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Assessing the Impact of Fouling on Shear Strength of Railway Ballast in Nigeria

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Abstract

Ballast aggregate-supported railway tracks are essential to train operations because they offer a reliable and effective mode of transportation from point of origin to point of destination. However, fouling elements infiltrating the ballast layer significantly compromise its shear strength, thereby affecting the stability of the railway infrastructure. This research investigates the impact of fouling materials on the shear strength of ballast used in the Nigerian railway system. Laboratory experiments were conducted using clean ballast samples as a control and introducing four types of fouling materials at varying percentage levels for comparison. The shear strength of these samples was then assessed using direct shear tests. The results demonstrate that increasing fouling levels in the ballast reduces shear strength across all confining normal stress levels, with a concurrent decrease in the friction angle. These findings underscore that fouling infiltration substantially diminishes the shear strength of ballast. To mitigate this issue, railway engineers must implement proactive maintenance measures and routinely monitor the ballast bed for fouling infiltration to preserve track stability and performance.

Keywords: Nigerian Railway Infrastructure, Ballast Aggregates, Fouling Materials and Index, Degradation, Load Application, Direct Shear Strength Test.

INTRODUCTION

Railway track ballast, a granular material, is a vital structural component of most railway foundation systems. Its primary functions include load distribution, drainage, and track stabilization. Ballast transfers wheel loads from railway equipment through the tracks and distributes them uniformly to the underlying foundation material (Wang et al., 20211). The performance of ballast aggregates is critical to the safety and longevity of railway systems, as they provide a stable and efficient means of transportation from origin to destination. Globally, ballast constitutes the largest volume component of track bed structures and is integral to railway infrastructure (Juhasz & Fischer, 2019).

Ballast aggregates play a crucial role by providing structural support and rigidity to the track, facilitating drainage to prevent contamination, and mitigating deformations in the track bed. Acting as a filtration medium, ballast ensures lateral resistance and uniformly distributes train loads to the underlying layers (Parsons et al., 2014). Consequently, the mechanical behavior of ballast is fundamental to the stability and functionality of railway infrastructure. Ballast performance, however, is often compromised by the presence of fouling materials that alter particle size distribution over time (Rampersad et al., 2018). These fouling materials adversely affect track settlement and reduce the shear strength of ballast, posing risks to railway operations (Anbazhagan et al., 2012, Chen et al., 2022, Rampersad et al., 2018). For instance, Danesh et al., (2018) demonstrated that degraded ballast samples exhibit significantly lower shear strength compared to clean ballast, with a 21% increase in ballast breakage leading to a 48% reduction in peak shear strength and a 31% decline in peak friction angle.

In Nigeria, however, research on the impact of ballast fouling on shear strength is limited, complicating efforts to determine fouling levels that could affect shear strength. This study addresses this gap by evaluating the effects of fouling on the shear strength of ballast aggregates specific to the Abuja-Kaduna standard gauge track. Using a direct shear test, the study assesses the mechanical properties of ballast aggregates under fouling conditions. The findings aim to assist railway engineers in implementing timely monitoring and maintenance strategies to prevent critical failures in track ballast beds.

LITERATURE REVIEW / THEORETICAL UNDERPINNING

Common fouling materials, such as clay, coal, sand, and crushed ballast, infiltrate the voids within ballast layers, diminishing shear strength and complicating the maintenance of track geometry (Li et al., 2002, Rohrrnan et al., 2017, Shi et al., 2023). Studies indicate that mineral aggregate breakdown and degradation account for up to 76% of fouling incidents along freight track lines (Qian et al., 2015). Additionally, moisture trapped in fouled ballast further destabilizes the ballast layer, as demonstrated by Qian et al., (2016), while Dissanayake et al., (2016) reported that fresh ballast exhibits higher shear strength than fouled ballast. Similarly, Ramadan et al., (2024) attributed reduced shear strength to lower porosity caused by sand fouling materials, and Rohrman & Ho, (2019)

highlighted how fouling increases variability in deformation behavior while reducing shear strength.

Research by Ishikawa et al., (2016) revealed that fouling materials significantly impact the soil-water characteristic curves and the relationships between saturation levels and peak shear strength. These effects become more pronounced with increasing water content and fines fraction. Triaxial tests conducted by Rahman et al., (2024) further showed that the consistency of fouling materials, saturation degree, and deviator stress levels significantly affect the strength and deformation characteristics of fouled ballast, with plastic fouling materials increasing the risk of track instability in moist conditions. Additional investigations have explored the impact of fouling on ballast stiffness. For example, Heydari et al., (2024) evaluated vertical and shear interlocking stiffness using laboratory tests on ballast samples contaminated up to 30%. The study derived an empirical formulation for ballast stiffness and observed substantial increases in sleeper acceleration and ballast layer forces, emphasizing the influence of fouling on track responses. The result indicates an increase in track responses up to a 30 % contamination level, based on gravimetric measurements, leading to substantial increases in maximum absolute accelerations of sleeper and ballast layer as well as exerted forces on the ballast layer by about 28 %, 21 %, and 46 %, respectively.

