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Effect of rock strength on the degradation of ballast equipped with under sleeper pad using discrete element method

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Abstract

This study investigates the influence of Uniaxial Compressive Strength (UCS) of ballast rock cores and the Bedding Modulus of Under Sleeper Pads (USP-BM) on railway track deterioration, investigating key factors such as settlement and aggregate fragmentation through Discrete Element Method (DEM) simulations. These simulations encompass three scenarios representing different types of ballast aggregates: without a pad, with a soft pad, and with a hard pad, with rock cores categorized by UCS values into soft (159 MPa), medium (210 MPa), and hard (285 MPa) classes. The model involves cyclic loading of a sleeper section embedded in ballast, subject to fluctuating vertical loads between 3 and 43 kN at a frequency of 3 Hz, with a total of 15 load cycles applied to emulate real-world conditions, and its accuracy is confirmed through experimental validation. The study concludes that a soft USP is most effective in mitigating ballast settlement and breakage, highlighting the pivotal role of UCS values of ballast rock cores in the management of track deterioration.

Keywords: Ballast Box Test; Uniaxial Compressive Strength (UCS); Under Sleeper Pads (USPs); Discrete Element Method (DEM); Degradation

1. Introduction

In light of the substantial increase in railway freight and passenger traffic in recent decades, several research methodologies have been conducted to mitigate the persistent issues related to the superstructure and substructures of railway tracks. Numerous fundamental concerns arise, notably, as passenger traffic and freight tonnage surge, the resultant pressures exerted on superstructure components correspondingly escalate [1, 2]. This leads to enhanced fatigue and degradation of tracks [3], particularly in stiffer subgrades such as crossings and bridges [4, 5]. Elevated stresses in the granular layer further amplify the deterioration of the track over time [6], leading to excessive vertical and horizontal deformations [7], fragmentation of the ballast [8], accumulation of debris in the ballast, and obstruction of drainage [9]. A multitude of field and laboratory tests have been carried out to examine the effects of Under Sleeper Pads (USPs), with the majority of them indicating favorable results. Bolmsvik [10] states that the utilization of USPs can reduce track misalignment. Additional research has indicated that USPs can effectively decrease both the wearing attrition of particles between objects and the erosion of the ballast material used to support railway sleepers [11, 12]. Studies conducted by Riessberger [13] and Abadi et al. [14] have found that the use of USPs results in an expansion of the contact area between the ballast and the sleeper, hence decreasing the pressure exerted at the contact point. The reason why USPs aid to reduce ballast damage is widely regarded in [11]. Lakusic et al. [15] found that the ballast embedding within USPs improved both the lateral stability and load distribution from the sleepers. Baghsorki et al. [16] found that USPs also decreased sleeper settlement in their laboratory experiments. Loy [17] argued that including USPs consistently leads to a track superstructure with more advantageous attributes compared to a track superstructure without USPs. Although field experience and laboratory investigations have found several benefits of

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USPs, there is still a lack of a comprehensive explanation for their functioning. Therefore, it is necessary to have a more profound comprehension of the impact of USPs on the interaction between sleepers and ballast aggregates. The Discrete Element Method (DEM), initially proposed by Cundall and Strack [18], provides a robust means of analyzing granular substances on a microscopic scale. In the past ten years, DEM has been effectively utilized in railway ballast applications [19]. In the first investigations of DEM modeling of ballast particles, a particle was shown as a basic sphere in order to examine ballast deterioration using the particle replacement technique. Several techniques were subsequently suggested to produce intricate forms of ballast particles [20-23]. Zhang et al. [24] employ DEM to examine the repetitive behavior of ballast combined with Crumb Rubber (CR). The simulation findings demonstrate that the impact of compaction ratio on the macro-mechanical characteristics of ballast, at various CR percentages, may be accurately represented. Li et al. [25] examine the impact of differentially layered ballasts on the reduction of track settlement. By utilizing DEM simulations, this study offers a detailed analysis of the particle interlocking mechanisms across various levels. These findings provide an optimal design for a two-layer ballast system, which may effectively reduce track maintenance costs. Chen et al. [26] employ DEM to precisely analyze the influence of coal fouling on the deformation and deterioration of ballast material when subjected to repeated loads. This study provides a detailed analysis of the mechanical behavior of fouled ballast, demonstrating that higher degrees of fouling intensify sleeper settlement, reduce the resilient modulus, and result in particle breakage. The current study used DEM to replicate the behavior of USPs in a box test. The USP is represented by three layers of hexagonally packed, bound spheres. At first, the simulation findings are quantitatively compared with the initial 15 cycles of experimental data from Esmaeili et al. [27] Subsequently, the function of the USP in the interaction between the sleeper and ballast is examined closely. Additionally, the study investigates the influence of the pad's stiffness and Unconfined Compressive Strength (UCS) of rock on aggregate settlement and breakage. The examination of particle abrasion further confirms the effectiveness of the USP in protecting track conditions.

