Evaluation of the ballast aggregates shape properties using digital image processing techniques

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ABSTRACT: The ballast layer is responsible for supporting the railway superstructure, being repeatedly loaded by the traffic. Performance and operation of railway structures can be influenced by ballast aggregates' shape properties, which include the form itself, angularity and superficial texture. The aggregates shape properties and the particle size may be directly affected by many factors such as: the track usage time, the fouling material that can modify the original granulometry and the maintenance processes. In this context, it is necessary the evaluation of the aggregates' shape properties aiming to verify how they can influence on railway's performance and operation. This work measures these aggregates properties collected from quarries (origin) and aggregates collected after some operation time using ABNT, and AREMA standards, as well as the DIP technique. Results indicated that both materials meet ABNT specifications, the same did not happen when AREMA standards were used. Concerning the DIP results, changes were observed on form, sphericity, and superficial texture, caused by structural efforts from the traffic, by the time of operation that produces fine material and, mainly, by the maintenance procedures (tamping).

1 INTRODUCTION

Performance and operation of the railroad structure can be influenced by shape properties of the aggregates composing the ballast layer, which include the shape itself, angularity and surface texture. The shape properties of the aggregates, as well as their granulometry, can be directly affected by several factors, such as: the time of use of the road, the contamination by thinner materials and the maintenance processes that cause breaking and the abrasion of the particles.

The ballast layer that forms the permanent track of the elastic superstructure is responsible for resist to stresses which come from the sleepers, the transmission of stresses to the subballast and to the subgrade layers, and to facilitate the drainage of the track. The fundamental measurements of shape characteristics for aggregates composing railroad ballast (flatness, roundness and sphericity) are essential for adequate quality control and for understanding their influence on the performance of the track structure. For Huang (2010), the shape properties of the aggregates are determinant in the resistance, the workability and the stability of railroad ballast. The mentioned author considers that both the angularity and the lamellarity of these materials should be used to verify the presence of particles of aggregates that could negatively affect the mechanical properties of the rail ballast. It is desired the existence of angular, rough and non-lamellar particles, increasing the shear strength of the aggregates. On the other hand, air-rounded particles with smooth texture can produce a set of aggregates less resistant to shearing and exhibit high resilient displacements, which is not recommended for the permanent way system.

Given the limitations on the determination of aggregate properties by traditional methods, such as the use of pachymeters, the application of Digital Image Processing to quantify the shape properties of the aggregates is realized as a fast and reliable data concerning the properties of the aggregates with the application of statistic parameters (Al Rousan 2004, Massad et al. 2005, Anochie-Boateng et al. 2011, Mvelase et al. 2012, Anochie-Boateng et al. 2013).

2 AGGREGATES SHAPE PROPERTIES

2.1 *Traditional characterization of the aggregates' shape properties*

ABNT NBR 5564 (2011) and AREMA (2013) specifications for the evaluation of the shape of coarse aggregates that compose the railroad ballast layer seek to identify the percentage of elongated and / or lamellar material in order to provide improvements on the stability of the railway. The first specification, with the direct measurement pachymeter (Fig. 1a), is more restrictive when classifying lamellarity and particles elongation by recommending the 1: 2 ratio. The second, with the special pachymeter (Fig.1b), presents a well-defined methodology for particle sampling, in addition to practically analyzing all the aggregates retained in the most representative sieves of the material, which contains more than 10% of retained material. Although ABNT NBR 5564 (2011) is more restrictive when compared to AREMA (2013) concerning the identification method, it is less restrictive concerning the maximum allowable quantity of non-cubic grains (15% versus 5% suggested by AREMA).

(a) (b)

Figure 1 – Equipment for traditional characterization of form: (a) ABNT NBR 5564 (2011) e (b) ASTM D4791 (2010).

2.2 *Characterization of aggregates' shape properties using Digital Image Processing (DIP) techniques*

Al Rousan (2004) analyzed thirteen types of coarse aggregates and five types of fine aggregates and performed three tests for each size with the same operator, besides using different operators for the same test. The aggregates evaluated in the study showed different mineralogical compositions, diverse sizes and significant variations in relation to the shape properties. Considering the results of the tests, an aggregate classification methodology was developed according to the values provided by the Aggregate Image Measurement System (AIMS) (Fig. 2) for each parameter in study. The author applied a statistical grouping method for the analysis of their results and established classification limits for each property obtained through AIMS, as shown in Table 1.

