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Laboratory Study of Freezing-Thawing Impacts on Railway Ballast Aggregates

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A B S T R A C T

The freezing-thawing phenomenon is one of the most well-documented causes of aggregate degradation. This study investigates the impacts of freeze-thaw cycles on railway ballast aggregates through comprehensive laboratory tests. The aggregates were subjected to freeze-thaw cycles according to BS EN 1367-1 standards, and deterioration evaluation indexes were determined. The results indicate significant increases in the Los Angeles abrasion, Micro-Deval impact, and crushing indices under freeze-thaw conditions compared to normal temperature conditions. The obtained results indicate that the durability indices under freezing-thawing cycles, led to an average reduction of 20%. The findings highlight the critical need for improved ballast materials and maintenance strategies to enhance the durability and performance of railway infrastructure in cold regions.

1. Introduction

The durability and performance of railway ballast aggregates under varying environmental conditions are critical for the safety and efficiency of railway infrastructure. Among these conditions, the freeze-thaw cycles pose significant challenges, particularly in regions experiencing harsh winters. The cyclic freezing and thawing can lead to the deterioration of ballast aggregates, affecting The freeze-thaw phenomenon is a well-documented cause of material degradation in civil engineering structures. For railway ballasted tracks, this degradation can result in reduced load-bearing capacity, increased maintenance costs, and potential safety hazards. Despite the critical nature of this issue, there is a paucity of detailed studies focusing specifically on the freeze-thaw impacts on railway ballast aggregates. Addressing this gap is essential for developing more resilient railway infrastructure, particularly in cold regions.

Several researchers have contributed to understanding the effects of freeze-thaw cycles on various construction materials. For instance, [1] conducted a pioneering study on the deterioration of Preplaced Ballast Aggregate Concrete (PBAC) during freeze-thaw cycles, highlighting significant reductions in compressive and tensile strengths as well as the relative dynamic modulus of elasticity. Similarly, [2]investigated frost heave in ballast, providing insights into the mechanisms of ice formation and particle movement under different moisture conditions. [3]established a discrete element model to investigate the ice–bonded

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ballast behavior under uniaxial compression. Their outcomes demonsterated that the strain rate significantly affects the deformation characteristics of the frozen specimens. [4]studied deals with the degradation of crushed rock aggregate in the structural layers of track and the factors influencing degradation and frost susceptibility of degraded aggregate. The research is based on literature review and laboratory analyses of degraded ballast samples from the ballast bed, new crushed rock aggregates and some natural coarse-grained soils. [5]studied the performance and structural changes in cement-treated soils under freeze-thaw impacts. Their results showed that the growths of water content may rise freez-thaw susceptibility. [6] examined the effects of freeze–thaw cycles on changing the microstructure and pore space of aggregates using laboratory tests. The findings showed that the aggregates under freeze–thaw tests moderately preserved the structural arrangement formed during the capillary moistening. [7] investigated the durability of ballast aggregates against freezing–thawing effects which are simulated by magnesium sulfate soundness tests. The laboratory tests, which were performed up to 40 cycles, demonstrated that the ballast charachteristics are significantly affected by freezing–thawing cycles. [8] studied the effect of seasons on the vibration characteristics of railway tracks. They were experimentally measured the vertical acceleration responses in railway ballasted and ballastless subgrades during unfrozen and frozen periods. [9] investigated the deformation of railway track subgrade due to the freeze-thaw cycles. They considered the effects of groundwater levels and temperature boundary conditions on freezeing-thawing in different types of railway subgrades such as buried structures (e.g. box and pipe culvertes).

