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Study of granulometric ranges in the behavior and useful life of railway ballast using dynamic testing equipment

Estudo das faixas granulométricas no comportamento e vida útil do lastro ferroviário utilizando equipamento de ensaio dinâmico

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Abstract: The particle size range directly influences the useful life of the ballast layer when subjected to loads generated by railway traffic. However, in Brazil, we only have two particle size ranges to be used. Those recommended by Brazilian regulatory bodies are quite uniform, and publications referring to more efficient mechanical behavior express the need for a well-graded lane, different from the lanes normally used on Brazilian roads. Therefore, the influence of the particle size of the ballast used on railways was the object of study, with the aim of verifying the mechanical behavior and its influence on the useful life of the track, mitigating the generation of fines and maintaining drainage efficiency. For this, two granulometric ranges were chosen: Range 3 of AREMA (Range A of the Brazilian Association of Technical Standards - ABNT) and Australian Range 50. For this study, using dynamic equipment that simulates railway traffic, two different granulometric ranges were analyzed, and with the data found on Cc, CNU, fineness modulus and maximum diameter, a better graduated particle size range and a particle size distribution that fit into this new range were proposed to be used, in order to improve the overlap between the grains, reducing their breakage , improving deformability, without compromising permeability.

Keywords: Mechanical behavior of railway ballast ; Particle size range ; Ballast Dynamic Test Equipment.

Resumo: A faixa granulométrica influencia diretamente na vida útil da camada de lastro quando submetida às cargas geradas pelo tráfego ferroviário. Porém, no Brasil, temos apenas duas faixas granulométricas disponíveis para uso. As recomendadas pelos órgãos reguladores brasileiros são bastante uniformes, e publicações referentes a comportamento mecânico mais eficiente expressam a necessidade de uma faixa bem graduada, diferente das faixas normalmente utilizadas nas estradas brasileiras. Portanto, a influência da granulometria do lastro utilizado nas ferrovias foi objeto de estudo, com o objetivo de verificar o comportamento mecânico e sua influência na vida útil da via, mitigando a geração de finos e mantendo a eficiência da drenagem. Para isso foram escolhidas duas faixas granulométricas: Faixa 3 da AREMA (Faixa A da Associação Brasileira de Normas Técnicas - ABNT) e Faixa Australiana 50. Para este estudo, utilizando equipamento dinâmico que simula o tráfego ferroviário, foram analisadas duas faixas granulométricas diferentes, e com os dados encontrados de Cc, CNU, módulo de finura e diâmetro máximo, foi proposta uma faixa granulométrica melhor graduada e uma distribuição granulométrica que se enquadrasse nesta nova faixa para ser utilizada, a fim de melhorar a sobreposição entre os grãos, reduzindo sua quebra, melhorando a deformabilidade, sem comprometer a permeabilidade.

Palavras-chave: Comportamento mecânico de lastro ferroviário; Faixa granulométrica; Equipamento de Ensaio Dinâmico de Lastro.

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1. Introduction

According to Brina (1988), railway pavement is composed of infrastructure and superstructure. The earthworks are the bed of the infrastructure, as are all other important services to be carried out below ground level. The superstructure is composed of: sub-ballast, ballast, sleepers, rails and fastening elements.

The ballast, according to Stopatto (1987), is a crushed material placed above the railway subgrade in order to provide uniformity and keep the track in the correct position, as well as to cushion impacts from traffic. Brina (1988) states that the ballast material is one of the elements of the railway superstructure located between the sub-ballast and sleeper layers. According to Paiva (2016), the ballast has the following functions:

- To ensure good drainage, preventing the sleepers from being immersed in water;
- To ensure good elasticity to the track, acting as a shock absorber for impacts from traffic, thus allowing smooth and comfortable transit;
- To ensure firm and stable support for the sleepers, absorbing and transmitting loads to the lower layers;
- To prevent movement of the sleepers, whether longitudinally or transversely;
- To ensure speed and efficiency in track maintenance, whether mechanical or manual, in leveling and in the alignment of the railway track.

Deformations in a railway pavement can be elastic or resilient (deflections) and plastic or permanent (sinking). Traditionally, permanent deformations are considered to be maintained in roads, since they are responsible for road level differences without the presence of traffic (Fernandes, 2005).

According to Bathust and Keer (1995), to determine stresses and deformations in all elements of a track, it is important to understand the mechanical behavior of a railway. However, this is not an easy problem to understand, as the number of variables we do not know is large. An example of this is the wide variety of properties of granular media throughout the entire route. To perform the analysis of the mechanical behavior of the railway, it must be divided into two stages. The first must be done on rails with a constant inertia beam. The next step is to analyze the response of the base that supports the rail, which is formed by support plates, rails, sleepers, ballast and sub-ballast (Bathrust, Keer, 1995).

According to Selig and Waters (1994), the appearance of fines in the ballast layer depends not only on the rock matrix being used as ballast on the track, but also on the purpose for which the track is being used. Analyses were carried out on ballast materials in several railroads in the North American continent, and it was found that approximately 76% of the fines present on the track came from ballast degradation. Of the other 24%, 13% were particles from layers below the ballast, such as sub-ballast or old ballast layer, 7% from other sources that entered the ballast layer from the surface, 3% from the ballast layer, subgrade and 1% from the natural wear of the sleeper.

When we study bands used in other countries, we discover that there are many more bands for use, which means that for each type of material and load, the behavior and service life of the ballast becomes different. In some cases, in Brazil, we import particle size bands used in other countries, mainly in the United States, even knowing that the stony characteristics of the materials are different. That is why this study is important.

The main objective of this work was to present a new particle size range for aggregate in the studio, based on the development of a methodology and technical procedure for behavior analysis using the Dynamic Ballast Testing Equipment.

For this purpose, the fundamental criterion of this study was the optimization and/or mechanical behavior through the development of tests, reproducing the focus area on a real scale, that is, less fines generation, better mechanical interlocking and good deformability.

The study was developed using equipment that applies a load of 20 tons, simulating rail traffic. The name of the equipment is: Ballast Dynamic Test Equipment (EEDL).

The study was carried out between 2016 and 2020, therefore, for the analysis of the results, all were based on the particle size range recommended by NBR ABNT 5564/2014.

2. Methodology

This study was developed experimentally with the objective of comparing two particle size ranges used in the United States/Brazil and Australia and, from there, presenting a suitable particle size range for the gneiss crushed stone used in the study, with a lower squaring index of the material. The Australian range 50 and the AREMA range 3 were chosen (ABNT Range A falls within AREMA Range 3).