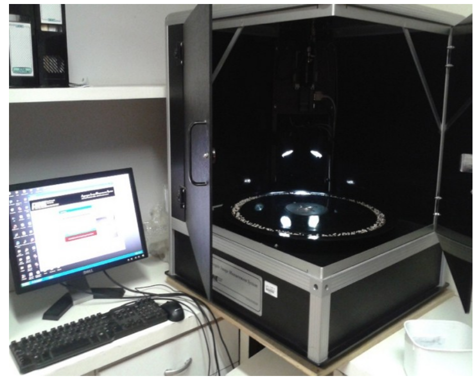


Figure 2 – Aggregate Image Measurement System (AIMS).

The aggregates' shape is evaluated by the radius method or by the Fourrier transform with measurements of short (d_C), intermediate (d_I) and long (d_L) radius. The projections of the particles are observed through the images captured by the camera and the microscope, and then two dimensions of radius can be obtained. The third dimension is obtained using the auto focus function of the equipment. The distance between the table and the camera is determined and taken as a reference. In sequence, the microscope moves and focuses on the surface of the particle. The difference between the two distances is taken as the third dimension of the particle. This analysis allows a differentiation between elongated or lamellar particles/ elongated and lamellar particles (Masad, 2003).

The angularity represents the corners of the aggregates and is obtained by the velocity-based gradient method in which the direction of the gradient vector is changed (Masad, 2003). The surface texture is analyzed using the wavelets method, which characterizes the surface of the materials through the average and standard deviation of the pixel values of the analyzed images. The texture index for each aggregate is obtained for a given level of decomposition. Al Rousan (2004) describes the texture as being the irregularities of the surface of the aggregate on a scale that is so small as not to affect the overall shape of the aggregate.

It is important to note that the equipment allows the analysis of particles with a maximum size of 25.4 mm, being characterized the coarse fractions with 50 particles of each sieve (25.4, 19.0, 12.5, 9.5, 4 , 75mm) and the fine fractions with 150 particles of each sieve (2.36, 1.18mm, 600, 300, 150 and 75µm).

Table 1 – Aggregates' shape properties classification using AIMS.

Properties (aggregates)	Limit values / Classification				
Form 2D (fine)	< 6,5 Circular	6,5 – 8,0 Semi-circular	8,0 – 10,5 Semi-elongated	>10,5 Elongated	-
Sphericity (coarse)	< 0,6 Flat Elongated	0,6 – 0,7 Low Sphericity	0,7 – 0,8 Moderate Sphericity	>0,8 High Sphericity	-
Angularity (fine and coarse)	<2100 Rounded	2100 – 4000 Sub-Rounded	4000 – 5400 Sub-Angular	>5400 Angular	-
Texture index (coarse)	<165 Polished	165 – 275 Smooth	275 – 350 Low Roughness	350 – 460 Moderate Roughness	>460 High Roughness

Source: Al Rousan (2004).

Thus, the aggregates that compose the grain size curve of the real material were characterized with the use of the AIMS, except for the particles retained in the sieves 37.5, 50 and 63.5 mm. However, the characterized shape parameters were replicated to the complete material used in the rail ballast. According to Bessa et al. (2013), aggregates retained in the same sieve with different mineralogical origins have in average the same shape, angularity and texture properties due to the similarity in the crushing processes used. In the specific case of lamellarity, there is a constant feature for different particle sizes, since the origin and maximum nominal size of the aggregates are the same. Therefore, it is believed that an offset in the grain size curve can represent a consistent approximation of the shape of the particles, in comparison with the actual size of the aggregates (Sevi 2008, Klincevicius 2011, Merheb 2014).

2.3 *Deterioration of aggregates and fouling of the voids*

Some studies report that about 70% of the contaminants have origin from ruptures in the ballast particles, depending on the type of track. This information implies the need to pay permanent attention to the components that are part of this layer in terms of maintaining the efficiency of the permanent pathway (Selig et al., 1988). The effect of aggregate degradation reflects on thin material that contaminates the ballast layer. For Selig & Waters (1994), the fine ballast contaminants are defined as the material passing in the 9.5 mm sieve.

