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Effect of Traffic-Induced Densification on the Monotonic Strength of Railway Ballast

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Abstract

Traffic-induced cyclic loading significantly affects the ballast column beneath sleepers by inducing particle rearrangement, rotation, and degradation. As ballast particles break and relocate, smaller fragments fill the voids within the granular assembly, leading to densification, and higher peak failure stress. This study investigates the evolution of peak failure stress in three railway ballast materials with different lithologies and mechanical qualities: high-quality basalt, medium-quality diabase, and poor-quality limestone. A large-scale triaxial testing program was performed in which specimens were subjected to one million loading cycles, approximately corresponding to three years of traffic for a track carrying 30 million gross tonnes. Two load cases were applied to represent moderate and intense traffic-induced densification, with different load amplitudes and frequencies. Subsequently, monotonic displacement-controlled shearing was conducted at a loading rate of 0.5 mm/min. The results show that cyclic densification improves particle interlocking and increases resistance against monotonic loading. Under moderate cyclic loading, all three materials reached comparable peak failure stresses, while their post-peak ductility differed. Under intense loading, material dependency became more pronounced. Basalt achieved the highest peak stress but exhibited sudden vertical stress drops, indicating brittle macroscopic failure, whereas diabase showed a smoother and more stable shearing response.

Keywords: railway ballast, traffic-induced densification, mechanical properties, monotonic loading, cyclic loading, large-scale triaxial tests.

1 Introduction

Ballasted railway tracks remain widely used because the ballast layer distributes sleeper loads, provides drainage, enables tamping and alignment correction, and contributes to lateral and longitudinal stability. Guo et al. [1] reviewed international ballast-selection practices and emphasised that ballast must satisfy mechanical, physical, geometric, and durability requirements rather than only a single grading or abrasion limit. Shi et al. [2] reviewed recent work on ballast geometry, distribution, and degradation, and described ballast performance as a particle-scale and track-system problem governed by particle size distribution, shape, parent rock, fouling, and degradation state. These functions and material requirements become more demanding under high axle loads, high traffic density, and high train speeds, because repeated train passages progressively alter the ballast fabric and particle condition [3, 4].

To effectively describe and predict progressive ballast degradation, it is crucial to understand the fundamental mechanical behaviour of the material under stress. This behaviour is commonly investigated using monotonic loading tests, in which the applied load is gradually increased to evaluate the strength and deformation response under controlled conditions. The monotonic strength of ballast is usually interpreted through large-scale tests, because the particle size and angularity of railway ballast cannot be represented reliably in small conventional triaxial specimens. Indraratna et al. [5] performed large-scale triaxial tests on latite basalt ballast and developed nonlinear relationships for shear strength, friction angle, dilation, and particle crushing as functions of confining pressure and principal stress ratio. Alabbasi and Hussein [6] reviewed large-scale triaxial and box testing of railroad ballast and concluded that monotonic triaxial tests are mainly used to quantify short-term shear strength, friction angle, stress–strain behaviour, and volumetric change, while cyclic tests are needed to represent traffic-induced deformation.

While monotonic loading defines the basic strength and deformation response of ballast, in real railway tracks this response is strongly influenced by the previous loading history created by repeated train passages. Traffic-induced densification is important because it changes the state at which monotonic shearing begins. Suiker et al. [7] conducted static and cyclic triaxial tests on ballast and sub-ballast, then sheared cyclically loaded specimens to static failure in postcyclic tests. They found that cyclic loading increased the postcyclic peak strength of the tested granular material relative to the virgin specimen, increased the corresponding Mohr–Coulomb friction angle, and raised the secant shear stiffness after 1,000,000 load cycles. They also observed that the axial strain at postcyclic peak strength decreased as cyclic stress level increased, meaning that a stronger postcyclic specimen could fail with less deformation warning. Bian et al. [8] performed cyclic and postcyclic triaxial tests on ballast, sub-ballast, and composite ballast–sub-ballast specimens, and reported that long-term cyclic densification changes friction angle and that increasing initial compaction increased the friction angle of the tested roadbed fillers. Huang and Qian [9] later introduced large-scale triaxial tests with load–unload–reload paths to reproduce repeated train-load particle rearrangement, and reported that conventional monotonic tests without these paths may underestimate ballast shear strength by up to 72.7% under otherwise identical density and confinement.

