity is 1, provided that there are no areas of concavity.

$$\text{Convexity} = \frac{V}{V_{CH}} \tag{6}$$

3.4. Roundness

Particle roundness was defined by Hayakawa and Oguchi [39] as an approximation ratio of the surface area of an ellipsoid (SA_e) to the surface area of the particle (SA_p). According to the equation in Eqs. (7)–(8), the ellipsoid's surface area was computed assuming that each ballast particle fit in a symmetric ellipsoid in which the dimensions correspond to the principal axes, as shown in Fig. 7.

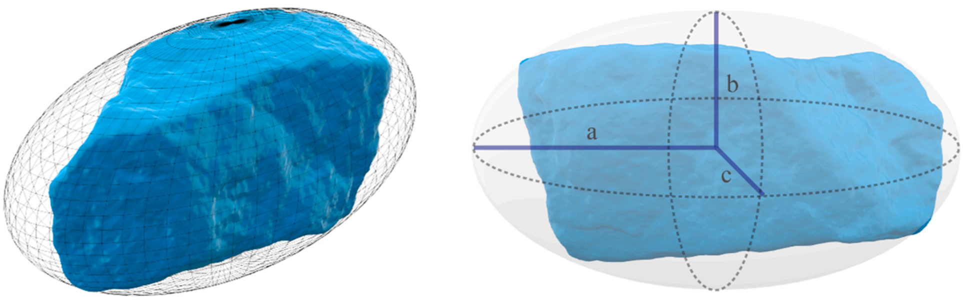

Fig. 7. Dimension of a symmetric ellipsoid.

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2} = 1 \tag{7}$$

$$SA_e = \int_0^{\pi}\int_0^{2\pi} \sin\varnothing\sqrt{a^2b^2\cos^2\varnothing + c^2(a^2\sin^2\theta + b^2\cos^2\theta)\sin^2\varnothing}\ d\theta d\varnothing \tag{8}$$

Where $a \geq b \geq c$ are principal ellipsoid radii and (θ, ϕ) are the spherical parameters for $0 \leq \theta \leq 2\pi$ and $0 \leq \phi \leq \pi$.

The surface area of the ballast particles (SA_p) is the sum of the triangles' areas comprising the particle surface derived from MATLAB software, dividing the surface mesh into triangular sub-surfaces.

4. Results and discussion

Ballast morphology properties are important factors that affect the stability and performance of railway tracks. This section presents the investigation results into fresh and used ballast morphology properties.

Flatness measures the degree to which a ballast deviates from being perfectly flat. It is a measure of the ballast's shape anisotropy or irregularity in the lane of a surface. A perfectly flat particle would have a flatness value of zero, while a more irregular particle would have a higher flatness value. The distribution of the flatness index is displayed in Fig. 8(a), which reveals that the distribution is relatively uniform for fresh and used ballast. Notably, the flatness index of the used ballast was higher than that of the fresh ballast. Additionally, the analysis showed that more than 10 % of the used ballast particles had a flatness index of nearly 1, which indicates that these particles were almost cubic or spheric in shape.

Elongation measures the degree to which a ballast deviates from being perfectly spherical or round. It is a measure of the ballast's shape anisotropy or irregularity. A perfectly spherical particle would have an elongation value of zero, while a more elongated or flattened particle would have a higher elongation value. According to Fig. 8(b), it was observed that the elongation distribution of both fresh and used ballast is uniform. Additionally, the values of elongation were found to be nearly identical.

The ratio between the flatness index and elongation index can provide useful information about the shape of ballasts. A high ratio indicates that the ballasts are relatively flat compared to their length, while a low ratio indicates that the ballasts are more elongated. The distribution of the flatness and elongation ratio (F&E Ratio) of fresh and used ballast is shown in Fig. 9(a). It can be observed that the distribution of both types of ballast is almost similar. An F&E Ratio of 1 indicates that the ballast has a cubic or spherical shape. It is clear from the graph that more than 60 % of the ballasts were flat particles, while 40 % were elongated particles. Additionally, most F&E Ratio distributions fall within the 0.75–1.25, accounting for more than 55 % of the total distribution.

