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INFLUENCE OF TRAIN AXLE LOAD ON MECHANICAL BEHAVIOR OF FOULED BALLAST

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ABSTRACT

This study evaluates the mechanical behavior of railway ballast under severe transient loading, using a laboratory drop weight impact test to simulate the effects of high-magnitude axle load events rather than direct axle loading. Crushed granite aggregates were subjected to standard characterization tests, including specific gravity, flakiness index, and elongation index, in accordance with AREMA specifications, confirming their suitability for railway applications. Ballast samples were prepared within a particle size range of 10–60 mm and tested in both clean and artificially fouled conditions at 10%, 30%, and 50% fouling levels using lateritic fines. A drop-weight impact test was conducted using a 19.2 kg hammer dropped from incremental heights of 200 mm to 1000 mm. Settlement, deformation ratio, resilient modulus and ballast breakage index (BBI) were measured to assess ballast performance under repeated loading. The results indicate a consistent decrease in resilient modulus and a corresponding increase in deformation ratio and BBI with increasing drop height and fouling level. Clean ballast exhibited superior stiffness and resistance to deformation, while heavily fouled ballast showed significant degradation in load-bearing capacity and elastic recovery. Quantitatively, the resilient modulus of 50% fouled ballast was 78% lower than that of clean ballast at a 200 mm drop height and BBI increased from 0.14 for clean ballast to 0.58 for 50% fouled ballast at 1000mm drop height. The findings establish an inverse relationship between resilient modulus and deformation ratio across all test conditions. Moderate fouling (10–30%) initiated noticeable performance deterioration, while fouling levels of 30% and above represented a critical threshold for the tested lateritic-fouled ballast under drop-weight loading. This threshold should be interpreted with caution, as field behavior may vary with moisture condition, fouling type, aggregate gradation, and drainage state. At 50% fouling, the ballast exhibited characteristics of a cohesive material with minimal resilience and high permanent deformation. Overall, the study demonstrates that ballast fouling significantly impairs mechanical performance by reducing particle interlock and increasing susceptibility to settlement. The results provide empirical data to support early intervention strategies and improve ballast management and track performance prediction under similar loading and material conditions.

Keywords: Railway Ballast, Fouling, Resilient Modulus, Deformation Behavior, Impact Energy, Settlement, Ballast Breakage Index

INTRODUCTION

The long-term performance of conventional ballasted railway tracks depends heavily on the condition of the ballast layer. Ballast supports sleepers, distributes loads to the substructure, and provides vertical and lateral restraint to maintain track alignment. Under traffic, ballast particles degrade through attrition and fracture, and the ingress of fines into the voids produces fouling. Fouling reduces permeability, weakens particle interlock, and leads to loss of stiffness, increased settlement, poor drainage, and higher maintenance demand (Indraratna, Salim, & Rujikiatkamjorn, 2011; American Railway Engineering and Maintenance-of-Way Association [AREMA], 2023). In Nigeria, these effects are compounded by inadequate maintenance, unauthorized level crossings, and the use of lateritic fines as the dominant fouling material, increasing the risk of track misalignment and derailment (Ogunleye et al., 2020).

Most existing studies on fouled ballast have focused on static or low-frequency cyclic loading, which represents steady-state wheel loads but not transient events (Selig & Waters, 1994). However, Nigerian railway operations experience significant impact loading from wheel flats, rail joints, weld defects, and discontinuities. These events generate short-duration, high-magnitude loads that can exceed static axle loads by 200–300% and occur within 1–10 ms (Kaewunruen, 2007). The combined response of fouled ballast to such impact loading is poorly understood, particularly for the crushed granite aggregates and lateritic fines commonly used on Nigerian railways. This gap matters because impact events are primary drivers of rapid ballast breakdown, sleeper damage, and track geometry deterioration (Indraratna et al., 2010; Kaewunruen & Remennikov, 2008).