2. Discrete element modeling

To investigate the simultaneous effect of the stiffness of USP and also the USC of the ballast aggregates, two types of hard pads with stiffness of 0.13 N/mm^3 and soft pads with stiffness of 30 N/mm^3 and three types of ballast from mines named S, A and K with UCS of 159, 210 and 285 MPa were used respectively. For example, USP30-K is a sample without USP for K mine and USP30-S is a sample with a pad with a stiffness of 30 N/mm^3 for S ballast mine.

2.1. Discrete element modelling of UCS test

Initially, the models are calibrated using three mines with varying UCS. In order to achieve this objective, the laboratory findings provided by Esmaeili et al. [27] were utilized. The samples were simulated using laboratory dimensions. According to the slope of the stress-strain diagram, the modulus of elasticity, and the ratio of shear strains to normal strains, Poisson's ratio has been calibrated, and the results of the characteristics of ballast aggregates are presented in Table 1.

Table 1 Clumps properties

Clumps properties	**Mine**		
	S	**A**	**K**
No. clumps	1672	1672	1672
Poisson’s ratio	0.2037	0.1506	0.2272
Shear modulus	45.31	46.12	36.22
c-dis	150	150	150
c-ratio	0.5	0.4	0.4
Density	2720	2690	2850
Damping coefficient	0.7	0.7	0.7

3. Discrete element modeling of box

The box test, which simulates the interaction between the ballast and sleeper on the rail seat of a track, has been effectively utilized in prior research [28]. The process involves repeatedly placing a sleeper segment (measuring 0.3

m×0.25 m×0.15 m) into the ballast and enclosing it within a box measuring 0.3 m x 0.7 m x 0.45 m. The sleeper part is subjected to a vertical load with a frequency of 3 Hz, alternating between 3 and 43 kN. In all simulations conducted for this investigation, the sleeper section was loaded for a total of 15 cycles. Due to computing time constraints, it is currently not feasible to perform a large number of cycles. Furthermore, the most significant changes in measured values often occur in the initial cycles. The use of a servo control system raises the stress level. This study utilizes the commercial DEM code PFC3D 5.0 [29]. Figure 1 depicts the DEM representation of the box test.

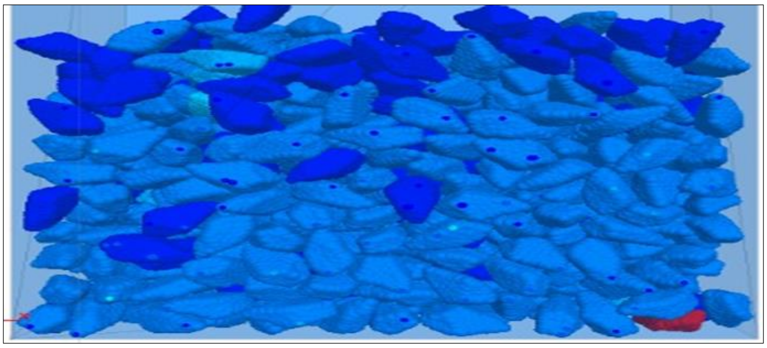


Figure 1 DEM sample of a box test

The subsequent procedure results in the following sample:

- The ballast particles, represented as 'clumps', are generated in a high container positioned above the box test device. Subsequently, they are allowed to settle under the influence of a standard gravitational force of -10 m/s^2.
- Modify the value of the gravitational constant to -50 m/s^2 and thereafter execute the experiment until reaching equilibrium conditions in order to compress the sample.
- Adjust the gravity constant to its standard value of -10 m/s^2, and thereafter execute the experiment till reaching a condition of equilibrium once more. All particles that are not completely contained within the box device or located within the border of the sleeper are removed. We use the Hertz-Mindlin contact model [29] to show the ballast particles.

4. Discrete element modeling of under sleeper pad

The USP consists of 13,550 spheres of varying thickness with a 1.65mm radius. These spheres are arranged in a hexagonally-close-packed structure and are linked together. Three contact models are used for intra-USP particle contacts: the linear contact model, contact bond model, and parallel bond model. The input parameters are listed in Table 2.