The ballast's convexity index measures the ballast's shape complexity. It is defined as the ratio of a ballast's surface area to the surface area of a sphere with the same volume as the ballast. A convexity index of one indicates a perfectly spherical particle, while a convexity index of less than one indicates a non-spherical or irregularly shaped particle. In Fig. 9(b), the distribution of the convexity index is shown. The study found that most of the convexity index is concentrated in a narrow range in fresh and used ballast. The convexity index of fresh ballast ranges from 0.75 to 0.9, while used ballast is distributed within the range of 0.85–0.95. Overall, the convexity of used ballast is higher than that of fresh ballast.

The sphericity index measures how closely the ballast resembles a perfect sphere. It is defined as the ratio of a sphere's surface area with the same volume as the particle to the surface area of the particle itself. A sphericity index of one indicates a perfectly spherical particle, while lower values indicate fewer spherical particles. The distribution of sphericity index values is shown in Fig. 10(a), with

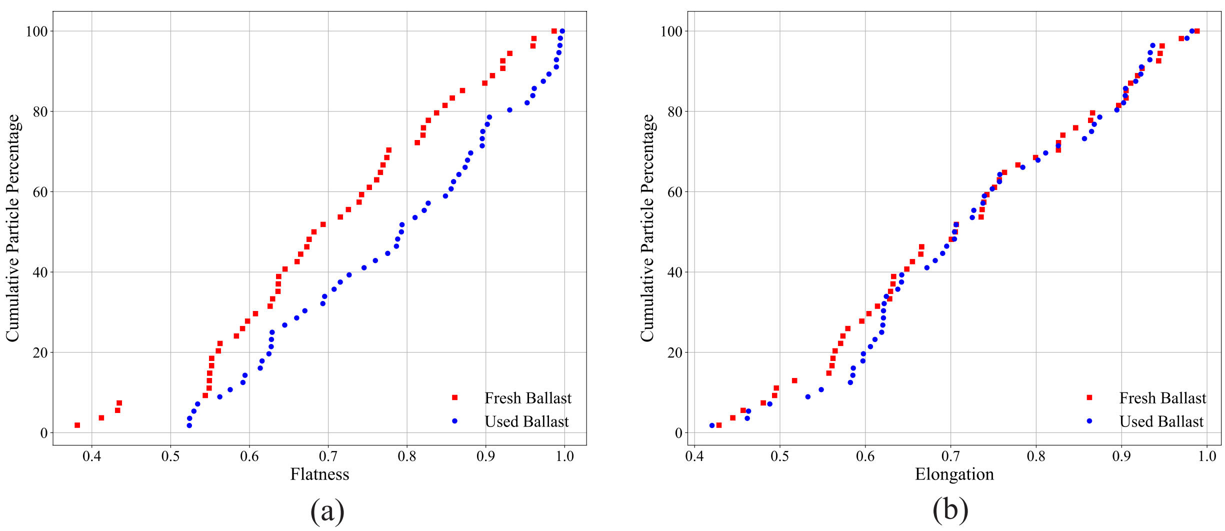

Fig. 8. Cumulative ballast particles percentage as a function of flatness (a) and elongation (b).