In relation to the filling of the voids, the mentioned authors proposed an index to analyze this property, the Fouling Index (FI). Such index is calculated by summing the percentage (by weight) of passing material in the 4.75 mm (No. 4) and 0.075 mm (No. 200) sieves. The assessment of the degree of fouling was based on classification of fouling levels, being less than 1 classified as clean, 1 to 10 as moderately clean, 10 to 20 as moderately fouled, 20 to 40 as fouled and greater than or equal to 40 as highly fouled.

Indraratna et al. (2011) argue that aggregates with non-uniformity coefficient (CNU - the relation between the diameter through which 60% of the particles of the material pass and the diameter through which 10% of the particles pass) higher than 2.2 have lower degree of rupture of the aggregates that compose the rail ballast. Concerning the drainage, these size distributions contribute to an adequate permeability in the permanent path, while the ballast is free of fines and the drainage system is functioning properly. The mentioned authors report the need to balance the higher ballast strength with adequate track drainage, in terms of grain size, recommending a new size distribution range for ballast with CNU between 2.3 and 2.6.

3 MATERIALS AND RESULTS

The material collected for the present study was used in railway ballast. One type of aggregate for use in the ballast was located in the quarry's ballast pile and the other was collected directly from a railroad with certain time of operation (five years of use in the permanent path). The source material passed through the primary and secondary crushers, respectively by jaw and cone crushers. The evaluated material collected after a certain time of use was from the main line of the industrial site responsible for inbound and outbound traffic of wagons and platforms that transport rails and sleepers to the railroad track under construction.

3.1 *Aggregates' deterioration and fouling of the voids*

The granulometry is an indirect indicative of several other characteristics of the ballast, including the resistance to breaking, the resilience, the accumulation of plastic deformation and the shear strength of the material. The grain size curve of the source/ballast aggregate is in the Australian range N ° 60 with a uniform characteristic (Fig. 3), with CC of 1, CNU of 1.9 and IC of 0.8%. For the aggregate of ballast with five years in service, the grain size curve was different from the ballast material curve, probably due to the wear of the particles and the formation of finer fragments, with CC of 1, CNU of 1.9 And IC of 0.2%. This way, the materials were more likely to breaking, from the conclusions of the study carried out by Indraratna et al. (2011) and classified as clean, based on the study from Selig & Waters (1994).

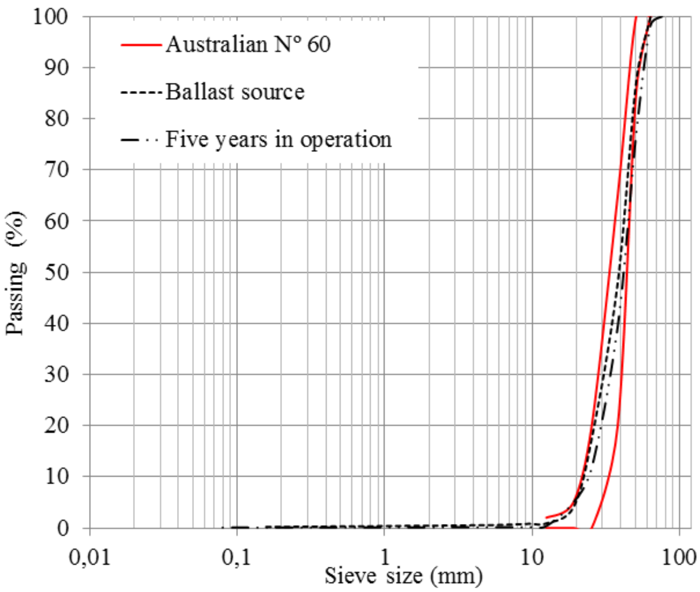
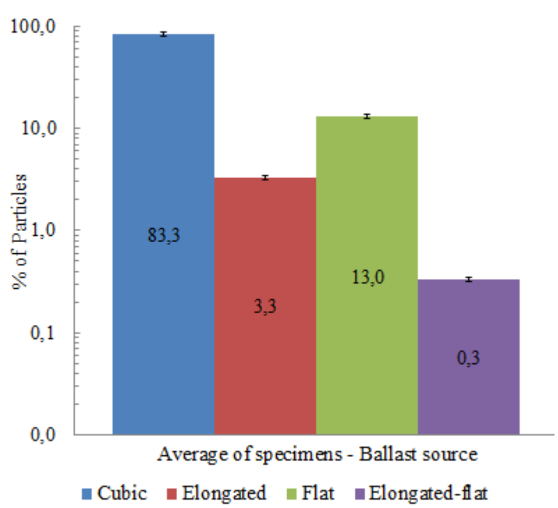