To address this, a drop weight impact test was used to simulate the energy and impulse of severe transient axle load effects. While axle load typically refers to the static/dynamic wheel load transmitted through the wheel-rail interface, drop height testing provides a controlled way to replicate the impulse energy and peak forces associated with impact events (Kaewunruen & Remennikov, 2008; Indraratna et al., 2010). Ballast breakage index (BBI), which compares particle size distribution before and after loading to give a material level measure of breakage (Indraratna et al., 2011). Varying drop heights therefore represent different magnitudes of sudden loading that fouled ballast may encounter in service.

Therefore, this study investigates the mechanical behavior of clean and lateritic-fouled Nigerian ballast under impact loading. The specific objectives are to:

i. Assess the strength, toughness, and durability of railway aggregates used in Nigeria.
ii. Determine the resilient modulus, deformation ratio, and settlement response of fouled ballast under these conditions
iii. Evaluate ballast degradation and performance under drop weight impact at varying fouling levels.

The scope is limited to laboratory testing. Clean and artificially fouled specimens were prepared at 0%, 10%, 30%, and 50% fouling indices using lateritic fines, and tested using a 19.2 kg hammer dropped from 200 mm to 1000 mm to simulate varying impact energy levels.

MATERIALS AND METHODS

Materials

Materials were used were crushed granite, and lateritic soil. Crushed granite was sourced from a commercial quarry in Kaduna State, Nigeria, and graded to 10–60 mm per AREMA (2010) specifications. The aggregate was washed to remove adhered fines and organic debris, then oven-dried at 107 °C for 24 hours. Lateritic soil from a borrow pit at Ahmadu Bello University, Zaria, was air-dried, pulverized, and sieved to pass the 4.75 mm sieve for use as fouling agent. Fouled specimens were prepared by mixing clean ballast with lateritic fines at 10%, 30%, and 50% fouling levels by weight.

Physical Property Tests on Ballast

Standard tests were conducted on clean granite to confirm suitability as railway ballast, aggregate crushing value (ACV), aggregate impact value (AIV), Los Angeles abrasion, water absorption, bulk specific gravity, flakiness index, and elongation index. All tests followed AREMA (2017) Chapter 4 procedures and were performed at the Highway and Transportation Engineering Laboratory, Ahmadu Bello University, Zaria.

Drop Weight Impact Test

The impact response of 10–60 mm per Selig & Waters (1994) Nigerian granite ballast was assessed using a drop-weight test. Samples were washed, oven-dried at 107°C for 24 hours, and compacted in a rigid cylindrical mould to establish a dry baseline. Impact energy was varied from 37.7 J to 188.5 J by adjusting drop height from 200 mm to 1000 mm with a 19.2 kg hammer, applying 10 blows per height in accordance with EN 13450:2003 on clean ballast and ballast fouled with lateritic fines at 10%, 30%, and 50%. Permanent settlement, deformation ratio, resilient modulus, and post-test Ballast Breakage Index were recorded to quantify degradation.

Ballast Breakage Index (BBI)

To quantify degradation mechanisms, seive analysis was conducted with EN933-1 to determine particle size distributions before and after impact test. Ballast breakage index (BBI) was calculated using the method proposed by Indraratna et al. (2011).

RESULTS AND DISCUSSION

Properties of Laterites

Table 1 shows the physical and index properties of laterite. Laterite is a highly weathered, residual tropical soil rich in iron and aluminum oxides. Properties vary with parent rock, climate, and degree of weathering, but typical ranges are below.

Table 1: Physical & Index Properties of Laterites

S/N	Property	Typical Range	Notes Ref
1.	Color	Red, reddish-brown, yellowish-red	Due to Fe_2O_3 and Al_2O_3 oxides
2.	Specific Gravity	2.55 – 2.81	Increases with degree of laterization
3.	Grain Size	Gravel 43–62%, Sand 13–37%, Silt+Clay 25–61%	Often classified as sandy silty clay or gravelly laterite
4.	Liquid Limit (LL)	37–57%	Medium to high plasticity
5.	Plastic Limit (PL)	19–37%	
6.	Plasticity Index (PI)	3.8–30%	PI < 12% preferred for subbase
7.	Linear Shrinkage	6.7–11%	Moderate to high shrink-swell potential
8.	pH	4.0–4.9 acidic	Can be alkaline if $CaCO_3$ present

Test on Aggregates

Preliminary test result is compared with AREMA (2023) as shown in Table 2. All aggregates align with AREMA (2023) standards.