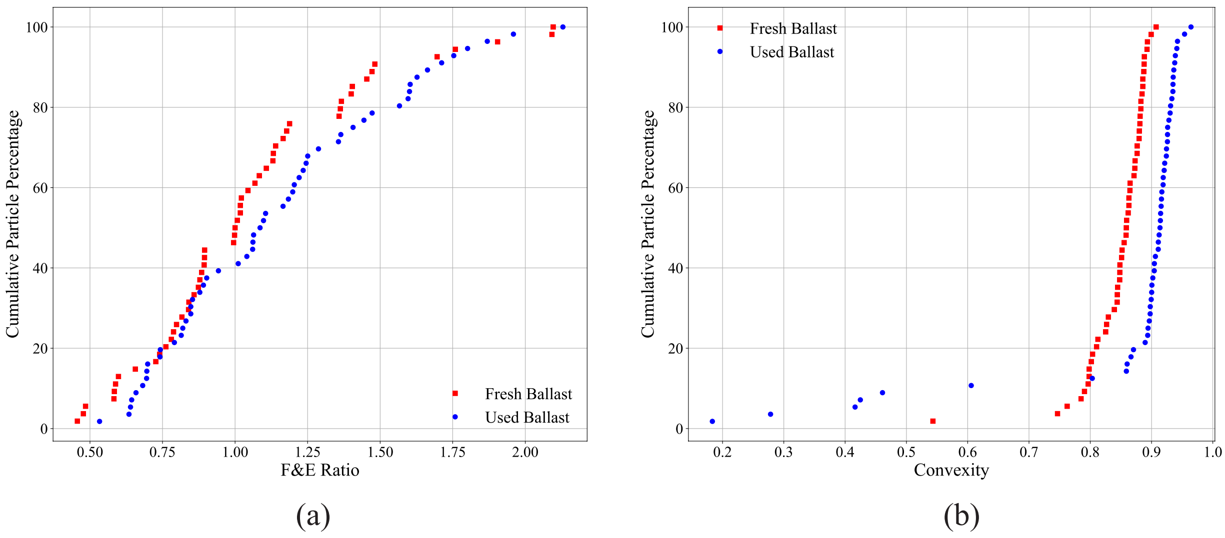

Fig. 9. Cumulative ballast particles percentage as a function of Flatness and Elongation ratio (F&E Ratio) (a) and convexity (b).

most indices found to be distributed within a narrow range for fresh and used ballast. The range of convexity index for fresh ballast is between 0.67 and 0.82, whereas for used ballast, it is distributed between 0.77 and 0.87. In other words, the sphericity of used ballast is greater than that of fresh ballast. This behavior is quite similar to the convexity behavior, as demonstrated in Fig. 9(b).

The roundness index, which measures how closely a ballast approximates a round in shape, is typically calculated by comparing the particle's surface area to the surface area of an ellipsoid with the same volume as the particle. Based on Fig. 10(b), the roundness indices for fresh ballasts are widely distributed, while the roundness indices of used ballasts are distributed within a small range. Approximately 70 % of the used ballasts' roundness indices remain almost constant, at around 0.95. Used ballasts contain more rounded particles than fresh ballasts.

For more analyzes, this study also focuses on a violin plot. It is a type of data visualization that combines the features of a box plot and a kernel density plot. It is used to display the distribution of numeric data for one or more groups. A kernel density plot is drawn on either side of a central box plot in the violin plot. The central box plot shows the data distribution's median, quartiles, and outliers. The kernel density plot shows the shape and spread of the distribution. The width of the violin plot at a given point represents the data density at that point. The wider the violin, the more data there is at that point. The violin plot's height indicates the data frequency at that point. A violin plot was used to visually compare multiple shape indices to display the relationship between fresh and used ballast shape indices, as depicted in Fig. 11. It was observed that the mean values of the F&E ratio, convexity, and sphericity were slightly different between fresh and used ballast. Additionally, the distribution of these indices was found to be quite similar. However, the roundness index of fresh and used ballast differed significantly in distribution and mean value. There was a significant overlap between the fresh and used ballast index data in all the shape indices. As a result, classifying fresh and used ballast proved to be a difficult task.

Fig. 12 illustrates a scatter index pair plot that displays the F&E ratio, convexity, sphericity, and roundness of fresh and used ballasts. Comparison of the shape index pairs revealed significant overlap between the data, rendering it impossible to distinguish between fresh and used ballasts in terms of shape. However, the roundness and convexity index pairs displayed a discernible division between the zones of fresh and used ballasts, with some overlap in a small portion (as demonstrated in the yellow zone in Fig. 13). This overlap makes it difficult to identify the exact separation point between fresh and used ballast.

To provide a clearer view, a magnified plot of the roundness and convexity index is shown in Fig. 13. It exhibits that the roundness and convexity index pairs displayed a discernible division between the zones of fresh and used ballasts, with some overlap in a small portion. The analysis revealed that most fresh ballast samples had a sphericity index below 0.8 and a convexity index below 0.9. In contrast, the majority of the used ballast samples had a sphericity index above 0.8 and a convexity index above 0.9. Besides, the analysis revealed that most of the fresh ballast samples had a sphericity index below 0.775 and a convexity index below 0.85 (pink zone in Fig. 13). In contrast, the majority of the used ballast samples had a sphericity index above 0.825 and a convexity index above 0.9 (purple zone in Fig. 13).