The strengthening effect of densification cannot be assumed to be purely beneficial, because the same traffic loading can also produce breakage and abrasion. Indraratna et al. [10], in another study, investigated ballast degradation under cyclic loading and showed that confinement strongly governs whether cyclic loading causes large deformation and particle damage. Lackenby et al. [3] extended this work and reported that a small increase in effective confining pressure can improve internal contact distribution, reduce tensile stresses in particles, and lower axial strain. Thakur et al. [11] tested latite basalt ballast under different frequencies and confining pressures and showed that both frequency and confinement significantly influence permanent deformation and degradation. Sun et al. [4] used cyclic triaxial tests with loading frequencies from 5 to 60 Hz, deviator stress levels representing 25 and 40 t axle loads, and confining pressures of 10, 30, and 60 kPa; they found that ballast degradation was more pronounced at higher frequency and had a strong effect on cyclic densification, while resilient modulus increased with frequency, cyclic deviator stress, confinement, and number of cycles. These studies show that traffic can increase density and stiffness, but it can also create a fast reaching post-traffic failure state if degradation dominates.

The balance between beneficial densification and harmful degradation is material-dependent. Guo et al. [1] showed that ballast standards differ internationally because parent rock, mineralogy, climate, and operating conditions vary, and they identified Los Angeles abrasion and Micro-Deval abrasion as common but not interchangeable durability tests. Abadi et al. [12] compared degraded UK railway ballast with fresh igneous ballast and stressed that the Los Angeles abrasion test measures toughness or breakage tendency, whereas the Micro-Deval test measures durability related to ballast life, so the two tests can rank materials differently. Qian et al. [13] used Los Angeles abrasion and image analysis to quantify degradation-related changes in gradation, shape, angularity, and texture, and showed why degradation should be treated as a change in particle morphology rather than only an increase in fines content. Qian et al. [14], in a separate research, tested new and degraded limestone ballast under dry and wet conditions and found that dry degraded ballast—typically denser than new clean ballast—did not necessarily lose shear strength and in many cases showed higher strength, whereas wet degraded ballast suffered more significant strength loss and permanent deformation.

The literature therefore provides three important but only partly connected findings. First, monotonic ballast strength is governed by confinement, dilation, particle morphology, and breakage [5, 13]. Second, traffic-like cyclic loading can densify ballast and increase postcyclic monotonic strength and stiffness through particle rearrangement and fabric evolution [7–9]. Third, cyclic loading can also degrade or break particles, and the severity of this damage depends on confinement, loading frequency, moisture, gradation, and material durability [3, 4, 14]. What remains insufficiently resolved is how traffic-induced densification affects the subsequent monotonic strength of different ballast materials when those materials have different mechanical properties and degradation tendencies. This paper investigates the post-densification monotonic strength response of railway ballasts with contrasting mechanical properties.

2 Laboratory Program

2.1 Test Bench

The tests in this study were conducted using a large-scale triaxial testing apparatus designed for railway ballast. The test bench consists of a rigid loading frame, a triaxial cell with a flexible membrane, a hydraulic actuator, servo valves, a control system, and a separate data acquisition system. Axial loading was applied hydraulically under servo-controlled conditions. Confinement was applied using a vacuum system equipped with regulators and pressure sensors. The vacuum was introduced through the top cap and monitored and controlled through the bottom cap to ensure stable confinement during testing. Test control data were simultaneously recorded by an independent acquisition system located beside the test bench, allowing synchronization between control and measurement channels. In addition to axial force, axial displacement, and vacuum pressure, circumferential deformation was measured using potentiometers mounted around the specimen. This allowed the radial response of the ballast specimen to be monitored during cyclic and monotonic loading.