With the results of the ballast breakage index, it is possible to verify the useful life of the layer when subjected to a cyclic load of 20 tons per wheel. This material decomposition data is important for designing a new particle size range for the material under study.

The ballast material used was collected from a quarry in the city of Santa Bárbara – MG. Its collection took place in the ballast pile located inside the company. The collection was carried out according to Annex G of NBR ABNT 5564/2014. The sub-ballast and subgrade materials also come from the North-South Railway (Hilário and Fernandes, 2021).

The ballast material characterization tests were those specified by NBR ABNT 5564/2014.

With the values found for Cc, CNU, fineness modulus and maximum diameter, a better-graded particle size range and a particle size distribution that fits within this new range were proposed for use as ballast, to improve the overlap between the grains, reducing breakage, improving deformability, without compromising permeability.

3. Sample preparation and services for analysis on the Dynamic Ballast Testing Equipment

The particle size range was placed in the Dynamic Ballast Testing Equipment to verify particle size efficiency, studying its breakage index and the service life of the ballast. This study made it possible to verify that the service life of the ballast and its breakage index are directly influenced by the particle size range used. This is why the analysis of the equipment is important.

Typical requests (in terms of stresses) of a railway structure were reproduced using a metal box to model the layers of what is normally designed in railway infrastructure. This state-of-the-art cyclic load application equipment was designed and built to investigate the resistance, deformation and degradation characteristics of ballast, sub-ballast, subgrade, sleeper and rails under cyclic load. The sequence of layer thicknesses is described below. The choice of these thicknesses was based on a type of section of a real railway:

- Subgrade: 35 cm;
- Sub-ballast: 20 cm;
- Ballast: 30 cm below the bottom of the sleeper.

To prepare the subgrade and sub-ballast layers, it was necessary to bring the materials to the ideal moisture content before compaction. The materials with the ideal moisture content were taken to be compacted in the equipment, first the subgrade and then the sub-ballast. Immediately after compacting the subgrade layer, the settlement rods were positioned in the appropriate locations. These two rods are used to measure the settlement of the subgrade layer. To avoid friction between the rod and the soil, PVC pipes were placed on each rod. After this process, the sub-ballast was compacted and two more rods were positioned. These are used to measure the settlement of the sub-ballast layer. To ensure that the layer was ready and correctly compacted, two tests were performed: Speedy and Sand Jar. The standard used to certify the values was ISF-207/2017 and the Infrastructure Services Specification – Sanitary Landfill (VALEC, 2017). After these two layers were ready, the ballast was sieved according to the particle size to be analyzed. It was homogenized and placed inside the metal box. As soon as the ballast was positioned, the crushed stone was manually crushed. When it reached 30 cm in height, the sleeper was positioned along with the rail and fasteners. After this sequence, the extensometers were positioned on the four rods and two on the sleeper. The extensometers positioned on the sleeper are used to measure how much the ballast is compressing.

To study these characteristics, a series of laboratory tests were carried out, using the same model of permanent way construction (rail, sleeper, ballast, sub-ballast and subgrade). The rupture forces of the ballast grains were then studied in a series of simple tests. In the simulator considerations, with a cyclic load device, we have a frequency of approximately 4.0 Hz, and its NCM (number of cycles per minute) of approximately 240 cycles/min (14,400 cycles/hour and 345,600 cycles/day). With this frequency, we can simulate a train at a speed of approximately 29 km/h. This speed is the maximum capacity that the equipment can simulate. A sensor was installed to count the beats. Figure 1 shows the sequence of the test setup.

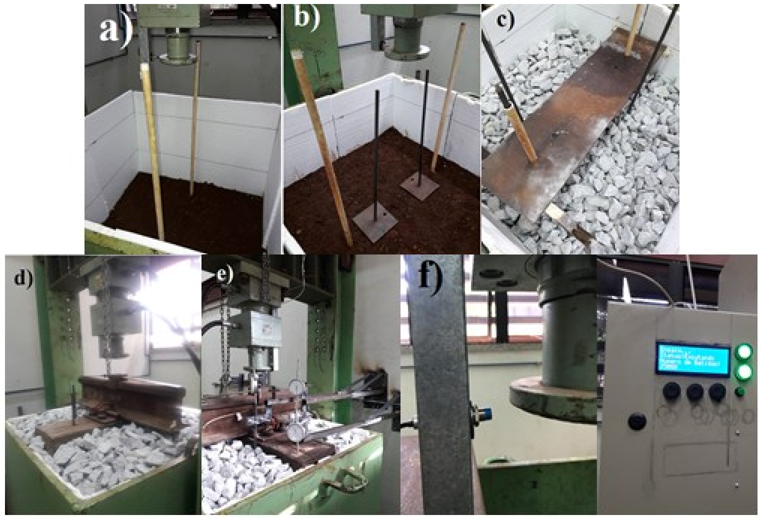

Figure 1 – a) Pressure rods positioned on top of the subgrade layer; b) Reinforcement rods positioned on top of the sub-ballast layer; c) Placement of crushed stone; d) Installation of sleepers, rails and fastening elements; e) Installed extensometers; f) Runout sensor and counter.
Source: Authors (2025).

4. Results and analysis

Figure 2 shows the graph of the initial curves of the two ranges studied.