5. Conclusions and recommendations

The decay of railway ballast due to continuous loading and environmental factors requires its replacement for track stability. However, the scarcity of fresh ballast poses challenges in replacing used ballast. This study aimed to define when ballast can be considered "used" by characterizing the morphology and shape properties of new and used ballast using digital images and advanced data analysis software. This study used four shape indices, namely flatness, elongation, sphericity, and roundness, to analyze the ballast morphology obtained from a 3D scanner using the SHAPE image processing platform. The concluding remarks and

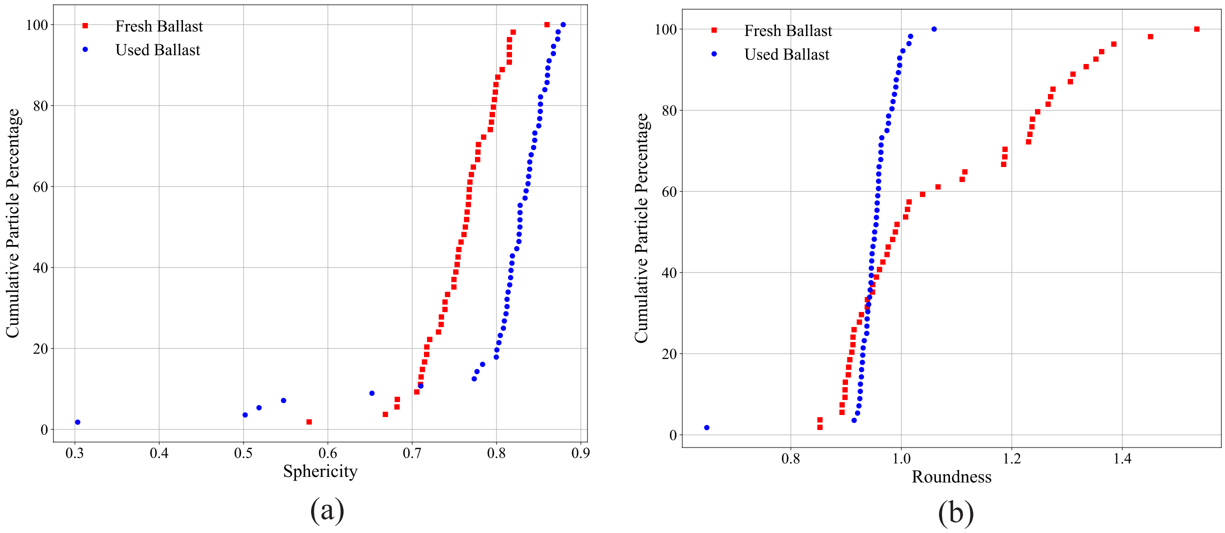

Fig. 10. Cumulative ballast particles percentage as a function of sphericity (a) and roundness (b).