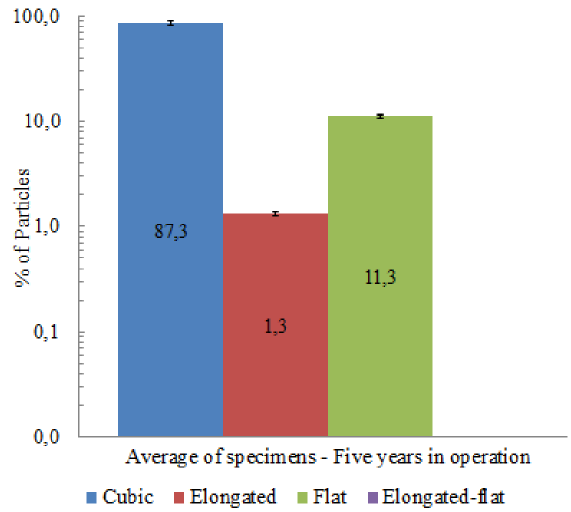
Figure 3 – Granulometric curve of aggregates: ballast source and five years in operation.

3.2 *Evaluation of the traditional form*

The shape values obtained by the ABNT specification NBR 5564 (2011), were similar for the three analyzed samples of each material. Figure 4 presents the average result obtained for the aggregates from origin / ballast (Fig. 4a) and after five years of use (Fig. 4b). It can be observed that the non-cubic particles (lamellar, elongated and elongated-lamellar) are a significant part of the two materials. The original material showed signs of being able to be used in the ballast layer because of a superior confidence interval of 85.4%, being acceptable by the specification of the Brazilian standard (15% limit of non-cubic fraction). The material with five years of use in the permanent way had the lowest confidence interval of 86.1%, making it acceptable for the percentage of non-cubic particles, established by ABNT NBR 5564 (2011).



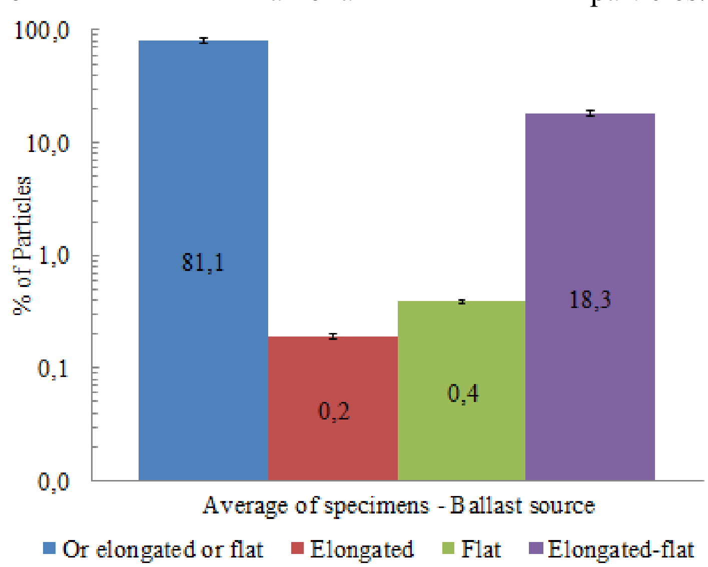
(a)



(b)

Figure 4 – Result of the traditional form test the NBR 5564 (2011): a) ballast source e b) five years in operation.

Figure 5 shows the average percentage found after performing the triplicate test as for the traditional ASTM D4971 (2010) standard established by AREMA (2013), Figure 5a for source material / ballast and Figure 5b for the material after five years in service. A representative percentage of elongated and / or lamellar particles in the source material / ballast is observed, making this material considered as inappropriate for the ballast layer in the maximum 5% allowed by AREMA (2013). The same can be observed for the aggregates after five years of use, with a lower proportion of the content of elongated and / or lamellar particles.