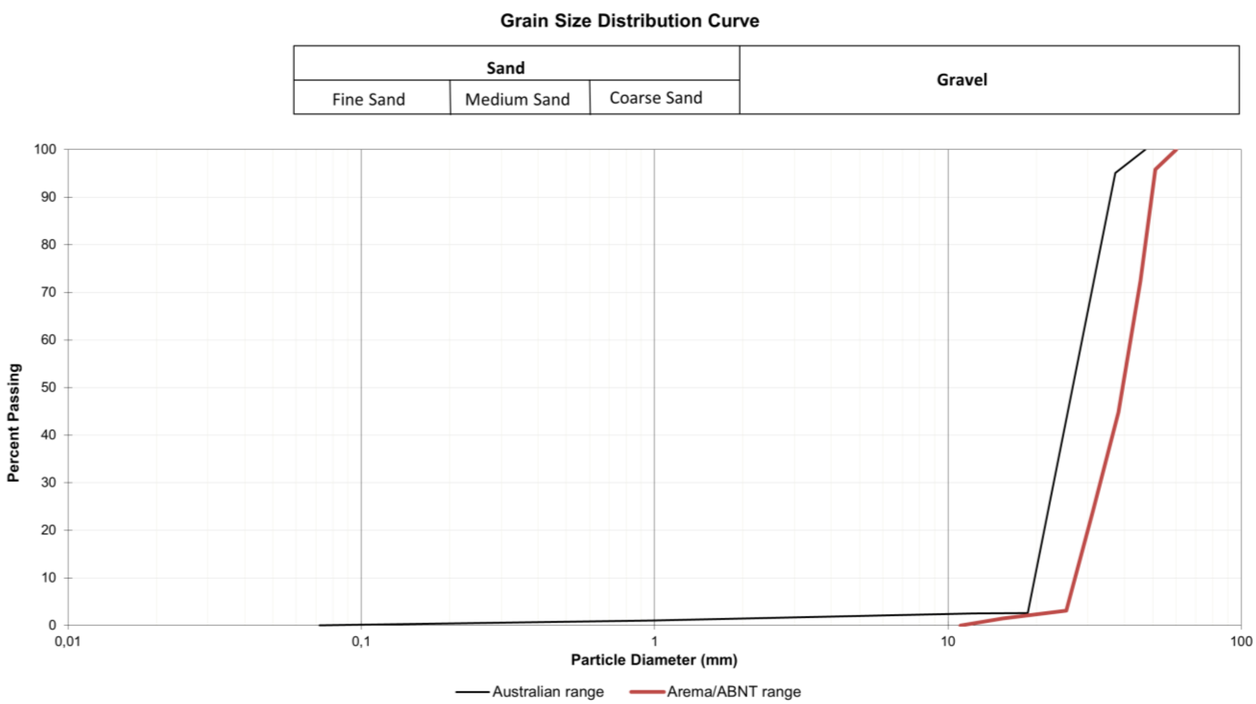

Figure 2 – Initial Particle Size Distributions of the Two Studied Strips.
Source: Authors (2025).

According to Figure 2, it was observed that the AREMA/ABNT range studied is coarser than the Australian range. This is evidenced by the initial Fineness Modulus of the curves. The AREMA/ABNT range has a value of 8.53 and the Australian range has a value of 8.03.

At the end of the cycles, a significant break was observed in the particle size distribution curve of the AREMA/ABNT range, as shown in Figure 3.

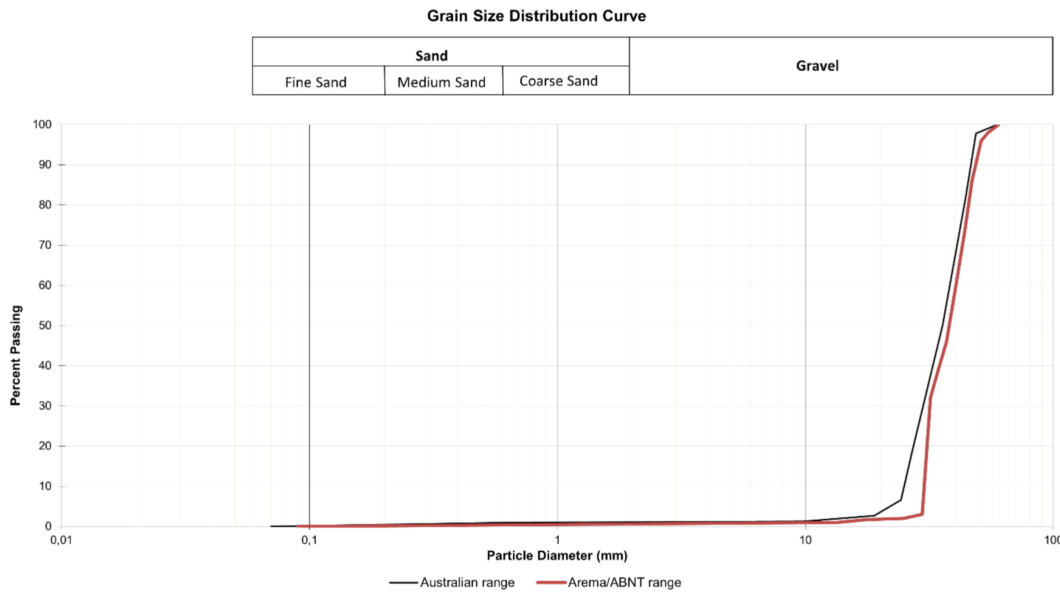

Figure 3 – Comparison of the Initial and Final Curve of the AREMA/ABNT Range.
Source: Authors (2025).

The shift in the particle size distribution curve evidenced by the particle size distribution that falls within the AREMA/ABNT range is not as evident when compared to the Australian range, as shown in Figure 4.

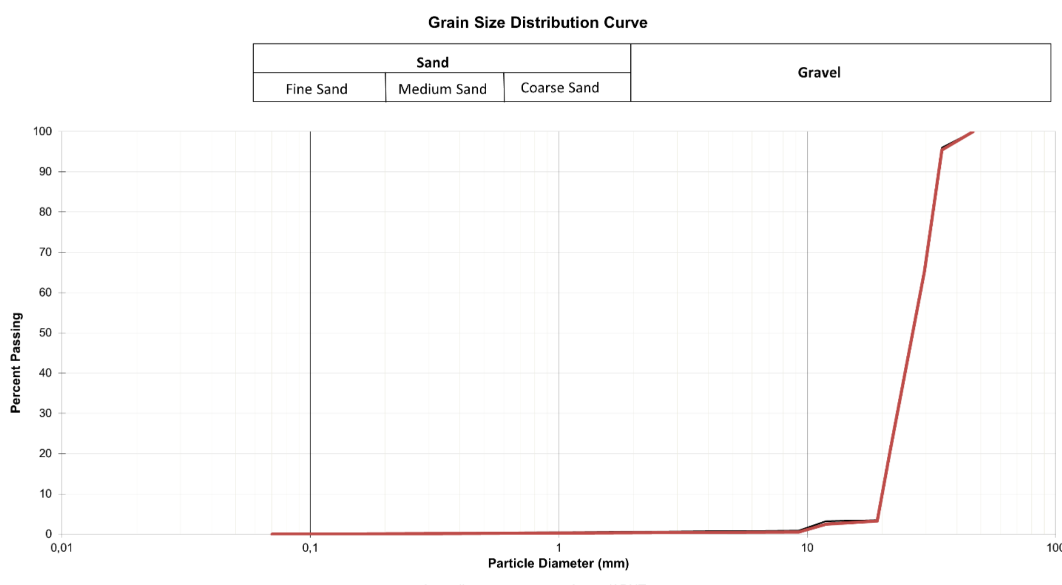

Figure 4 – Comparison of the Initial and Final Curve of the Australian 50-pound Band.
Source: Authors (2025).