Table 2 Pads properties

Pads properties	**Soft pad**	**Hard pad**
No. of spheres	15632	15632
Radius of spheres	1.6	1.6
Density	3150	1500
Damping coefficient	0.7	0.7
Friction	0.5	0.5
Parallel bond normal and shear stiffness	8×10^{7}	5×10^{7}
Parallel bond normal and shear strength	1×10^{50}	1×10^{50}
Contact bond normal and shear stiffness	900	500
Contact bond normal and shear strength	1×10^{50}	1×10^{50}
Normal and shear stiffness of mini sphere	900	500

5. Validation

In order to verify the accuracy of the ballast box, the outcomes of the first 15 simulation cycles were compared to the laboratory findings carried out by Esmaeili et al. [27]. The properties of the used pads and ballast particles in the simulation closely resemble their corresponding values in the laboratory. Figure 2 demonstrates a satisfactory correlation between the trend of settlement changes and numerical simulation values, as well as the findings of laboratory investigations.

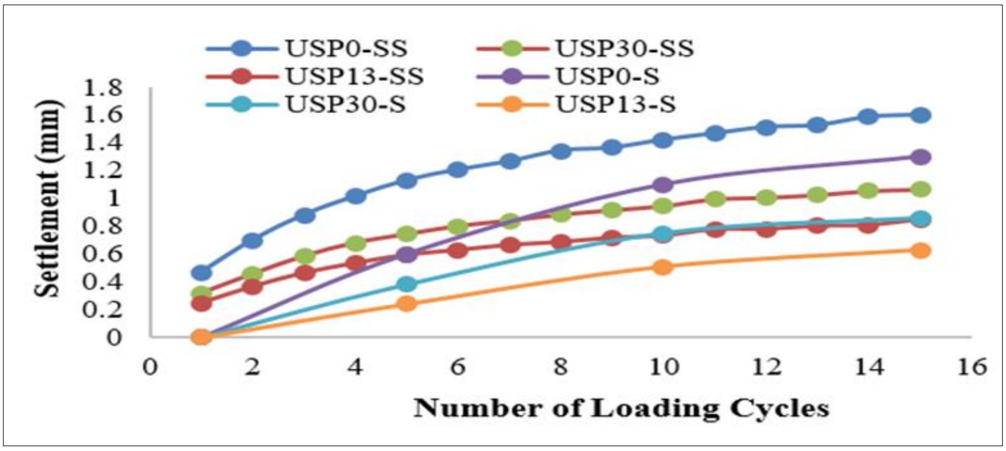


Figure 2 Validation of box test modeling

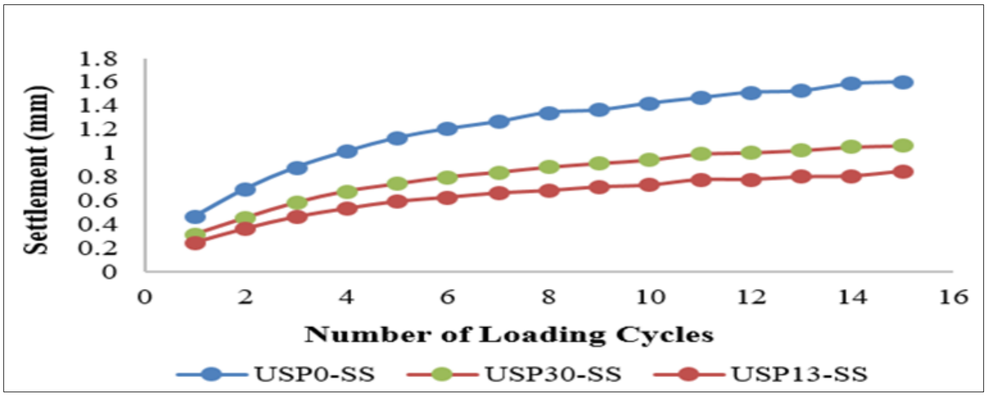
6. Ballast box simulation results

The following sections investigate the effects of various UCS values of the parent rock and different types of USP (USP stiffness) on the settlement and fragmentation of the samples. The reported findings have been assessed using output data from the ballast box simulation.