[10] studied the characteristics of ballastless track under extreme temperature conditions. Their results demonstrated that under the freeze–thaw cycles, the material performance deteriorates signicantly and the substructure of railway track does not approve the requirements of structural cracks and reinforcement yield stress. [11] focused on the railway track failures which were related to freeze-thaw conditions in Alberta,Canada. In this study, the contribution of geotextiles was applied to reduce the excessive differential vertical and lateral deformations of this failures in a track section with 877 m long. [12] conducted a field investigation to evaluate the mechanism of freeze-thaw cycles in railway embankment. The measurements indicated that the frost depth of the track embankment affected by the freezing index and winter snow cover. Also, the comparison of track geometry before freezing and after thawing showed that the track geometry became poorer and more rugged due to freeze-thaw cycles. [13] investigated the unfrozen and frozen conditions on the vertical acceleration of the embankment which are induced by high-speed trains. By performing a series of field tests, obtained results show that vertical acceleration in the frozen condition is lesser than the unfrozen condition. [14] compared the mechanical properties of of the ballast-ice specimens in different freezing environment throught laboratory tests and discrete element modeling. The results indicated that the compressive strength, and the brittleness of the ballast-ice specimens gradually increased when the temperature conditions decreased upto results –30 °C. [15] investigated the damage mechanism of railway asphalt concrete layer due to freezing–thawing cycles. The results indicated that the asphalt mixtures designed by polymerized composite and 2% air voids provided waterproofing performance and appropriate freeze–thaw damage resistance. Also, an internal deterioration surveying on asphalt mixtures layers (e.g. core, intermediate, and outer layers) conducted which the obtained results exhibited that the lower air void contents in the outer shell layer caused to slower the freeze–thaw damage.

While these studies have provided valuable insights into the freeze-thaw degradation of railway ballast aggregates, there is still a need for further research to address the following:

- Long-term effects: Most previous studies have focused on short-term freeze-thaw cycles. A comprehensive understanding of the long-term effects of repeated freeze-thaw cycles on the physical and mechanical properties of ballast aggregates is essential.
- Influence of environmental factors: The impact of environmental factors such as temperature fluctuations, moisture content, and chemical contaminants on the freeze-thaw degradation of ballast

aggregates needs to be further investigated.

- Mitigation strategies: Developing effective mitigation strategies to reduce the adverse effects of freeze-thaw cycles on railway ballast aggregates is crucial for ensuring the long-term performance and sustainability of railway infrastructure.

By addressing these research gaps, this study aims to contribute to a deeper understanding of the freeze-thaw degradation mechanisms of railway ballast aggregates and provide valuable insights for developing improved maintenance strategies and materials.

Despite these contributions, there remains a significant gap in the literature specifically addressing the freeze-thaw impacts on railway ballast aggregates. Especially, this study focused on the freezing-thawing of ballast aggregates regarding deterioration and degradation points of view such as Los-Angeles, Micro-Deval, impact, and crushing indices. This research aims to fill this gap by providing a detailed analysis of the freeze-thaw effects on railway ballast, thereby contributing to the body of knowledge necessary for improving railway track design and maintenance strategies. This study will offer several key contributions to the field:

- Detailed Laboratory Analysis: Conducting extensive freeze-thaw cycle tests on railway ballast aggregates to measure changes in physical and mechanical properties.
- Mechanistic Insights: Providing a deeper understanding of the degradation mechanisms at play during freeze-thaw cycles.
- Practical Implications: Offering practical recommendations for railway maintenance and design to mitigate the adverse effects of freeze-thaw cycles.

By addressing these aspects, the research will not only fill a significant gap in the existing literature but also provide actionable insights for engineers and policymakers involved in railway infrastructure development and maintenance.

the stability and longevity of railway tracks. This study aims to investigate the impacts of freeze-thaw cycles on railway ballast aggregates through comprehensive laboratory tests.