As observed in Figure 4, there was an overlap of the analyzed curves. The Fineness Modulus value showed a slight reduction, starting at 8.03 and decreasing to 7.99. The percentage of breakage was also lower when compared to the AREMA/ABNT range. This shows that with a lower fineness modulus, the grain overlap is less, consequently reducing breakage.

This is evident when comparing the particle size distribution curves of the two analyzed ranges (Figure 5).

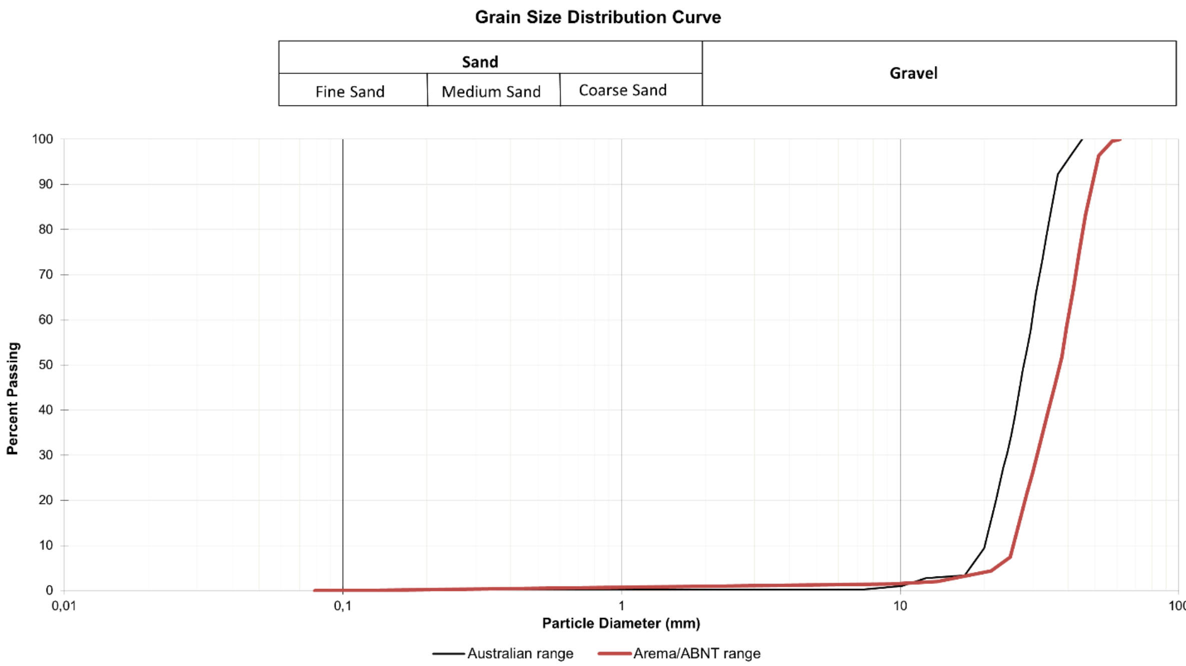

Figure 5 – Comparison of Final Particle Size Distribution - AREMA/ABNT and Australian.
Source: Authors (2025).

The particle size distribution curve of the AREMA/ABNT range remained uniform, as did that of the Australian range.

Regarding the Cc value, there was an improvement in both ranges, but the Australian range became well-graded. Despite the improvement in the Cc value of the AREMA/ABNT range, the curve remained poorly graded.

The CNU value of the Australian range remained the same compared to the initial value, which was 1.50. In the AREMA/ABNT range, there was a significant improvement in this standard. The initial value was 1.45, and the final value was 1.54.

The contamination index of the analyzed particle sizes is presented in Table 1.

Table 1 – Comparison of Contamination Indices.

Particle Size Range	Contamination Index
Band 3 AREMA (A ABNT)	1.1
Australian 50 Series	0.5

Source: Authors (2025).

The result of the Contamination Index shows a particle size distribution for ballast, with the presence of less coarse materials, with a lower fineness modulus, providing a lower breakage index. By reducing this breakage index, the service life of the ballast tends to increase. This causes the permanent deformation to be smaller, with less material breakage.

According to the contamination index, it was possible to project the service life of the material. For this, the contamination index (FI) was calculated at the end of each cycle, as shown in Table 2.

Table 2 – Contamination Indices (FI) at the end of each cycle.

Particle size	0	100 thousand	200 thousand	300 thousand	400 thousand	500 thousand
AREMA/ABNT	0	0.21	0.38	0.63	0.93	1.17
Australian	0	0.12	0.20	0.23	0.29	0.47

Source: Authors (2025).

Based on the data in Table 2, a graph was created to estimate the service life of the material used in each particle size range. Figures 6 and 7 show the graphs of the variation in the service life of the material from AREMA/ABNT and the Australian material, respectively.

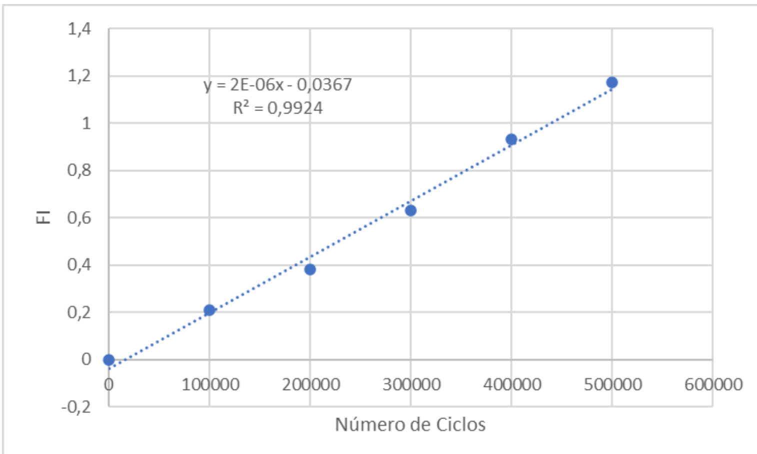

Figure 6 – Graph of number of cycles x FI – AREMA/ABNT.
Source: Authors (2025).