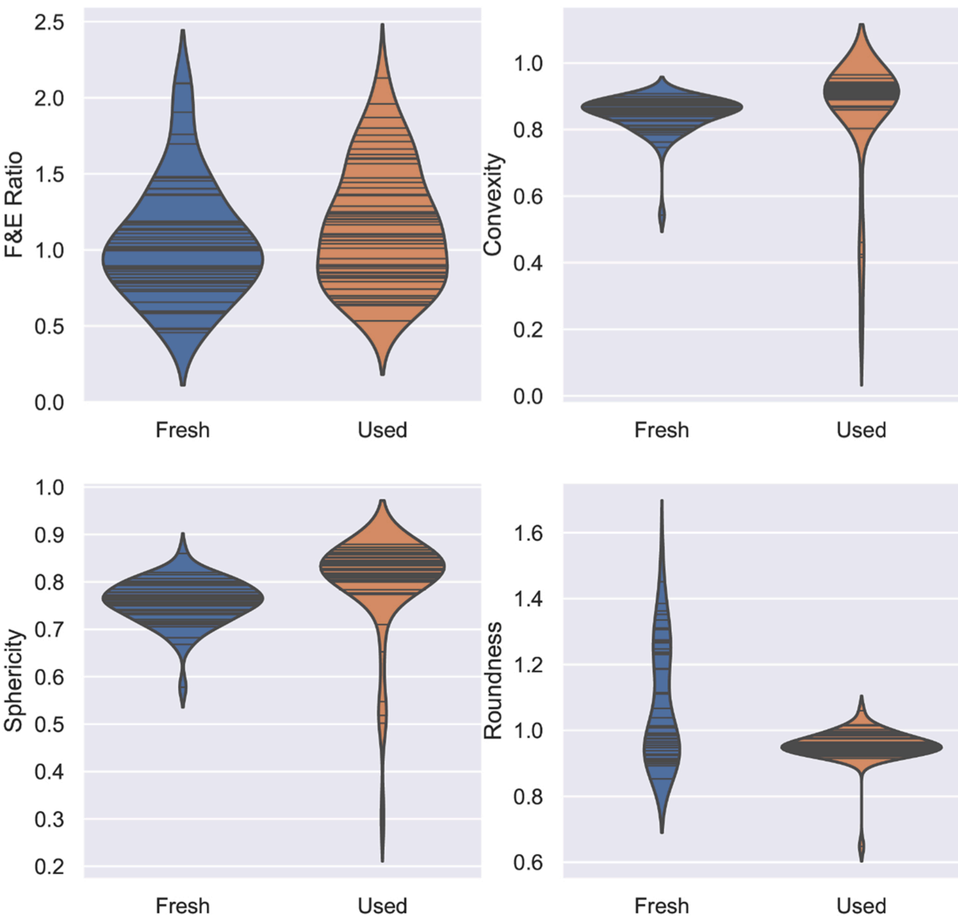

Fig. 11. The violin plot of F&E Ratio, convexity, sphericity, and roundness of fresh and used ballast.