2. Abbreviations and Acronyms

LA	Los Angeles Abrasion
MD	Micro-Deval Abrasion

3. Materials and Method

3.1. Characteristics of ballast aggregates

Railway ballast, a critical component of railway infrastructure, is subjected to various environmental and operational stresses, including freeze-thaw cycles. These cycles, particularly prevalent in regions with cold climates, can significantly degrade the physical and mechanical properties of ballast aggregates, leading to track instability, reduced train speeds, and increased maintenance costs. The degradation of railway ballast due to freeze-thaw cycles poses a significant challenge to the railway industry. The economic consequences of track instability and increased maintenance costs are substantial. Additionally, the safety implications of degraded ballast cannot be ignored. Therefore, a thorough understanding of the underlying mechanisms of freeze-thaw degradation is essential to develop effective mitigation strategies and ensure the long-term reliability and safety of railway infrastructure. A series of tests were conducted to investigate the thermal-environmental effects on the durability of ballast aggregates using various ballast samples. The mechanical properties of the ballast aggregates examined in this study are presented in Table 1. These aggregates were sourced from the Shahriar mine in Tehran Province, which is geologically classified as igneous rocks (andesitic) [16-20] As illustrated in Figure 1, the ballast samples used in this research range in size from 20 to 60 mm. For each deterioration test, including the Los Angeles and Micro-Deval abrasion tests, 10 kg of samples were used, with a distribution of 50% from sieves 31.5 mm to 40 mm and 40 mm to 50 mm. The exact ratio, with quantities of 1.5 kg, was maintained for impact and crushing tests due to space limitations in the uniaxial compressive strength testing apparatus. The specifications and properties of the ballast aggregates are detailed in Table 1.

Figure 1. Samples of ballast aggregates

Table 1. Specifications and Properties of Ballast Aggregates Examined in the Present Study

Property	Unit	Value/type	Standard No.
Parent rock type	-	Andesite	-
Water absorption	%	1.3%	ASTM C127
Bulk mass density	kg/m³	1407	ASTM C29
Compacted bulk density	kg/m³	1589	ASTM C29
SSD specific gravity	kg/m³	2750	ASTM C128

3.2. Laboratory tests of freezing-thawing condition

To investigate the effects of freeze-thaw cycles on the durability of ballast aggregates, a series of laboratory tests were conducted. The durability of the ballast aggregates under these conditions was compared to a reference condition at normal temperature (+22.5°C). The mechanical resistance of the aggregates was evaluated using five criteria: Los Angeles abrasion, Micro-Deval abrasion, crushing under drop weight impact, crushing under static pressure loading, and breakage potential of ballast degradation.

The freeze-thaw phenomenon subjects the aggregates to expansion-contraction stresses caused by the increase and decrease in the volume of water within them, leading to aggregate breakage. The simulation of freeze-thaw conditions on ballast samples was conducted in accordance with the EN 1367 standard (Committee, 2007). The freeze-thaw test machine is depicted in Figure 2. The simulation of freeze-thaw cycles was carried out using a time-temperature programmable chamber, where the samples were placed. A freeze-thaw cycle was executed in five stages, following the sequence outlined in EN 1367-1. The ballast samples underwent 10 freeze-thaw cycles as specified by EN 1367-1.

4. Impact of freezing-thawing conditions on ballast aggregates

4.1. Evaluation indices of ballast deterioration

To evaluate the mechanical resistance of ballast aggregates under freeze-thaw conditions, four tests were utilized: Los Angeles abrasion resistance, Micro-Deval abrasion, impact resistance, and crushing resistance. The abrasion resistance of the aggregates was determined using the Los Angeles and Micro-Deval abrasion tests, following the BS EN 1097-1 and 1097-2 standards [21, 22]. The impact resistance of the aggregates was assessed according to BS EN 1097-2. The crushing resistance of the materials under pressure and static load was evaluated through a crushing test. In each of deterioration tests including Los Angeles and Micro-Deval abrasion tests, 10 kg of samples were used with distribution of 50% from sieves 31.5mm to 40mm and 40mm to 50mm. The same ratio with quantities of 1.5 kg was maintained for impact and crushing tests due to space limitations in the uniaxial compressive strength testing apparatus.

After subjecting the samples to the freeze-thaw conditions outlined in the previous section, the

(a)

(b)

Figure 1. Freeze-thaw test setup: a) Freezing-thawing machine, b) Ballast aggregates in chamber

deterioration of the ballast aggregates was measured using Los Angeles abrasion, Micro-Deval abrasion, drop weight impact, and crushing tests. Following these tests and the grading of the materials, the mechanical resistance and degradation of the aggregates, as well as the ballast breakage potential, were calculated to assess the effects of freeze-thaw cycles. Consequently, the deterioration of the aggregates was evaluated using five indices: Los Angeles abrasion index (LAI), Micro-Deval abrasion index (MDI), impact index (IMI), crushing index (CRI), and ballast aggregate breakage index (BBI). The calculation formula of each index is provided as following equations:

$$LAI = \frac{m_i - m_{LA}}{m_i} \times 100 \quad (1)$$

where m_i represents Initial sample weight and is m_{LA} Weight passing through the 1.7 mm sieve after LA test,

$$MDI = \frac{m_i - m_{MD}}{m_i} \times 100 \quad (2)$$

m_{MD} is Weight passing through the 8 mm sieve after MD test,

$$IMI = \frac{m_i - m_{IM}}{m_i} \times 100 \quad (3)$$

m_{IM} indicates Weight passing through the 5/16" sieve after impact test,

$$CRI = \frac{m_i - m_{CR}}{m_i} \times 100 \quad (4)$$

m_{CR} shows Weight passing through the 5/16" sieve after crushing test.

4.2. Impact of freezing-thawing condition on ballast deterioration

In this section, the impact of freeze-thaw cycles on ballast aggregates is examined and assessed. The aggregates were subjected to 10 freeze-thaw cycles following BS EN 1367-1 [23], and the deterioration evaluation indices were subsequently determined. Figure 3 shows the graded forms of aggregates before and after the LAA and MDA tests. The values obtained for these indices under freeze-thaw conditions are presented in Table 2.

Table 2. Evaluation Indices of ballast aggregates under Freeze-Thaw condition

Test issue	Values of indices
LA Index (%)	27.73
MD Index (%)	17.21
Impact Index (%)	17.33
Crushing Index (%)	14.53

Furthermore, Figure 4 illustrates a comparative chart of the percentage values for the indices under freeze-thaw conditions and normal conditions (+22.5°C). The results indicate that the values for Los Angeles abrasion, Micro-Deval abrasion, and crushing indices under freeze-thaw conditions increased by 37%, 27%, 39%, and 21%, respectively, compared to the normal temperature range. The most significant percentage increases were observed in the Los Angeles abrasion and impact indices.

the 1" sieve under these environmental conditions.

Figure 6 provides the rate of changes in evaluation indices under freeze-thaw conditions compared to normal temperature. It shows that

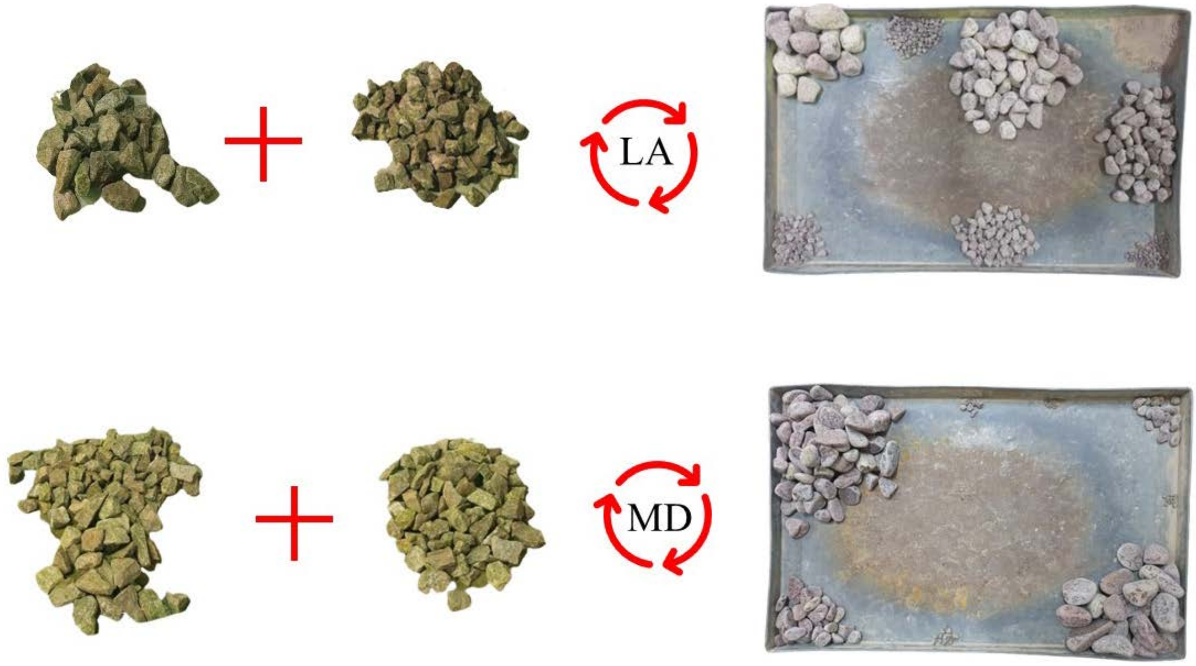


Figure 3. Images of graded aggregates before and after LAA and MDA tests.