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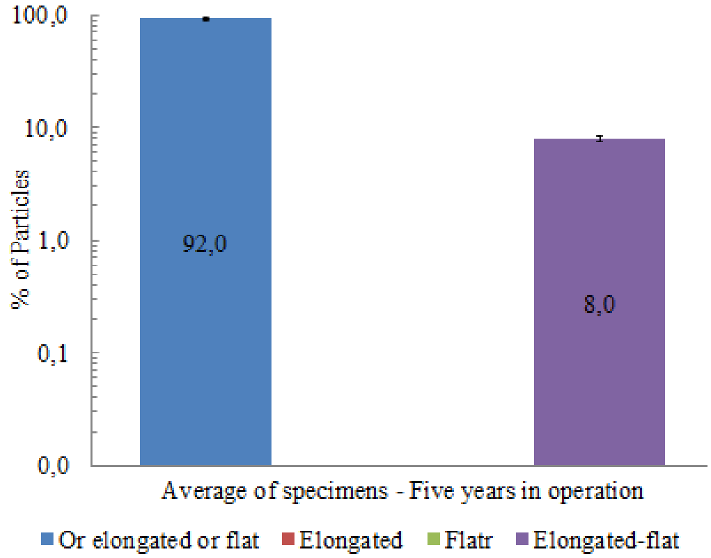

(b)

Figure 5 – Result of the traditional form test the ASTM D4971 (2010): a) ballast source e b) five years in operation.

3.3 *Analysis of the shape properties using the DIP*

Regarding the use of PDI, Table 2 shows the shape properties of the aggregates in relation to the percentiles of particles in each classification range. There was no change in the 2D shape (44.7% of semi-elongated and 33% of circular), sphericity (38.0% of flat-elongated and 34.5% of low sphericity) and surface texture (28.8% of low roughness and 48.4% of smooth) of the evaluated aggregates. Regarding the angularity, the same classification of the fine and coarse aggregates for the same material was observed. In order to understand the behavior of the aggregates with respect to the lamellarity of the aggregates, the relation between the lower and higher values of each particle was obtained. The statistical parameters for each material are shown in Table 3. The variation coefficients presented high values, implying that the particles have different behaviors in relation to the lamellarity when the various sizes are evaluated, and the material after five years in service has the lower ratio of lamellarity compared to that obtained for the origin / ballast material.

Table 2 – Classification of the aggregates' shape properties for the highest percentage of particles in the range.

Shape properties	Evaluated aggregates	
	Ballast source	Five years in operation
Form 2D	Semi-elongated	Circular
Sphericity	Flat Elongated	Low sphericity
Angularity	Sub-rounded	Sub-rounded
Texture index	Low Roughness	Smooth

Table 3: Statistical parameters for lamellarity obtained in AIMS

Aggregates	Average	Std. Deviation	CV (%)
Ballast source	2.82	1.16	41.1
Five years in operation	2.31	0.77	33.3

4 CONCLUSIONS

This study compared shape, angularity, and texture properties of original ballast aggregates (collected in the investigated quarry ballast pile) with aggregates used in the rail ballast layer with five years of operation. In the evaluation of the aggregates, the traditional methodologies ABNT NBR 5564 (2011) and ASTM D4971 (2010) were used, as well as the PDI with the use of AIMS.

Concerning the characterization of shape of aggregates by ABNT NBR 5564 (2011), both materials presented indications for application in the railway ballast layer by meeting the maximum specifications of non-cubic particles (15%). For the specifications of ASTM D4971 (2010), both materials were found to be unsuitable for containing more than 5% of lamellar and / or elongated particles. It is noted the difference between the two methodologies, with ABNT NBR 5564 (2011) being more restrictive with respect to lamellarity and particle elongation (1:2 ratio), but less critical in the maximum amount of non-cubic particles. In general, the source material contains more elongated and / or lamellar particles compared to the material after five years in operation on the permanent pathway. The ratio of lamellarity, shape and sphericity extracted from AIMS confirmed this higher quantitative in the origin material.

Changes in shape, sphericity and texture of the aggregates in the origin source (semi-elongated, flat / elongated and low roughness) compared to five years of use (circular, low sphericity and smooth) can be explained by the distribution of stresses from traffic, by the rigidity of sleepers and the friction between particles, by the time of use generating fine material and, mainly, by the process of maintenance with insertion of metallic blades on vibration causing the wear and the abrasion of the particles.

Thus, the shape properties of the aggregates after five years in service are susceptible to generate sliding in the contact between particles, altering the structure of the ballast with rearrangement of particles, causing changes in the mechanical behavior. Considering the obtained results, it is suggested to evaluate the mechanical behavior of both materials in order to predict the resistance to permanent deformation of the ballast and the possible geometric alteration of the track.

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