2.2 Ballast Types

Three ballast materials are considered in this study: basalt, diabase, and limestone. These materials are among the most commonly used ballast materials in the Austrian railway network. Basalt is a dark volcanic rock formed from cooled lava. It is mainly composed of silicate minerals, which commonly give the rock a dense and fine-grained structure. The texture of basalt is usually relatively uniform, although it can vary depending on the cooling conditions. Diabase is an igneous rock formed from molten rock that has cooled below the ground surface. It has a composition similar to basalt and usually contains silicate minerals in a medium-grained structure. Compared with basalt, diabase typically cools more slowly, which results in a more visible crystalline texture. Limestone is a sedimentary rock mainly composed of calcium carbonate, usually formed from accumulated carbonate sediments and biological remains. Its composition and texture can vary depending on the depositional

Ballast type	Quality	Quarry	Rock type	LA abrasion (% loss)	Micro-Deval (% loss)	Impact test (%)	Water absorption (%)	Density (Mg/m^3)
Basalt	Good	Appel (Austria)	Igneous	12	9	17.8	0.8	2.843
Diabase	Medium	Saalfelden (Austria)	Igneous	19	15	17.2	0.8	2.718
Limestone	Bad	Kamnolon Verd (Slovenia)	Sedimentary	29	9	33.6	0.3	2.688

Table 1: Material properties of the investigated ballast types.

environment and geological history. Limestone may contain small amounts of clay, silica, or other minerals, depending on the source formation. The materials are treated as contrasting quality groups in the experimental matrix, with basalt representing the good-quality ballast, diabase representing the medium-quality ballast, and limestone representing the weaker ballast group. The main properties of these stones are summarized in Table 1. These properties are included because ballast selection is commonly based on mechanical resistance, durability, density, water absorption, particle shape, and gradation [1,6].

2.3 Gradation

Railway ballast is generally designed as a coarse, narrowly graded granular material rather than a well-graded soil. This relatively uniform and open-graded structure is required to provide high permeability, rapid drainage, strong particle interlock, and sufficient resistance against lateral spreading under repeated train loading. The particle size distribution (PSD) in this study is taken from a field measurement in the Austrian railway network. The analysis was reported according to EN 933-1 using square sieves. The measured gradation is summarized in Figure 1.

2.4 Sample Preparation

The ballast specimens were prepared with a diameter of 300 mm and a height of 600 mm. As described, the same particle size distribution was used for all ballast types in order to isolate the influence of lithology on the mechanical response. Each specimen was prepared inside a split mold in six layers. For each layer, the ballast was compacted using a shaking table while a dead load was applied on top of the layer. This procedure was continued until the target density was reached as uniformly as possible throughout the specimen height. After preparation, the specimens were subjected to a confining pressure of 35 kPa. This value was selected to represent the lateral confinement measured and reported by Inderartna [15].

2.5 Cyclic Loading Program

To evaluate traffic-induced densification, the ballast specimens were subjected to cyclic loading prior to monotonic shearing. Repeated train passages are known to induce progressive densification of ballast layers, particularly during the early stages of track

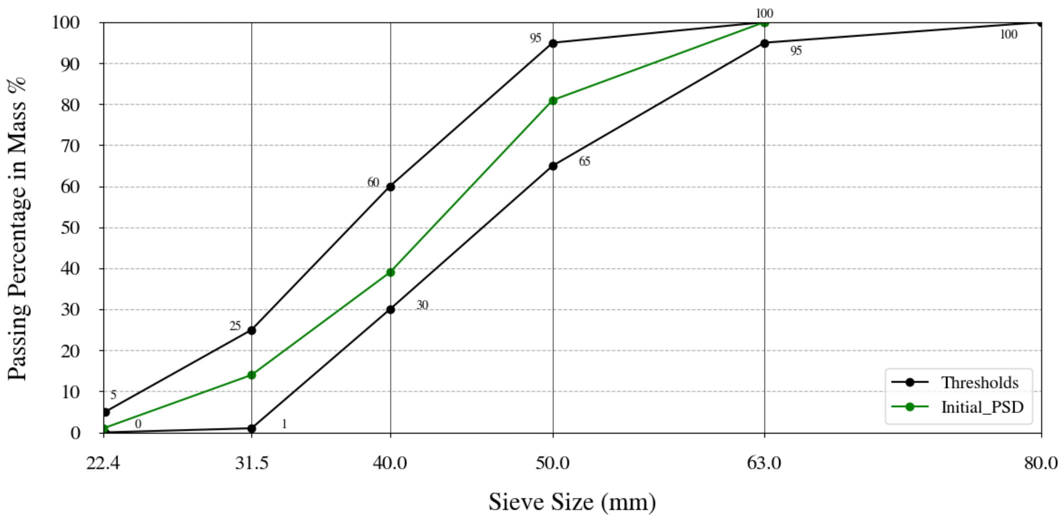

Figure 1: Particle size distribution curve.

service [4, 7, 8]. The objective of the cyclic loading stage was therefore to reproduce the densified state of ballast resulting from traffic loading before evaluating its monotonic strength.