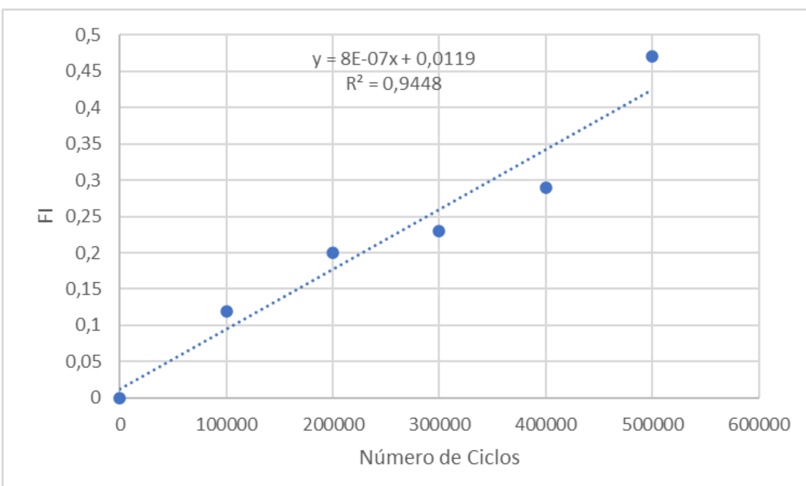

Figure 7 – Number of cycles x FI graph – Australian.
Source: Authors (2025).

Another methodology was used to account for ballast contamination. An analysis was performed considering the material passing through the 3/8” sieve as contaminating material. Table 3 presents this quantity at the end of each cycle.

Table 3 – Contamination indices at the end of each cycle considering material passing through the 3/8" sieve

Granulometria	0	100 thousand	200 thousand	300 thousand	400 thousand	500 thousand
AREMA/ABNT	0	0.20	0.40	0.70	1.0	1.2
Australiana	0	0.14	0.23	0.30	0.36	0.51

Source: Authors (2025).

Based on the data in Table 3, a graph was created to show the variation in the percentage passing through the 3/8" sieve. Figure 8 presents the AREMA/ABNT particle size distribution graph, and Figure 9 shows the Australian particle size distribution graph.

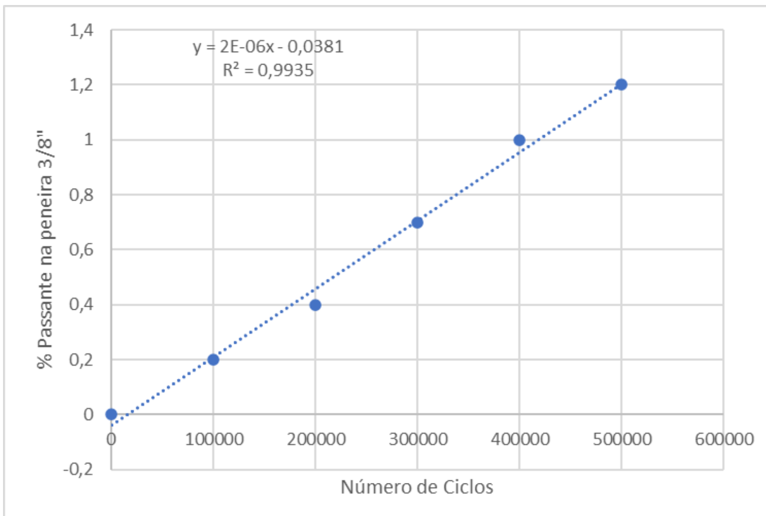

Figure 8 – Graph of number of cycles x passing 3/8" – AREMA/ABNT.
Source: Authors (2025).

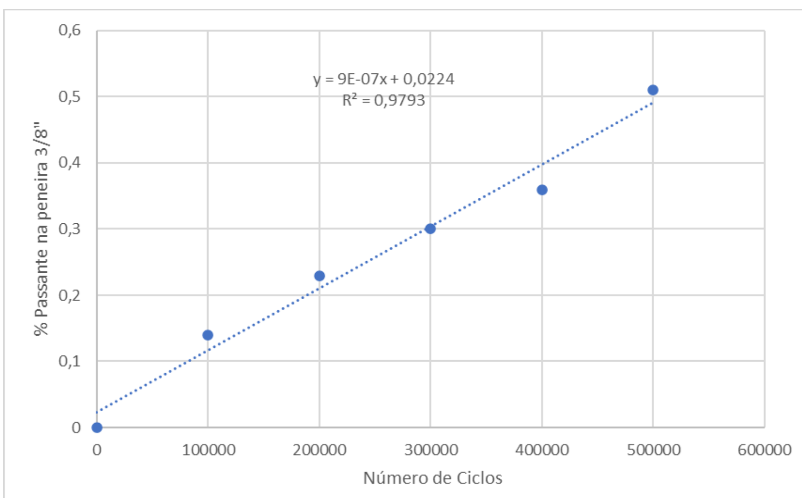

Figure 9 – Number of cycles x through 3/8" graph – Australian.
Source: Authors (2025).

Using the equations generated by the graphs in Figures 8 and 9, we can project the number of degreasing cycles. Considering the generation of 50% fines, we have the following values for the number of cycles, according to the methodology used (Table 4).

Table 4 – Number of cycles to generate 50% fines.

Particle size	FI	% Passing through 3/8 sieve
AREMA/ABNT	25,018,350	25,019,050
Australian	62,485,125	55,530,667

Source : Authors (2025).

To arrive at the result of producing 50% fines, both for the FI analysis and for the material passing through the 3/8" sieve, an extrapolation was performed. The growth was linear, but for a number of 500,000 cycles. It would be interesting in future studies to perform a larger number of cycles to verify the tendency of this curve, whether it will be linear or not.

The use of a material with a lower fineness modulus does not compromise one of the ballast's functions, which is drainage. On the contrary, with a lower fineness modulus, there was less material breakage, producing a smaller amount of fines, reducing the level of ballast clogging. This increased the material's lifespan. This becomes evident when projecting the number of cycles sufficient to generate 50% fines.

Regarding the permeability coefficient, the Australian range had a reduction of approximately 5% in permeability. The AREMA/ABNT range had a reduction of approximately 8.2%.

4.1 Analysis of Geogauge H4140 Results

Table 5 presents the results of the Geogauge H4140 test for the AREMA/ABNT and Australian ranges.

Table 5 – Geogauge H4140 Test Result.

Material	Rigidity - K (MN/m)	Elastic Stiffness Modulus - Egeo (MPa)	Resilience Module - MR (MPa)	Shear Modulus - G (MPa)
AREMA/ABNT - Initial	10.56	45.92	160.32	70.65
AREMA/ABNT - Final	10.75	46.74	161.86	71.91
Australian – Initial	11.71	50.91	169.50	78.32
Australian final	11.81	51.38	170.34	79.05
New Proposed Track	11.89	51.70	170.92	79.54

Source: Authors (2025).