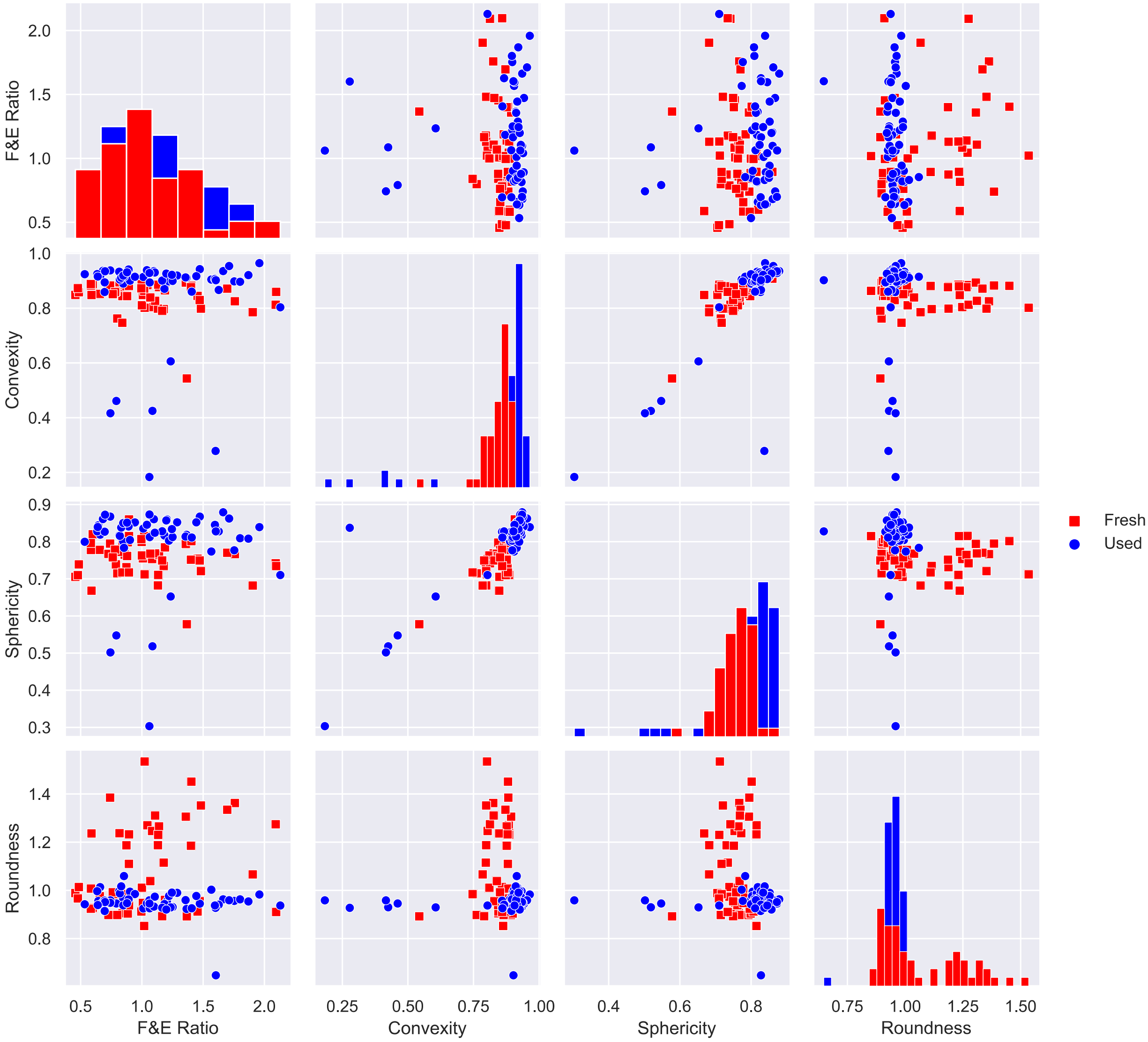

Fig. 12. The pair plot of F&E Ratio, Convexity, Sphericity, and Roundness of fresh and used ballast.

recommendations can be made as follows.

- The used ballast, generated from fresh ballast using the LAA method, exhibited a higher flatness index, with more than 10 % of particles having a flatness index close to 1, indicating a nearly cubic or spherical shape. The elongation distribution and F&E Ratio of fresh and used ballast were uniform, and their values were almost identical.
- The convexity and sphericity indices of used ballast were higher than those of fresh ballast. The roundness indices of used ballast were distributed within a small range, with approximately 70 % remaining constant at around 0.95. In contrast, the roundness indices of fresh ballast exhibited a wider distribution. Although some overlap was observed in the data between fresh and used ballast, specific pairs of shape indices, such as roundness and convexity, showed significant differences and potential for distinguishing between the two types.
- A systematic definition of used ballast based on the basic morphology indices alone was not feasible. Only the combination of sphericity index (> 0.825) and convexity index (> 0.9) could roughly classify fresh and used ballast, although a minor overlap persisted. Further exploration using advanced statistical techniques and machine learning is recommended to develop a more accurate definition. Utilizing sophisticated algorithms and models may unveil subtle differences in the shape index data.

Finally, while differentiating between fresh and used ballast remains challenging, advanced statistical techniques and machine learning can contribute to this distinction. Future studies should investigate the degradation of used ballast under repeated loads and real field conditions.

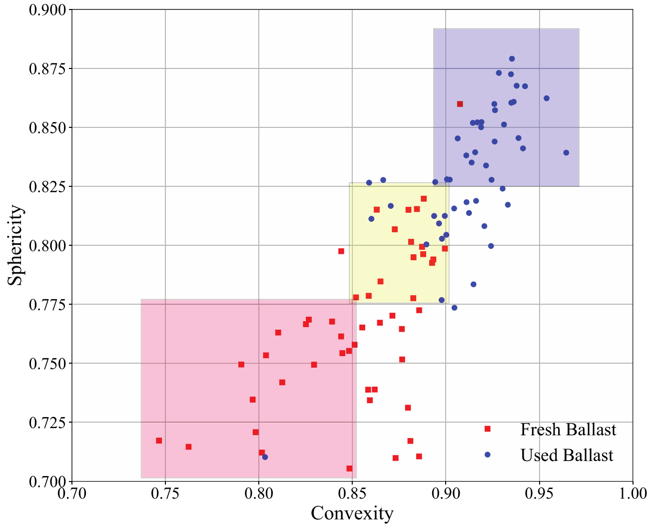

Fig. 13. The magnified view of the relation between Sphericity and Convexity.

CRediT authorship contribution statement

Krittaya Varuntanya: Data Analysis, Methodology, Writing – original draft. **Sararat Kwunjai:** Data Analysis, Methodology, Writing – original draft. **Theechalit Binaree:** Data Analysis, Methodology, Writing – original draft. ***Peerapong Jitsangiam:** Conceptualization, Methodology, Writing – original draft, Project administration. **Guoqing Jing:** Writing – review & editing. **Peyman Aela:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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