The cyclic loading was applied through the hydraulic actuator under stress-controlled conditions while maintaining a constant confining pressure of 35 kPa throughout the test. The loading history was designed using two Load Cases (LC) with different loading intensities and frequencies to represent harsh and normal traffic conditions. The loading parameters are summarized in Table 2. To characterise the loading intensity, the peak cyclic stress ratio was adopted. The deviator stress was calculated as

$$q = \sigma_1 - \sigma_3, \tag{1}$$

where σ_1 is the axial stress and σ_3 is the confining pressure. The corresponding mean stress was determined as

$$p = \frac{\sigma_1 + 2\sigma_3}{3}. \tag{2}$$

The stress ratio was calculated from the maximum stress state reached during each loading cycle according to

$$\left(-\frac{q}{p}\right)_{\max} = -\frac{q_{\max}}{p_{\max}}, \tag{3}$$

where $q_{\max}$ and $p_{\max}$ denote the maximum deviatoric and mean stresses obtained from the peak force within the loading. The resulting peak cyclic stress ratios for the two loading cases are given in Table 2.

To quantify the effect of cyclic densification and verify the development of a densified ballast state, an additional virgin basalt specimen was tested without prior cyclic

Load case	$(-q/p)$	Confinement (kPa)	Frequency (Hz)	Cycles
LC1	2.1	35	8	10^6
LC2	2.3	35	14	10^6

Table 2: Cyclic loading parameters.

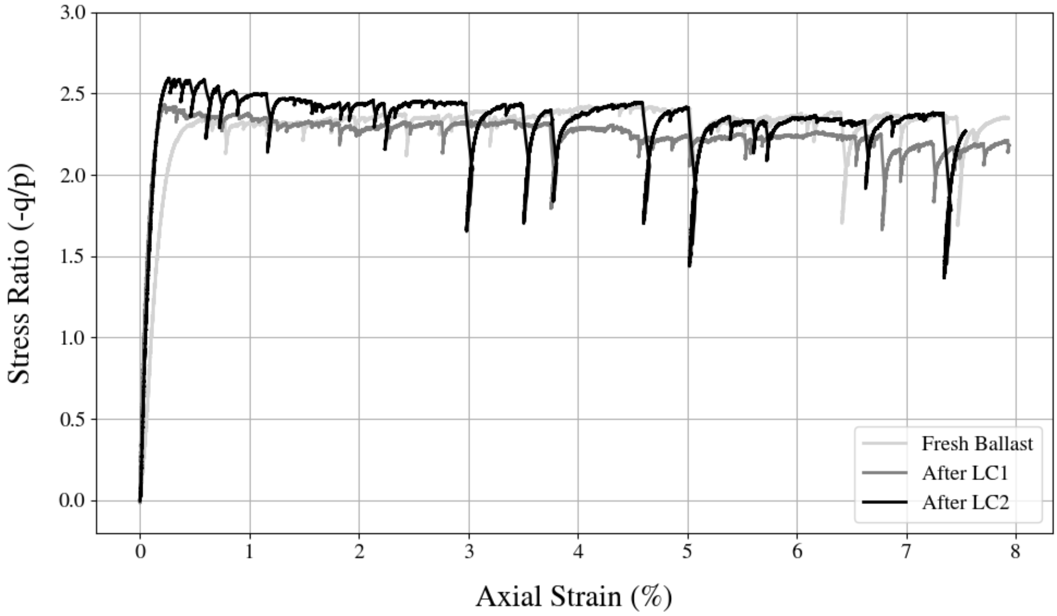

Figure 2: Monotonic stress ratio curves for basalt under fresh and post-cyclic conditions.

loading. Consequently, three monotonic loading conditions were evaluated only for basalt: (i) virgin ballast, (ii) ballast subjected to LC1, and (iii) ballast subjected to LC2. For diabase and limestone, only the specimens subjected to LC1 and LC2 were tested. This testing matrix was selected because basalt represents the highest-quality ballast material and serves as the reference material for assessing the influence of cyclic densification on subsequent monotonic behaviour. Following completion of the cyclic loading stage, all specimens were sheared monotonically without disturbing the sample.