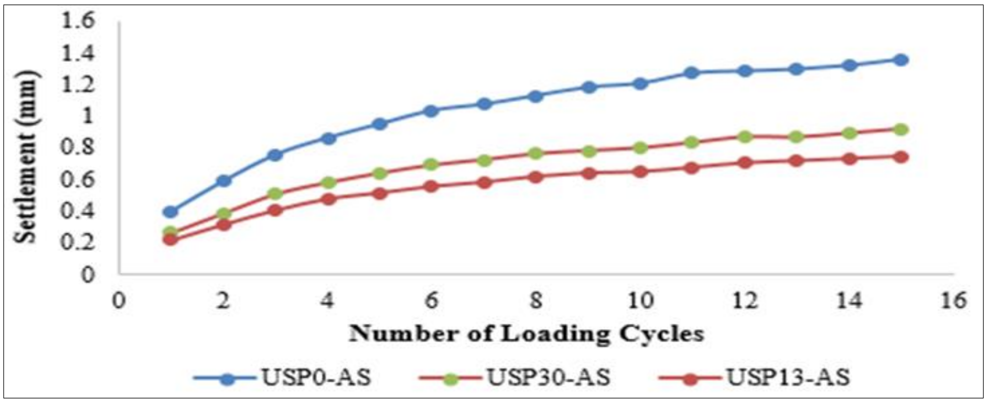
6.1. Settlement of samples

Figure 3 demonstrates that the permanent settlements projected by the DEM simulation are somewhat more than the experimental findings. Figure 3 demonstrates a decrease in settlements when utilizing pads, compared to without pads. This drop may be attributed to a reduction in stiffness. Comparing the samples using USP13 soft pad to the test samples using USP30 hard pad, a more significant decrease in settlement has been observed. By comparing the USP13-KS and USP0-KS samples, as shown in Figure 3, it is visible that the settlement of USP13-KS has reduced by about 1.3 mm in comparison to USP30-KS, which reduced by around 0.4 mm.

Typically, settlement of ballast aggregates decreases as UCS of the aggregate increases. This is clearly seen in Figure 3. On the other hand, it is clear that as USC rises, the amount of settlement reduces.



a



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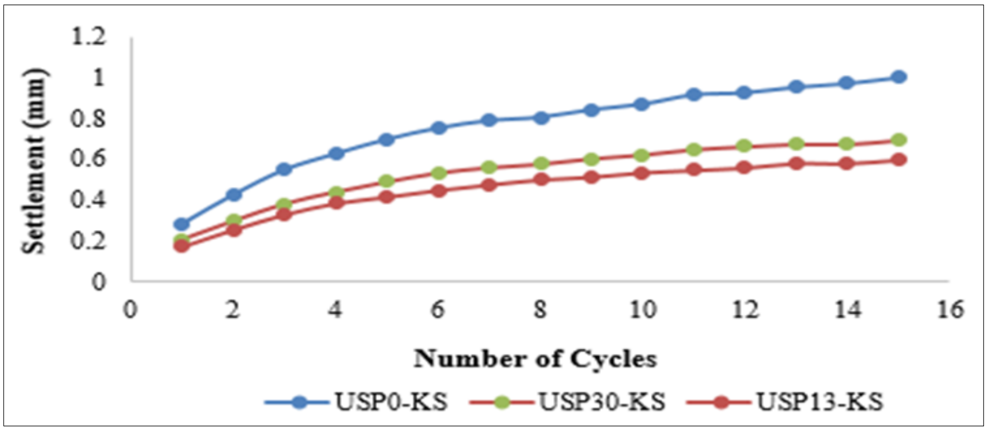

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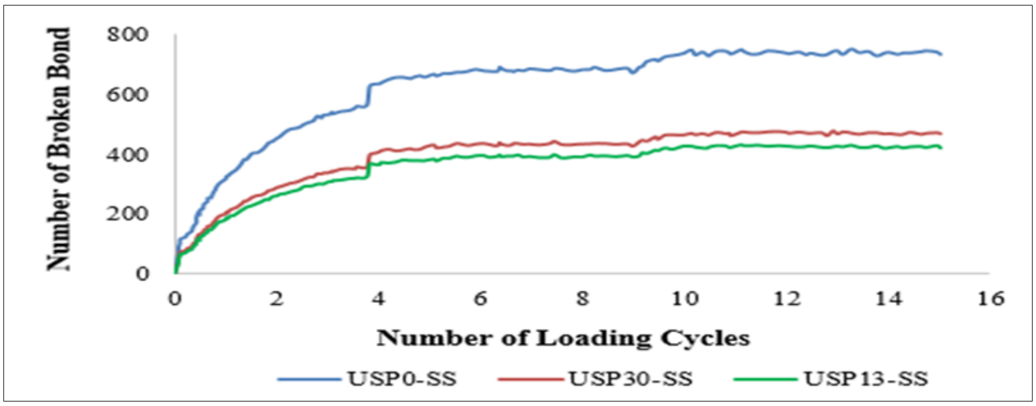
Figure 3 Comparison of sleeper settlement for various pads with different UCS a)SS b)AS c)KS

6.2. Breakage of ballast particles

Particle breakage is a primary factor contributing to ballast deterioration. The aim of this study is to examine the effect of USP and USC of ballast aggregates in connection with ballast breakage. This study is intended to determine the total number of fractured linkages inside aggregates that make a clump. Figure 4 indicates that the failure of ballast particles is reduced to a greater extent when utilizing the USP13 pad compared to the USP30 pad and the case without a pad, while maintaining the same resistance of ballast aggregates. Furthermore, when the resistance of the top aggregates in the same pad condition has increased, there has been a corresponding reduction in the number of broken particles, as seen in Figure 4.