Consequently, it can be concluded that the freeze-thaw phenomenon significantly reduces resistance due to impact. This is likely because the freezing of water within the pores of the aggregates leads to crack formation. With subsequent thawing and refreezing, these cracks continue to propagate, which, under impact loads such as those in the Los Angeles abrasion and impact tests, have the greatest effect on the aggregates. The results demonstrate that Los Angeles abrasion and impact indices exhibit the highest rates of increase. Under freeze-thaw conditions, impact abrasion shows the highest increase, while crushing abrasion shows the least.

The grading curves derived from the Los Angeles abrasion and Micro-Deval tests for both freeze-thaw and normal temperature conditions (22.5°C) are illustrated in Figure 5. These curves reveal that the greatest fragmentation occurs at

the percentage changes relative to normal conditions in the Los Angeles and Micro-Deval indices differ by approximately 5% and 0%, respectively, whereas for the impact and crushing indices, the difference is up to 10%. Similar differences were observed in the study by Hebert et al. [24]. The most significant changes in BBI are associated with Los Angeles abrasion in freeze-thaw environments, with a value of 24.8%, representing an 11% increase compared to 22.5°C.

5. Conclusion

The results of this study demonstrate that freeze-thaw cycles significantly impact the mechanical properties of railway ballast aggregates. In this study, the ballast aggregates were subjected to freeze-thaw cycles, and the deterioration evaluation indexes were determined.

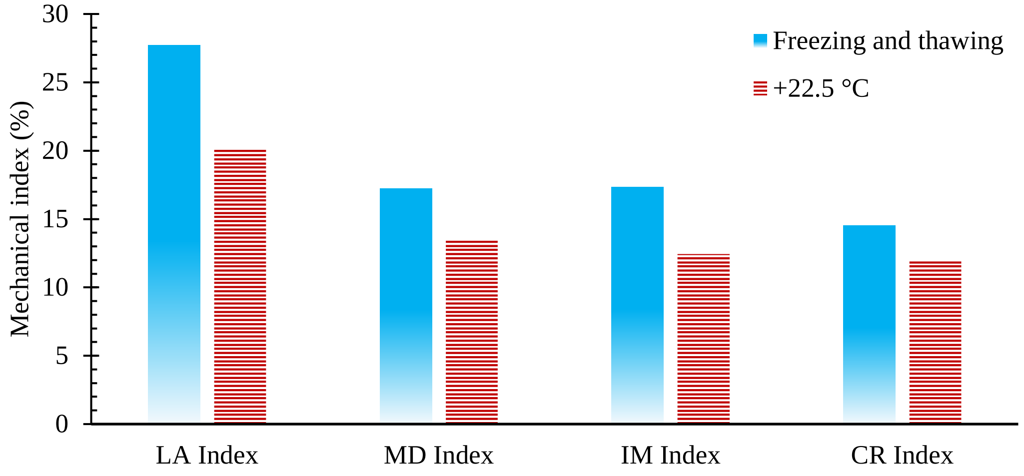
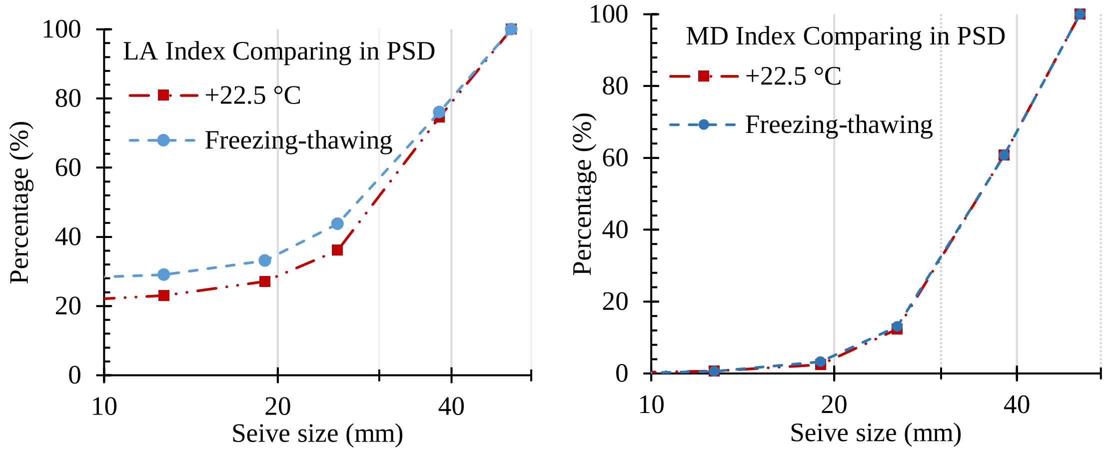