Table 2: Physical Properties of Aggregates Compared with AREMA (2023)

S/N	Physical properties	Standard code	Results	Min	Max	Remarks
1.	Aggregate Crushing Value (ACV)	AREMA 4.3.1	26.03%	Not specified	30%	Satisfied
2.	Aggregate Impact Value (AIV)	AREMA 4.3.2	25.03%	Not specified	35%	Satisfied
3.	Water absorption	AREMA 4.3.3	0.52%	0.5%	2.5%	Satisfied
4.	Los Angeles abrasion	AREMA 4.3.4	18.4%	Not specified	30%	Satisfied
5.	Specific gravity	AREMA 4.3.5	2.86	2.6	Not specified	Satisfied
6.	Bulk density	AREMA 4.3.6	1547 kg/m³	1400 kg/m³	Not specified	Satisfied
7.	Elongation index	AREMA 4.3.7	8.69%	Not specified	15%	Satisfied
8.	Flakiness index	AREMA 4.3.8	25.7%	Not specified	30%	Satisfied

Table 2 confirms that the crushed granite used meets all AREMA 2023 criteria. The Aggregate Crushing Value of 26.03% and Aggregate Impact Value of 25.03% are below the 30% and 35% limits, indicating adequate resistance to crushing and impact. A Los Angeles Abrasion value of 18.4 % shows high abrasion resistance, while Flakiness and Elongation Indices of 25.7% and 8.69% confirm angularity and cubicity needed for interlock and load transfer.

Results on Fallen Heights Test on Aggregates

Table 3a, 3b, 3c and 3d respectively shows laboratory results for clean and fouled ballast after impact test.

Figure 1a: Clean Ballast Dried in an Oven for 24 Hours

Figure 1b: Ambient temp cooling of clean ballast

Figure 1c: During fallen height test

Figure 1d: Settlement after fallen height test

Table 3a: Test Results After Impact Test for Clean Ballast

Drop height (mm)	Initial height (mm)	Final height (mm)	Settlement (mm)	Deformation ratio= Strain	Applied stress (MPa)	Resilient modulus (MPa)
200	300	296	4	0.0130	0.0107	0.823
400	300	292	8	0.0267	0.0107	0.401
600	300	285	15	0.050	0.0107	0.214
800	300	279	21	0.070	0.0107	0.153
1000	300	271	29	0.0967	0.0107	0.111

Table 3b: Test Results After Impact Test for 10% Fouled Ballast

Drop height (mm)	Initial height (mm)	Final height (mm)	Settlement (mm)	Deformation ratio= Strain	Applied stress (MPa)	Resilient modulus (MPa)
200	300	294	6	0.020	0.0107	0.535
400	300	289	11	0.036	0.0107	0.297
600	300	282	18	0.060	0.0107	0.178
800	300	275	25	0.083	0.0107	0.130
1000	300	268	32	0.107	0.0107	0.100

Table 3c: Test Results After Impact Test for 30% Fouled Ballast

Drop height (mm)	Initial height (mm)	Final height (mm)	Settlement (mm)	Deformation ratio= Strain	Applied stress (MPa)	Resilient modulus (MPa)
200	300	292	8	0.0267	0.0107	0.401
400	300	286	14	0.0467	0.0107	0.229
600	300	277	23	0.0767	0.0107	0.140
800	300	273	27	0.09	0.0107	0.119
1000	300	265	35	0.1167	0.0107	0.092

Table 3d: Test Results After Impact Test for 50% Fouled Ballast

Drop height (mm)	Initial height (mm)	Final height (mm)	Settlement (mm)	Deformation ratio= strain	Applied stress (mpa)	Resilient modulus (mpa)
200	300	282	18	0.06	0.0107	0.178
400	300	278	22	0.073	0.0107	0.147
600	300	267	33	0.110	0.0107	0.0973
800	300	261	39	0.130	0.0107	0.0823
1000	300	259	41	0.137	0.0107	0.0781