3 Monotonic Test Results

The loading program continued with the monotonic shearing for the post-cyclic specimens. The loading was performed under displacement-controlled conditions at a constant strain rate of 0.5 mm/min [16].

To systematically isolate the structural consequences of traffic-induced densification, the high-quality basalt reference material was subjected to monotonic shearing across three distinct operational baselines: (i) the baseline virgin state (without prior cyclic loading), (ii) following the normal traffic conditions of LC1, and (iii) following the harsh traffic environment of LC2. The combined experimental trends, evaluated in terms of the stress ratio ($-q/p$), are shown in Figure 2.

The experimental results demonstrate a clear evolution in the material response as a function of cumulative cyclic energy. For the virgin specimen, the stress ratio increases gradually, requiring substantial axial deformation to mobilise its peak strength. This prolonged pre-peak phase indicates that a significant portion of the initial monotonic loading path is consumed by macroscopic volume reduction, air-void elimination, and local boundary adjustment of the loose particles before effective shear planes can fully develop.

On the contrary, both the post-LC1 and post-LC2 curves exhibit a severe initial stiffness magnification, with the ultimate peak bearing capacity shifted drastically toward the very initiation of the shearing path (mobilised at less than 0.3% axial strain). This force mobilization matches the fundamental experimental behaviour reported in tests performed by Suiker and Selig [7]. This behaviour indicates that prior cyclic loading effectively acts as a conditioning phase, eliminating unstable voids and packing the particle assembly into a tight, locked configuration prior to monotonic shearing.

Furthermore, a higher cyclic loading intensity and frequency (LC2 compared to LC1) result in a distinct amplification of the peak stress ratio. This progressive growth in maximum shear resistance suggests that traffic-induced densification, accompanied by controlled particle abrasion and minor degradation at highly stressed contacts, yields a highly locked-in aggregate fabric. The generated micro-fines and broken edges can temporarily fill localized interstitial gaps, increasing the total interparticle contact area and thus enhancing the frictional interlocking mechanism among the larger rock fragments.

The engineering takeaway from this comparative phase is dual-natured. As hypothesised, induced traffic loading enhances the mechanical stability of the track layer by driving volumetric compaction and directly elevating its load-bearing capacity. However, within the broader context of track-system performance, this strengthening phenomenon must not be interpreted as purely beneficial. The continuous accumulation of traffic-induced densification and accompanying particle degradation progressively reduces the layout's hydraulic conductivity, leading to clogged drainage paths [14]. Concurrently, the sharp inflation of the ballast layer's secant stiffness creates a rigid track bed, which accelerates vibrational transmission to the sleeper components and parent subgrade structures.

The post-cyclic stress–strain response of the three investigated ballast materials under LC1 conditions are evaluated individually in Figures 3, 4, and 5. In the basalt specimen, (see Figure 3) the cyclic densification causes the peak bearing capacity at 33 kN ($\sim$450 kPa) to shift entirely to the early stage of shearing, occurring at less than 0.2% axial strain. This confirms that the pre-compacted particle assembly mobilises its maximum shear resistance almost immediately upon loading. The high hardness