According to the results of the Geogauge H4140 test, regarding the stiffness of the AREMA/ABNT strip, there was a slight improvement in the parameters of the final cycle compared to the initial one. Regarding the results of the Resilient Modulus (MR), Elastic Stiffness Modulus (Egeo), and Shear Modulus (G), there was also an improvement in the results. This was due to the better interlocking of the grains in the final cycle compared to the initial cycle.

Regarding the results of Stiffness (K), Resilient Modulus (MR), Elastic Stiffness Modulus (Egeo), and Shear Modulus (G) of the Australian strip, there was also an improvement in the parameters when comparing the initial cycle to the final cycle. With the breaking of the materials, there was a better fit of the particles that make up the ballast, that is, there was a better interlocking of the material, thus reducing the voids and becoming more compact. When analyzing the results of the particle size distributions used in the study, the best results were obtained from the Australian distribution. Regarding material breakage, it is evident that the grain imbrication in the Australian distribution is better. This is evident when analyzing the results with the Geogauge H4140.

The results support the efficiency of the Australian distribution compared to the AREMA/ABNT distribution, for gneiss material, and for a railway with a load capacity of 40 t/axle. It is evident that the ABNT NBR 5564/2014 standard needs to undergo a broader study regarding the particle size distributions to be used as ballast and specifying the rock matrices.

When analyzing the values obtained by the Geogauge H4140 considering the new proposed distribution, it is observed that the results are very close to those of the Australian distribution. This corroborates that, even with materials retained in a larger number of sieves, the rigidity of the layer was not significantly affected.

4.2 Proposal for a new particle size range for ballast material

After conducting the analyses, taking into consideration the following points :
• Cc;
• CNU;
• Fineness Modulus;
• Breakage of materials by sieve;
• Contamination Index;
• Settlement of the ballast layer;
• Need for a more well-graded strip;
• Improved permanent deformation;
• Reduction in the number of voids;
• Improved grain imbrication.

An ideal particle size range was proposed for the material under study, considering that this material is gneiss aggregate, and the required load is 20 t/wheel, simulating a railway with a load capacity of 40 t/axle.
Figure 10 shows this new proposed range.

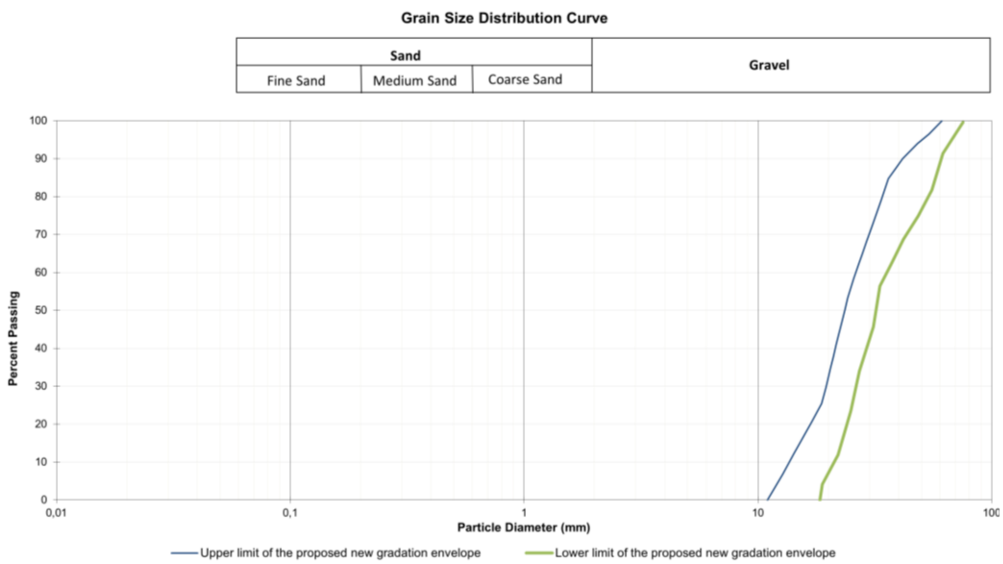

Figure 10 – Proposal for a new particle size range for the material under study.
Source: Authors (2025).

This new range provides a better graded particle size distribution, unlike the ABNT range, which is very uniform. With this better graded range, there are aggregates of different sizes in order to provide better interlocking of the grains. Table 6 shows the limits of this range.

Table 6 – Limits of the Proposed New Lane.

SIEVE OPENING (INCHES)	% PASSING (IN MASS)	
	LOWER LIMIT	UPPER LIMIT
3	-	-

2 ½	90	100
2	75	95
1 ½	62.5	87.5
1	22.5	55
¾	15	25
½	0	3

Source: Authors (2025).

When a particle size distribution is used that includes both coarser and less coarse aggregates, the layer performs better, that is, it has less permanent deformation.

A particle size distribution curve was designed that fits within this new range in order to have parameters for comparison with the particle sizes used. This particle size distribution is shown in Figure 11.

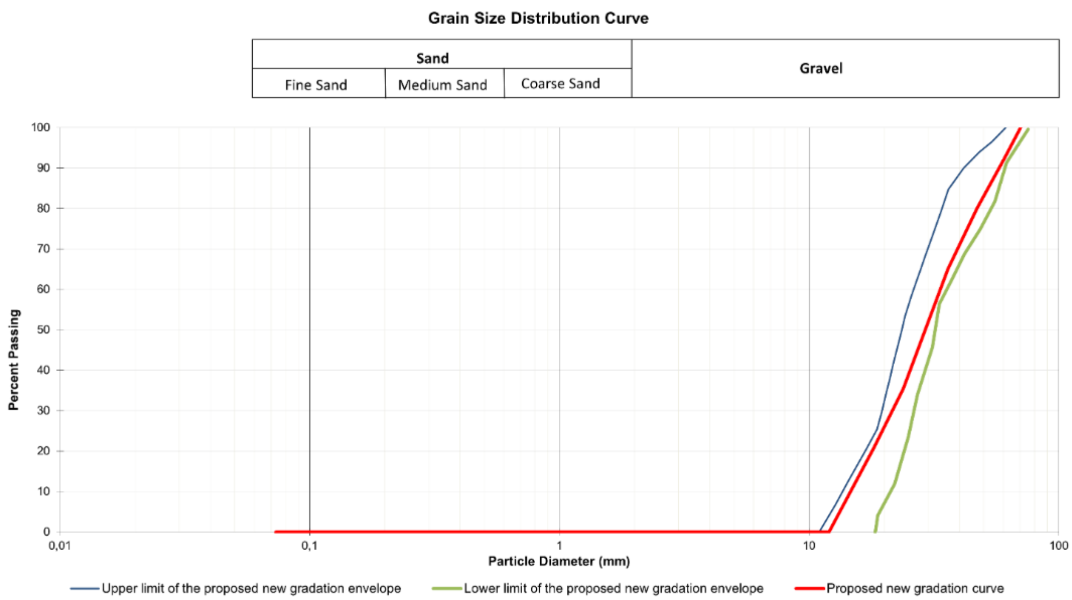

Figure 11 – Framing of Granulometry in the New Proposed Zone.
Source: Authors (2025).