Tables 3a–3d show settlement and deformation ratio increase while resilient modulus decreases with higher drop height and fouling. Clean ballast settlement rises from 4mm at 200mm drop to 29mm at 1000mm drop, with modulus dropping from 0.823 MPa to 0.111 MPa. At 50% fouling, settlement reaches 41mm and modulus falls to 0.0781 MPa at 1000mm drop. This trend matches Indraratna et al., (2010) large-scale triaxial and box test studies. Indraratna et al. (2011) reported that

increasing fouling reduces resilient modulus and increases permanent strain due to loss of particle interlock, void filling by fines, and higher contact stresses.The inverse relationship between settlement, deformation ratio and resilient modulus also agrees with (Selig & Waters, 1994) and Ebrahimi et al. (2019), who linked modulus degradation to particle breakage and fouling. Thus the impact test results are consistent with established literature, fouling and impact energy cumulatively degrade ballast stiffness and increase deformation.

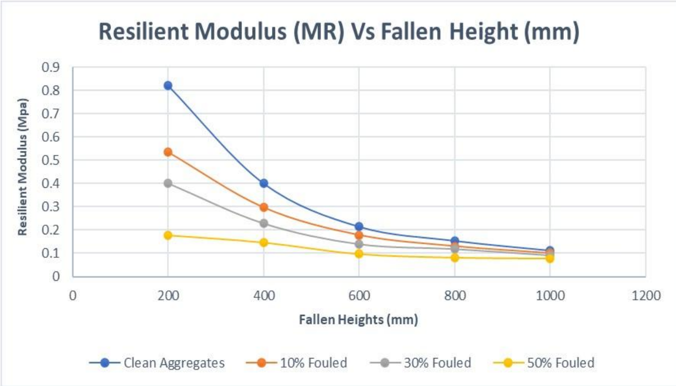

Figure 2: Resilient Modulus vs Drop Height for Clean and Fouled Ballast (0%, 10%, 30%, 50%)

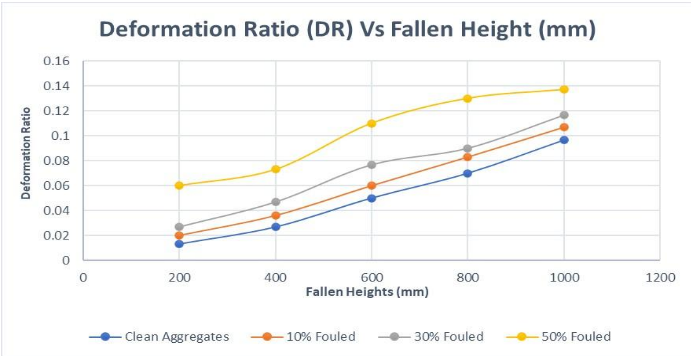

Figure 3: Deformation Ratio vs Drop Height for Clean and Fouled Ballast (0%, 10%, 30%, 50%)

Figures 2 and 3 show resilient modulus decreases and deformation ratio increases systematically with fouling and deformation, confirming deformation ratio as a strong degradation indicator. A critical transition occurs at 30% fouling, where ballast behavior shifts from elastic to inelastic, causing accelerated settlement and poor load distribution. Clean ballast maintains superior elastic recovery, while heavily fouled ballast behaves inelastically and promotes rapid settlement, consistent with AREMA limits in Table 4. GPR provides early warning through indicative signatures, uniform reflectors with high electromagnetic wave velocity for clean ballast, and signal attenuation, velocity <0.08 m/s, and chaotic diffractions as fouling exceeds 25–30%. Integrating GPR screening with spot BBI tests enables condition based maintenance. Tamping, cleaning, or replacement should be prioritized at rail joints, welds, and level crossings when GPR anomalies match the mechanical instability threshold.