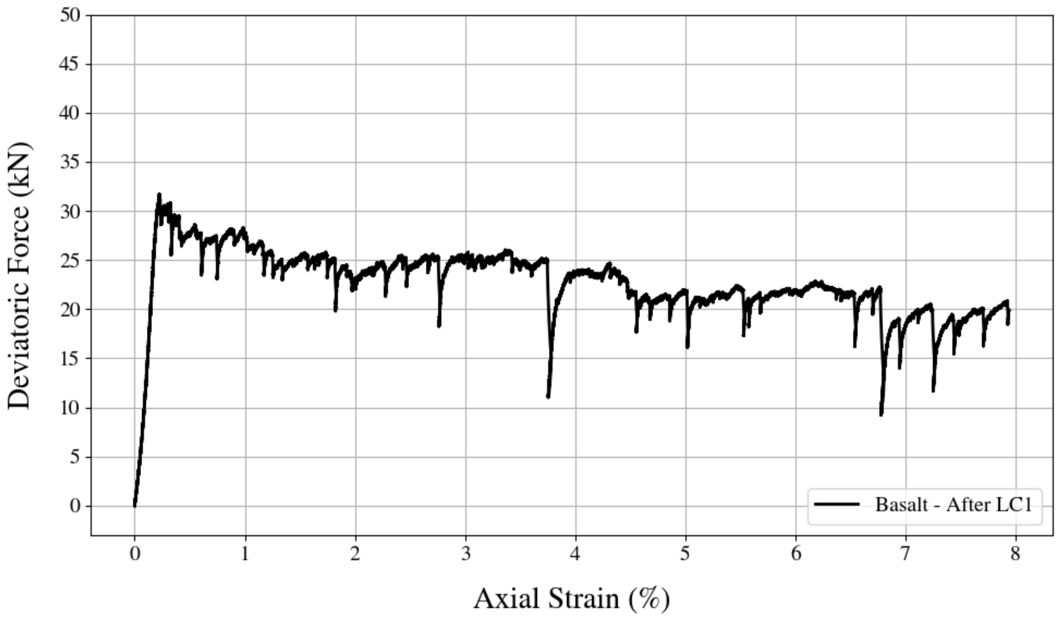

Figure 3: Basalt ballast monotonic response under LC1 conditions.

and angularity of basalt generate a stiff initial matrix capable of reaching its maximum bearing capacity at very low deformations.

The experimental results for the limestone ballast are presented in Figure 4. The material exhibits a rapid initial stiffening, reaching its peak deviator stress in the range of 30 to 35 kN ($\sim$ 425-495 kPa) at an axial strain of roughly 0.25%. This behaviour clearly demonstrates the characteristic trend where traffic-induced cyclic densification shifts the peak bearing capacity toward the initiation of the monotonic shearing path. After reaching the early peak value of deviatoric stress, the material shows a fluctuating pattern with a macro-softening trend down to approximately 320 kPa at 8% axial strain, accompanied by frequent minor stress drops indicative of continuous local particle rearrangement and abrasion of the weaker sedimentary grains.

The behaviour of the medium-quality igneous ballast is captured in the Figure 5, representing the diabase specimen. In contrast to the other materials, diabase demonstrates a highly ductile and sustained post-densification response. While it rapidly mobilises a major portion of its strength $\sim$31 kN (exceeding 430 kPa) within the first 0.3% of axial strain, the ultimate peak stress ($\sim$450 kPa) is reached later at an axial strain of approximately 2.6%. Following the peak, the specimen maintains a stable, resilient shear state with minimal structural collapse.

An overarching comparison reveals that all three ballast materials eventually mobilise a maximum failure stress within a region between 30 to 35 kN. This demonstrates that under identical initial grading, specimen geometry, and confinement, the primary influence of rock lithology under post-cyclic conditions manifests not in the absolute peak value itself, but rather in the ductility of the pre-compacted fabric and