When comparing the 3 (three) particle sizes, we observed a difference in the curve between them. This comparison is shown in Figure 12.

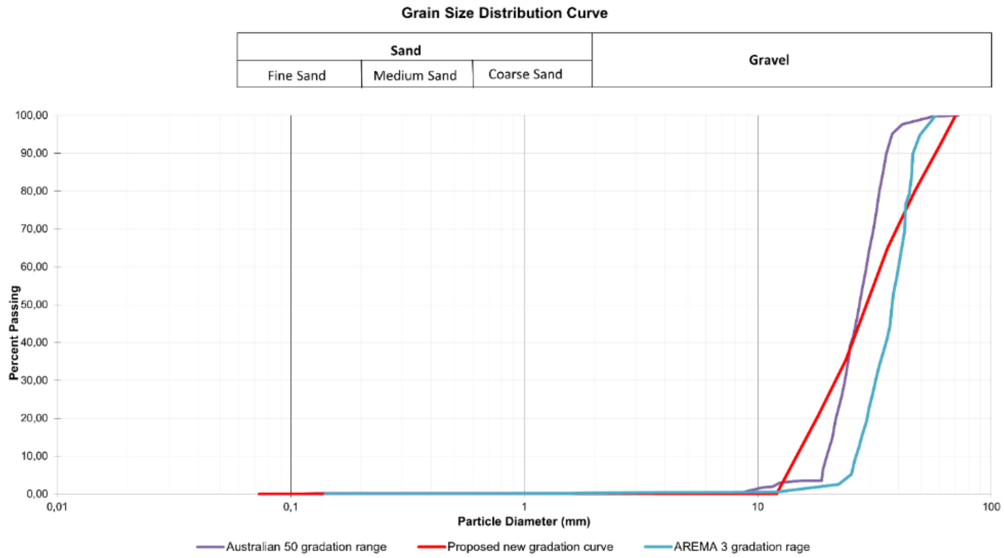

Figure 12 – Comparison Between Granulometric Ranges.
Source: Authors (2025).

Comparing the 3 (three) particle size distribution curves, it is possible to see that the curves from the AREMA/ABNT and Australian ranges are very uniform, unlike the particle size distribution based on the particle size distribution range proposed in this study.

The new curve is steeper, with a more graduated shape, which is supported by studies already mentioned in this work. This is clearly evident when comparing the CNU and Cc parameters of the curves, presented in Table 7.

Table 7 – Comparative Values of Cc and CNU.

	Cc	CNU
AREMA/ABNT	0.79	1.45
Australian	0.96	1.50
New Particle Size Distribution	1.1	2.33

Source: Authors (2025).

As observed in Figure 12 and Table 7, the particle size distribution curve proposed by the new strip became better graded. This is evidenced by the Cc value found, which was between 1 and 3, indicating a well-graded curve. This is different from what was found for the AREMA/ABNT and Australian strips.

Regarding CNU, the value found falls within the range proposed by Buddhima Indraratna and Salim (2002), which is from 2.3 to 2.6. CNU values within this range are ideal for use as railway ballast, without harming track drainage, according to the authors.

Using the Alaymani and Sem Formula (1993), a k value of 2.69 cm/s is obtained. This value is lower than those of the AREMA/ABNT and Australian strips.

When comparing the value found with the reference value of Terzaghi (1967) apud Marchioni and Silva (2010), it is concluded that the new granulometric range does not impair the drainage of the track.

Fernandes et al (2012) conducted a flow test study using granulometric ranges from AREMA and Australia. The test was performed using a PVC cylinder with a diameter of 100 mm and a length of 350 mm (equivalent to the thickness of the ballast layer). The flow values were 1.35 cm/s and 0.73 cm/s for the Australian and AREMA ranges, respectively. When comparing the values found in the study with the value of the new range, it can be seen that the drainage was not impaired.

Ferreira et al (2015) studied the drainage capacity of different types of materials used as railway ballast. In their study using crushed stone as ballast, which was classified as reasonably clean, the average permeability coefficient (k) was 0.0049 cm/s. In the same study, but using steel slag as ballast (classified as moderately clean), the average permeability coefficient (k) was 0.0034 cm/s.

Raymond et al (1976) stated that, for efficient drainage, the permeability coefficient of the ballast would have to be greater than 10-5 m/s.

The hydraulic conductivity of the ballast decreases according to the increase in its degree of contamination, as shown in Table 8 below.

Table 8 – Hydraulic conductivity for the ballast.

Degree of Contamination	Contamination Index	Hydraulic Conductivity (kh)	
		(in./sec.)	(cm/s)
Clean	< 1	1 - 2	2.5 – 5.0
Moderately Clean	1 - 9	0.1 - 1	0.25 – 2.5
Moderately Contaminated	10 - 19	0.06 – 0.1	0.15 – 0.25
Contaminated	20 - 30	0.0002 – 0.06	0.0005 – 0.15
Highly Contaminated	> 39	< 0.0002	< 0.0005

Source: Selig et al (1994); Adapted by the authors (2025).

Based on the permeability coefficient result presented by the new particle size range (2.69 cm/s), the value falls within the specification of Selig et al (1994).

The k value for the new proposed curve was lower compared to the values found for AREMA/ABNT and the Australian range. However, according to the range for CNU values proposed by Buddhima Indraratna and Salim (2015), the new proposed particle size does not impair road drainage. And since the particle size tends to provide better grain interlocking, the layer mosaic will work better, providing less material breakage and increasing its lifespan. Because there will be less breakage, drainage is not impaired in the long term.

The DMC of the new curve was 63.0 mm. Even with a higher DMC compared to the values of the AREMA/ABNT and Australian range, the material interlocking becomes better because the curve is more continuous and well-graduated, making the fit of the ballast particles better.

Another parameter that should be considered is the Fineness Modulus. A comparison of this value is presented in Table 9.

Table 9 – Comparative Values of the Fineness Modulus.

	Finura Module
AREMA/ABNT	8.53
Australian	8.03
New Particle Size Distribution	8.13

Source: Authors (2025).