Table 4: Overall Consistency with AREMA (2022)

Fouling Level	AREMA Classification (2022)	Experimental Confirmation
Clean	Good/new ballast	High modulus, low deformation
10%	Early staged degradation	Moderate stiffness loss
30%	Poor ballast condition	Critical deformation
50%	Failed ballast	Very low modulus, high plastic deformation

Particle Size Distribution (PSD)

Table 5a shows the initial gradation with 2% passing 0.075mm and 80% passing 25mm, representing clean, well-graded ballast. After impact, Tables 5b–5e show a particle size distribution (PSD) for all fouling levels and drop heights. At 1000mm drop, fines at 0.075mm increased to 4.5% for clean ballast Table 5b and 11.0% for 50% fouled ballast Table 5e. Coarse fractions also reduced, with percentage passing 25mm dropping to 75% for clean and 61% for 50% fouled ballast. This indicates particle corner breakage and fragmentation under impact. Indraratna et al. (2011) reported similar PSD shifts in large-scale box and triaxial tests, where pre/post PSD comparison was used to calculate BBI.

Table 5a: Shows Initial Gradation Before Impact

Seive Size (mm)	% passing
60	100
37.5	95
25	80
19	65
13.2	50
9.5	38
4.75	25
2.36	15
0.075	2

Table 5b: After Impact Gradation for Clean Ballast 0% Fouled

Seive (mm)	200mm	400mm	600mm	800mm	1000mm
60	100	100	100	100	100
31.5	94	93	93	91	90
25	79	78	77	77	75
19	64	63	62	62	60
13.2	49	48	47	46	45
9.5	37	36	35	35	33
4.75	24	23	22	22	20
2.36	14	14	13	13	12
0.075	2.5	3.2	3.1	4.0	4.5

Table 5c: After Impact Gradation for 10% Fouled Ballast

Seive (mm)	200mm	400mm	600mm	800mm	1000mm
60	100	100	100	100	100
37.5	93	90	90	89	86
25	76	73	73	71	67
19	61	58	58	56	52
13.2	46	43	43	41	37
9.5	34	31	31	29	25
4.75	21	19	19	18	15
2.36	13	12	12	11	10
0.075	4.0	5.2	5.2	5.0	7.0

Table 5d: After Impact Gradation for 30% Fouled Ballast

Seive (mm)	200mm	400mm	600mm	800mm	1000mm
60	100	100	100	100	100
37.5	92	90	90	89	86
25	76	73	73	71	67
19	61	58	58	56	52
13.2	46	43	43	41	37
9.5	34	31	31	29	25
4.75	21	19	19	18	15
2.36	13	12	12	11	10
0.075	4.0	5.2	5.2	5.0	7.0

Table 5e: After Impact Gradation for 50% Fouled Ballast

Seive mm	200mm	400mm	600mm	800mm	1000mm
60	100	100	100	100	100
37.5	90	89	86	85	82
25	73	71	67	65	61
19	58	56	52	50	46
13.2	43	41	37	35	31
9.5	31	29	25	23	19
4.75	19	18	15	14	11
2.36	12	11	10	9	8
0.075	5.0	6.8	6.5	9.5	11.0

Ballast Breakage Index

Table 6: Values of BBI at Varied Fouling Percentages

Drop Height (mm)	0% Fouling	10% Fouling	30% Fouling	50% Fouling
200	0.14	0.20	0.28	0.38
400	0.21	0.28	0.37	0.46
600	0.27	0.34	0.36	0.53
800	0.33	0.41	0.49	0.57
1000	0.38	0.45	0.52	0.58