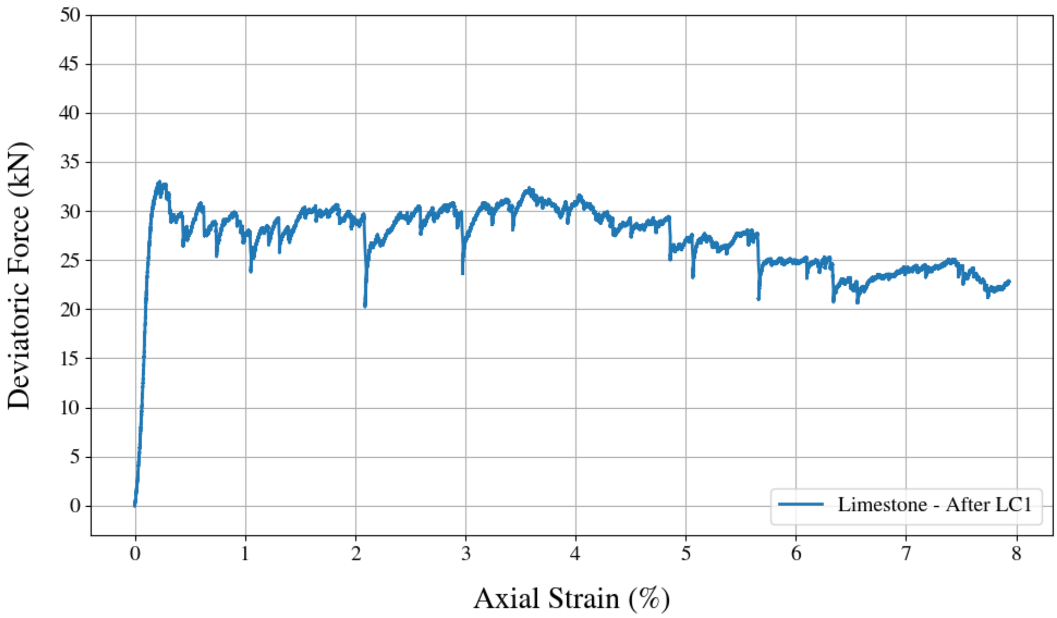

Figure 4: Limestone ballast monotonic response under LC1 conditions.

the nature of its post-peak degradation, which is slightly more evident in diabase (see Figure 6).

To better highlight the ductility and post-peak degradation, the test results of all stones are compared in Figure 6. The test curves show that the fundamental trends observed under normal traffic intensity (LC1) are retained and amplified at higher loading intensity. All materials exhibit an increase in their initial secant stiffness, with the peak bearing capacity shifted entirely toward the very beginning of the shearing stage. However, a major difference emerges regarding the absolute intensity of the peak load. The basalt specimen mobilises a significantly higher peak deviator force of 47.5 kN (∼675 kPa) compared to the diabase specimen at 36 kN (∼505 kPa), and limestone. This indicates that traffic-induced densification is much more pronounced in the basalt material, allowing its highly angular and hard mineral structure to establish an extremely locked-in, high-capacity particle matrix during the cyclic phase.

The post-peak regimes further illuminate the contrasting mechanical signatures of the lithologies. The basalt curve is characterised by highly frequent, abrupt, and severe vertical stress drops across the entire shearing path. These sharp drops can be directly interpreted as a distinctly brittle macroscopic behaviour, where high-strength interparticle contacts undergo sudden structural collapse, including chipping, splitting, and loss of force-chain continuity. These events suggest that individual stone displacements and major relocation against each other are highly pronounced in the basalt assembly when the interlocking threshold is exceeded.

In contrast, the other specimens (especially diabase) display a much softer, more continuous shearing response. After reaching its peak, the stress reductions are smoother

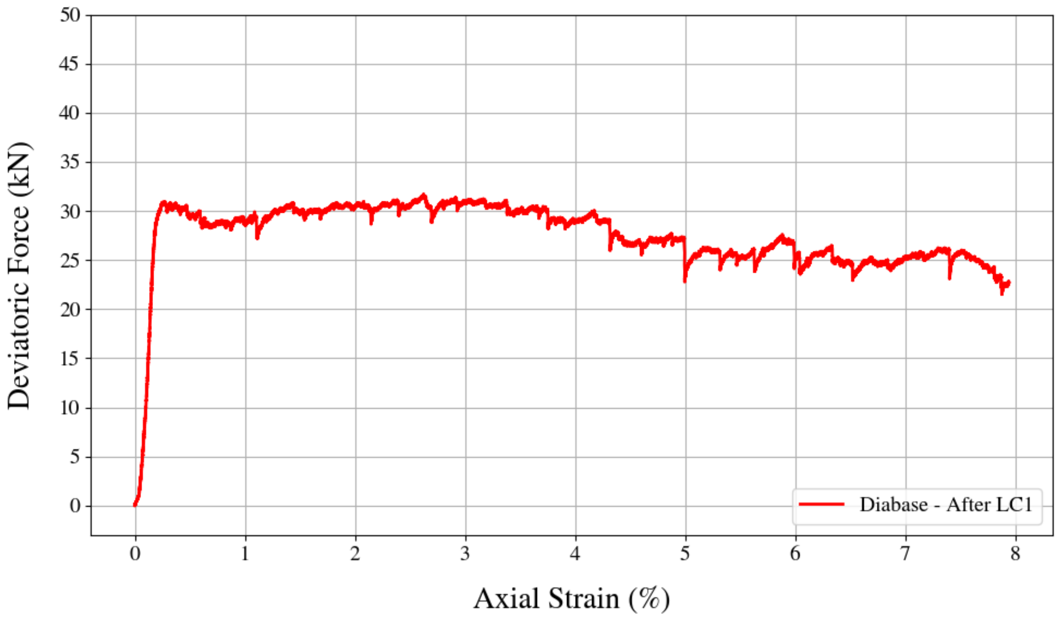

Figure 5: Diabase ballast monotonic response under LC1 conditions.