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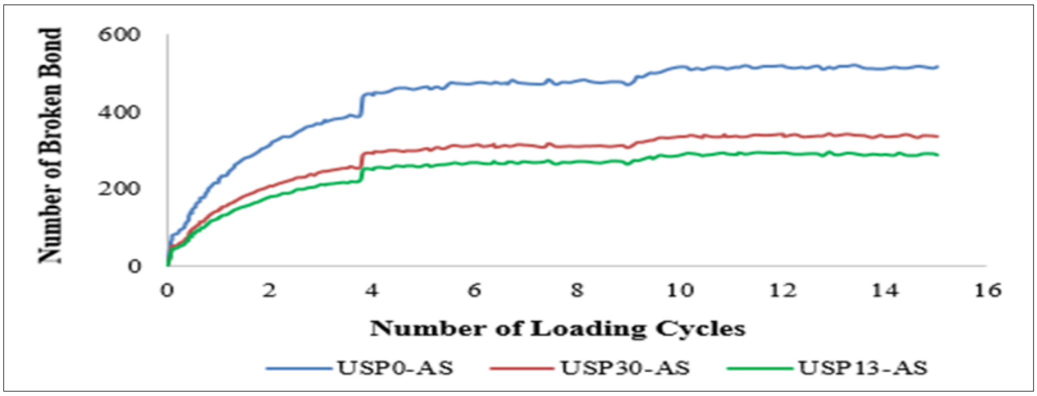

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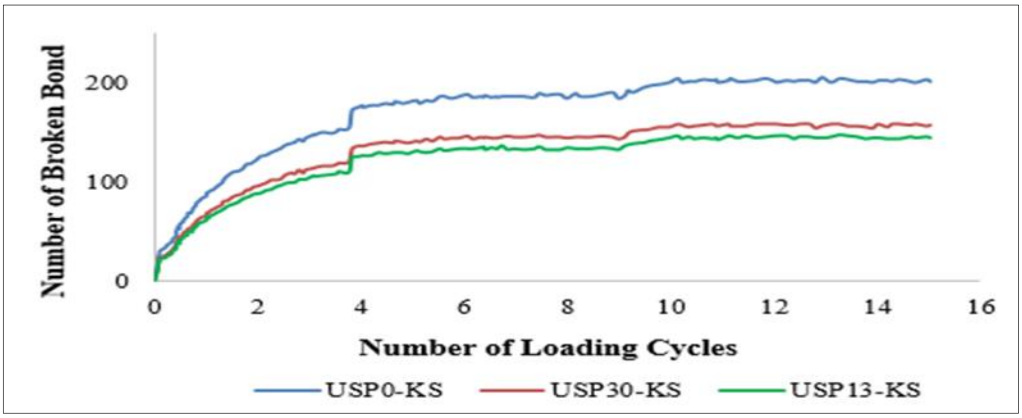

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Figure 4 Comparison of broken asperities for various pads with different UCS a)SS b)AS c)KS

7. Conclusion

Numerical modeling was conducted on three UCS samples in three different states: without a pad, with a soft pad, and with a hard pad. The modeling was performed over 15 cycles and then assessed. The loading frequency was 3 Hz, and the highest loading value was 43 kN. The modeling findings are shown in terms of the number of fragmented ballast particles and the extracted settlement. The study examines the effects of the UCS parameter of the ballast parent rock and the hardness of the traverse pads on these factors. The outcomes of the ballast box modeling are as follows:

- The settlement of the samples decreased as the resistance increased. Additionally, for samples with the same UCS, the soft pad showed better efficiency compared to the hard pad, resulting in a greater reduction in settlement.
- The number of fractured particles decreased as UCS value increased during 15 cycles. Furthermore, while using the pad, this metric dropped. The soft pad showed more efficacy than the hard and without pad cases in minimizing particle breakage.
- According to the assessed parameters of settlement and fractured particles, the pad with lesser stiffness, USP13, performed better in various UCSs. Additionally, the ballast aggregates with a higher UCS, K, showed reduced settlement and fragmentation (ballast deterioration).

Compliance with ethical standards

Disclosure of conflict of interest

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

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