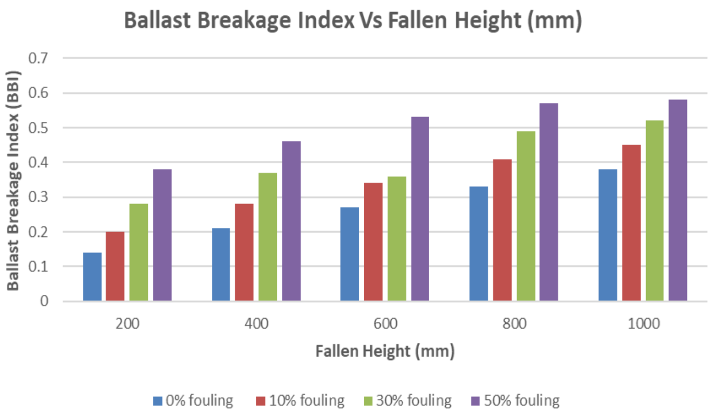

Figure 4: Ballast Breakage Index Vs Fallen Height at 0%, 10%, 30% and 50% fouling

Table 6 and Figure 4 show BBI increases with drop height and fouling. Clean ballast BBI rises from 0.14 at 200mm to 0.38 at 1000mm. At 50% fouling, BBI increases from 0.38 to 0.58, with BBI >0.5 reached beyond 600mm drop. This aligns with Indraratna et al. (2011) triaxial and box test studies, which reported BBI 0.2–0.4 for clean ballast and >0.5 when fouling index FI >30 due to loss of interlock and higher contact stresses. The steeper BBI rise at 30–50% fouling confirms Indraratna's critical threshold, where ballast shifts from dilative to contractive behavior. Thus, the impact tests reproduce the similar fouling driven degradation mechanism Indraratna (2010) observed under cyclic loading and confining pressure.

CONCLUSION

The mechanical behavior of clean and lateritic-fouled Nigerian granite ballast was evaluated under drop weight impact loading. Drop height served as a laboratory control variable to simulate varying impact energy levels, rather than representing actual train axle loads. This impact testing was supported by comprehensive aggregate physical tests to assess material suitability. Physical characterization confirmed that the granite possessed adequate strength and durability for ballast use. The Aggregate Crushing Value of 26.03% and Aggregate Impact Value of 25.03% were both below the 30% and 35% specification limits, indicating sufficient resistance to crushing and impact. A Los Angeles Abrasion value of 18.4% demonstrated high abrasion resistance. Furthermore, Flakiness and Elongation Indices of 25.7% and 8.69% respectively confirmed the presence of angular, cubic particles necessary for effective interlock and load transfer per AREMA requirements. Despite these favorable parent rock properties, increasing impact energy from 200 mm to 1000 mm drop height and fouling index from 0% to 50% produced progressive particle breakage. At 1000 mm drop height, Ballast Breakage Index increased from 0.38 for clean ballast to 0.58 for 50% fouled ballast, reflecting greater fines generation and aggregate fracture. This degradation directly impaired performance, settlement increased from 29 mm to 41 mm, deformation ratio rose from 0.0967 to 0.137, and resilient modulus decreased from 0.111 MPa to 0.078 MPa. A critical transition in behavior was observed at 30% fouling. Beyond this threshold, the rate of settlement and BBI increased sharply while resilient modulus declined more rapidly, marking the shift from stable to unstable ballast response under impact. The strong correlation between BBI and the aggregate physical indices confirms that BBI serves as a reliable indicator of degradation that aligns with field-relevant performance measures.

RECOMMENDATIONS

Maintenance action is required before lateritic fouling reaches 25–30%, especially at rail joints, welds, and level crossings, as the impact test data show that BBI and settlement increase rapidly while resilient modulus deteriorates past this threshold. Peak impact loads generated by wheel flats and rail discontinuities should be reduced through wheel defect monitoring and scheduled rail grinding, since high impact energy causes degradation even when ACV 26.03%, AIV 25.03%, and LAAV 18.4% meet specification limits. Fines ingress must be controlled by sealing unauthorized crossings and enhancing shoulder drainage, because particle angularity indicated by flakiness 25.7% and elongation 8.69% cannot maintain interlock once voids are filled with lateritic material. Ballast assessment should integrate Ballast Breakage Index from sieve analysis with ACV/AIV/LAAV, with BBI >0.45 denoting severe breakage and offering a more reliable prediction of field performance. The 30% fouling threshold for Nigerian track conditions requires confirmation through wet ballast and cyclic loading tests to account for local environmental and operational factors.

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