The fineness modulus of the new range fell between the AREMA/ABNT and Australian values. This is because the AREMA/ABNT particle size distribution has a higher presence of aggregates in the coarser sieves, without any presence in the finer sieves. The Australian sieves' particle size distribution has little material in the coarser sieves and is better distributed from the 1” sieve onwards.

The new proposed sieve mixes coarser materials with smaller grain sizes, resulting in better distribution. The calculated fineness modulus shows a finer, better-distributed particle size distribution, with aggregates ranging in size from 2 ½” to ½”, forming a better mosaic between the grains, better imbrication, allowing for less permanent deformation and reduced material breakage, and consequently a longer service life for the ballast layer.

When analyzing the results of Geogauge H4140, the parameters of the Australian 50 sieve proved more efficient than the AREMA/ABNT. By improving the particle size distribution curve parameters with the new proposed sieve, the Geogauge H4140 results showed slightly greater stiffness than the Australian sieve. However, this increase was not significant. Even with the stiffness of the Australian sieve being greater than that of the AREMA/ABNT, the material breakage was much lower. The trend is that with the improvement of the CNU, Cc, fineness modulus, stiffness and resilience modulus parameters, the new grade tends to be more efficient, with a lower ballast breakage rate.

A more finely graded particle size distribution was one of the proposed studies in Muniz's work (2002). The question was why, in Brazil, a very uniform particle size distribution is used. The particle size distribution for ballast should be more finely graded, that is, less uniform. In addition, more finely graded, unlike those usually used.

As recommended by ABNT, two grades to be used in Brazil are not sufficient due to the different load requirements and the number of rock matrices that can be used as railway ballast. Each matrix has its resistance characteristics, and this must be taken into account, as well as the load that passes through the track.

4.3 Analysis in relation to ABNT NBR/2014 Standard

Based on the results presented, it is evident that railway concessionaires need to rethink and conduct studies to propose more efficient particle size ranges for ballast layers, taking into account not only the rock matrix being used, but also the load passing through the track. And subsequently, ABNT (Brazilian Association of Technical Standards) should validate these studies through standards.

The number of particle size ranges recommended by ABNT is not sufficient for the different types of cargo, and consequently weights, transported by our railways (general cargo, ore, and passengers). In addition to the different types of cargo, another factor is the different rock matrices that can be used as railway ballast layers (limestone, granite, gneiss, among others).

The Brazilian Standard does not consider that the rock matrix being used as ballast material has a direct relationship with the strength and lifespan of the ballast layer.

In addition, the two ranges recommended by ABNT are very uniform, which causes greater grain breakage, reducing the lifespan of the layer and resulting in higher maintenance costs.

The Australian standard recommends not just two strips, but six (6) strips to be used as ballast, as does the European standard. The American standard, however, recommends seven (7) possible strips to be used.

Regarding some tests, it could be analyzed whether the aggregate can still be used if it does not meet certain standard values, provided it meets other requirements (resistance and shape tests, for example). The porosity test is an example. If the material does not meet the standard values, it is discarded, as it is one of the prohibitive tests. This test was adopted by ABNT (Brazilian Association of Technical Standards) based on existing standards in the United States, where the freezing effect of the material is considered due to low temperatures.

These low temperatures cause the water in the pores of the aggregate to freeze, causing fractures, resulting in loss of resistance and consequently breaking the material and reducing its lifespan. This freezing compromises the mechanical behavior of the aggregate used as ballast. This sample freezing problem does not occur on Brazilian railways, as the climate is predominantly tropical.

There are studies with ballast materials that have porosity and absorption values higher than the standard values, but exhibit high resistance values, fitting into the Los Angeles Abrasion, Impact Resistance, and Axial Compression tests.

Studies conducted by Oliveira (2013) and Fernandes (2010) showed that porosity and absorption values outside those recommended by the standard did not interfere with the mechanical characterization results. The studies were done with ferroalloy slag and steelmaking slag, respectively. The steelmaking slag used in the study underwent a stabilization process.

Faria et al (2019) conducted a characterization study of basaltic aggregates used as railway ballast on the North-South Railway. According to the results obtained, two materials presented porosity and absorption values above those recommended by the standard, but, in relation to mechanical tests, they fell within the reference values.

This shows that it is necessary to analyze not only the tests recommended by the standard, but also to develop studies of the material's petrography, in order to analyze the real parameters that would support its use, or not, as a ballast material.

5. Conclusions

The ballast material specified by ABNT NBR 5564/2014 was less efficient compared to the Australian 50 range material. Although the ABNT material is coarser, with higher DMC and Fineness Modulus, it presented a significantly higher percentage of breakage due to less grain interlocking. This occurred because the grain interlocking was less efficient.

Regarding the results of the particle size distribution curves of the ballast material, the need to use a material with a less uniform and better-graded curve was verified, in order to improve grain interlocking, provide better track elasticity, and a lower breakage rate, which, consequently, increases the service life of the ballast. Range A, specified by ABNT 5564/2014, proved to be very uniform and poorly graded, not being efficient for the conditions studied. For the applied load and the stone material used, the particle size distribution was not efficient, having a much higher breakage rate than the Australian 50 range.

American, Australian, and European standards offer a wider variety of particle size ranges, allowing for better adaptation to different types of loads and available stone materials. Brazil has a slightly smaller territorial extension compared to the United States and Europe, and a larger one compared to Australia. In these regions, as in Brazil, there is a large quantity of stone materials to be used, as well as railways with different standard axle load values, but in this country, only two particle size ranges are recommended, with the most commonly used being Range A, which is for main lines.

Thus, Range A is recommended for use on the vast majority of Brazilian tracks. This is unreasonable. As mentioned earlier, the range indicated by ABNT is not efficient for use as a ballast layer, as shown in the thesis, because it does not consider the type of load and the rock matrix of the aggregate. More detailed studies should be carried out to increase the ranges that can be used, as well as different rock matrices. These bands should be less uniform and more well-graded, unlike those currently recommended by ABNT.

The number of granulometric bands specified by ABNT (two bands) is insufficient, considering the diversity of rock matrices available in Brazil for use as railway ballast. Each matrix has its own resistance characteristics, and this must be taken into account, as well as the load passing through the track.

Considering the high breakage rate of the ballast material in the two bands studied, a new granulometric band is proposed that takes into account the gneiss rock matrix and a load per axle of 40 tons.

The proposed band was designed based on parameters obtained from the granulometry results of the material that fit within the AREMA/ABNT and Australian bands. Based on the results obtained from tests with the new range, it was observed that the particle size distribution that fits within it tends to have less fine deformation, less permanent deformation, and consequently, a longer lifespan for the material used as a ballast layer.

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