and lack the immediate drops seen in the basalt. This softer shearing mechanism aligns with the trends observed under LC1 conditions, where diabase also demonstrated a more ductile evolution than basalt, although the distinction was less visible at lower traffic intensity. The amplified contrast under LC2 confirms that while the intermediate toughness of diabase yields a lower absolute peak resistance under harsh cyclic compaction, its mineralogical fabric provides greater structural stability, allowing for continuous, less destructive particle rearrangement during monotonic deformation.

4 Conclusions

In this paper, large-scale triaxial tests were performed to evaluate the post-cyclic monotonic strength of three different ballast types. The comparison of the results indicated that, at the lower-intensity loading scenario, the maximum force required for shearing the samples fluctuated within a certain range (30-35 kN). Therefore, the influence of rock lithology was not strongly underlined at this load case. Nevertheless, by increasing the densification, which is associated with further degradation and higher interlock among the stones, the peak values increased considerably for basalt in comparison to diabase. In addition, the post-shearing behaviour of basalt was mostly brittle, with sudden changes and sharp drops, while the response of diabase was comparatively smooth.

Rock lithology is therefore an effective factor, especially at higher levels of interlocking. According to ballast selection criteria, comparison between Los Angeles abrasion, Micro-Deval, and dynamic impact test results can provide further hints re-

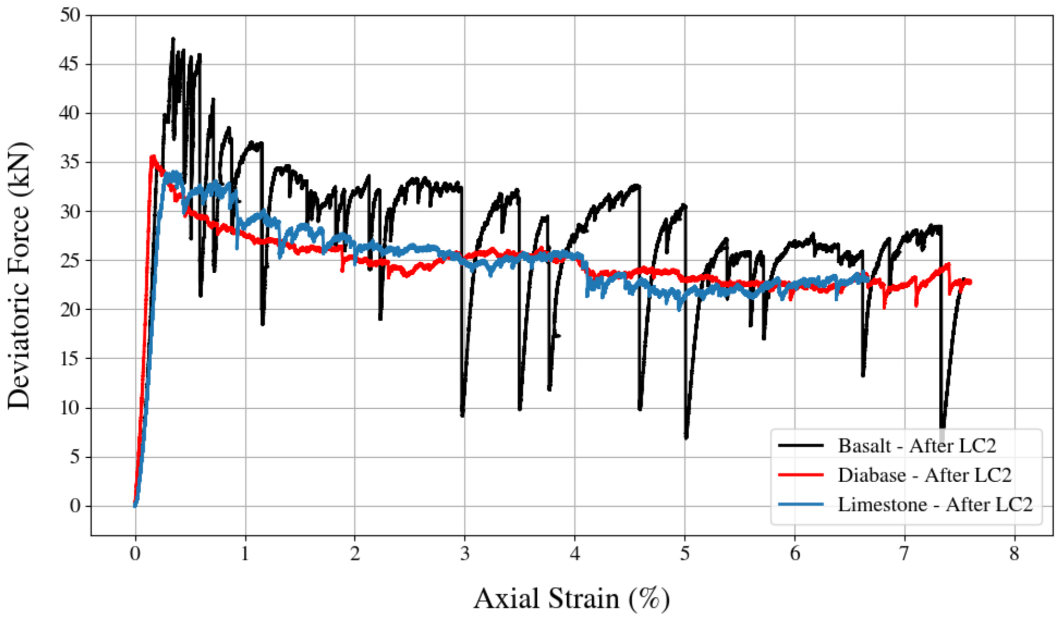

Figure 6: Comparison of monotonic shearing paths for basalt and diabase specimens under LC2 conditions.

garding the explanation of such behaviour. There are multiple rock types and variants with different rock lithologies already being used as railway ballast; however, there is still a missing link between post-cyclic behaviour and different rock types. It is also worth mentioning that these values were acquired under dry testing conditions. In the field, ballast is exposed to wet seasons and rainstorms, which may affect the behaviour of the ballast assembly depending on its lithology.

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