Figure 4. Evaluation Indices obtained from freezing-thawing test



(a) (b)

Figure 5. Grading curves of the ballast aggregate breaking index for freeze-thaw conditions compared to normal conditions after performing tests: (a) Los Angeles abrasion, (b) Micro-Deval abrasion

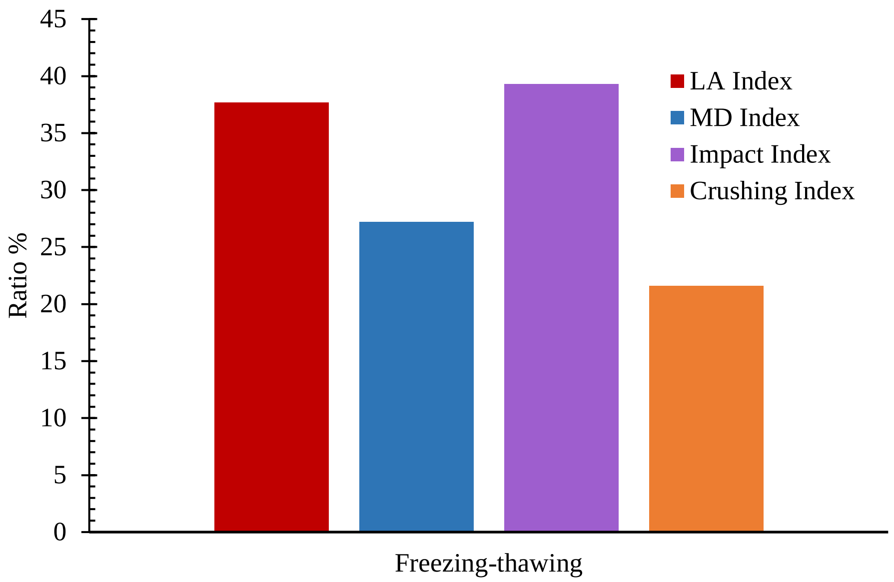


Figure 6. Changing rates of evaluation indices under freeze-thaw conditions compared to normal temperature

The obtained results for the freeze-thaw conditions showed substantial increases in the Los Angeles abrasion (LA), Micro-Deval (MD) impact, and crushing indices compared to normal temperature conditions. Specifically, the values of the LA, MD impact, and crushing indices increased by 37%, 27%, and 39%, respectively, under freeze-thaw conditions. The greatest percentage increase was observed in the LA and impact indices, indicating that the freeze-thaw phenomenon significantly reduces the resistance of ballast aggregates to impact loads.

Future research should focus on developing more resilient ballast materials and exploring advanced treatment methods to mitigate the adverse effects of freeze-thaw cycles. By addressing these aspects, the research will contribute to developing more durable and reliable railway systems, ensuring safer and more efficient train operations in regions prone to harsh winter conditions.

Declaration of Competing Interest

The authors state that they do not have any known financial or personal interests that could have influenced the work reported in this paper.

Data availability

Data will be made available on request.

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