Although, some laboratory test conducted on certain geogrid materials expected to degrade ballast and reduce the shear strength of ballast aggregates does the opposite of yielding higher strength due to such reinforced material inclusions. For instance, Qian et al., (2015) reported that ballast degradation did not necessarily result in significant strength loss from the monotonic compression tests on dry specimens. On the contrary, in most cases, the dry degraded ballast with or without fines yielded higher strength properties than those observed in the new ballast specimens. While Esmaeili et al., (2024), indicates that the inclusion of tire geo-scrap material to degrade ballast and reduce shear strength, rather increased the shear strength and internal friction angle by 28% and 9% respectively.

The widespread presence of fouling materials highlights the critical need for continuous monitoring and effective management to mitigate their detrimental impact on ballast shear strength, as evidenced by numerous studies (Chen et al., 2022, Danesh et al., 2017, Indraratna et al., 2013, Rahman, 2013). Ballast fouling has emerged as a major contributor to the degradation of ballast systems, significantly compromising the shear strength of ballast aggregates (Mayuranga & Navaratnarajah, 2023). Implementing proactive monitoring and maintenance strategies is essential to maintain the safety, reliability, and longevity of railway infrastructure.

METHODOLOGY

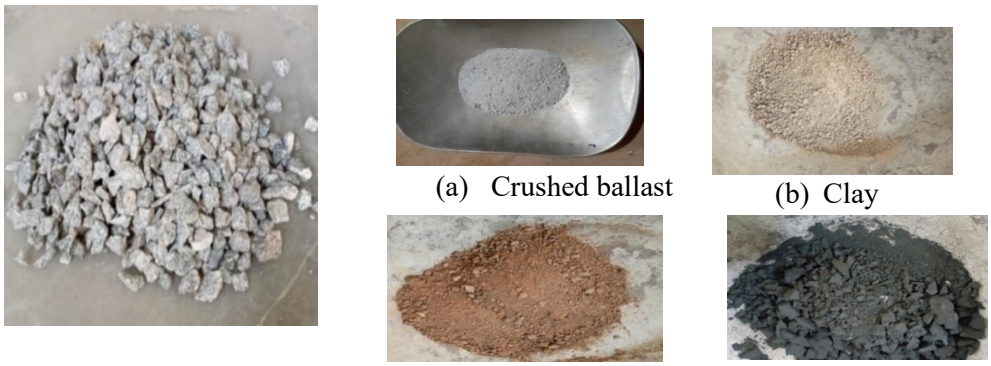
A direct shear box, depicted in Figure 1, was fabricated and assembled in the Civil Engineering Department laboratory at Ahmadu Bello University, Zaria, Nigeria, for testing the shear strength of ballast. The shear box, weighing 96 kg, was constructed from corrugated iron steel to ensure durability and functionality. It is made up of a medium-sized square box that has

been divided into two equal halves horizontally: the bottom box layer is 300 mm x 350 mm with a depth of 150 mm, and the top box layer is 300 mm x 300 mm with a minimum depth of 150 mm. When a shear force (horizontal load) is supplied, the bottom layer moves horizontally, but the top layer, where the vertical normal load is applied, is held constant. The diameter of the shear force jack is 7.5 cm, while the normal force jack measures 5.3 cm.



Figure 1: Direct shear box
Source: Author's work (2025)

Similar to the ballast aggregate used in the Abuja–Kaduna standard gauge rail line, a sample of ballast material was obtained from approved quarries in order to perform the shear strength test. In compliance with BS 812-102:1989, the samples were made up of a variety of particle sizes that were run through sieves measuring 12.7 mm, 19.05 mm, and 25.4 mm. A total of 20 kilogram of 25.4 mm particles and 15 kg of 12.7 mm and 19.05 mm particles make up the 50 kg sample weight of clean, unfouled ballast. According to the Nigerian Railway Corporation, (2025), larger particle sizes are employed in combination with smaller particles for the construction of the ballast track bed which varies from one country or region to another as indicated by Guo et al., (2022). Fouling materials, such as crushed ballast, were obtained by crushing ballast aggregates through abrasion. Clay fouling was sourced from clay deposits, sand fouling from river shores based on the properties of sand at the trackside, and coal fouling from BUA, a coal freight transport company in Nigeria. The sample aggregates and fouling materials are presented in Figure 2.



(a) Ballast aggregate (a) Crushed ballast (b) Clay (c) Sand (d) Coal

Figure 2: Sample of ballast aggregate and fouling materials
Source: Author's work (2025)

In this test, three sets of shear strength tests were conducted. The first set tested clean ballast aggregate (i.e., without any fouling material). The second and third sets tested ballast aggregate with 12% and 25% fouling materials, respectively. According to earlier research by Huang et al., (2009) and Selig & Waters (1994), these percentages correspond to moderately fouled ballast (12%) and fouled ballast (25%), within the fouling index ranges of 10% to 20% and 20% to 40%, respectively. The weight of fouling materials used is detailed in Table 1.

Table 1: Weight of fouling materials for shear strength test

Fouling Material (%)	Weight of Clean Unfouled Ballast Aggregate (kg)	Weight of Fouling Material (kg)
(1)	**(2)**	**(3)=(1)x(2)**
12	50	6
25	50	12.5

The 50 kg sample of clean ballast was prepared in six layers: three in the bottom shear box and three in the top shear box. Each layer was compacted 25 times with a hand tamper to achieve the desired dry density of the ballast as shown in Table 2. TolouKian et al., (2018) also used a hand tamper to compact ballast aggregate to achieve dry density in their study. The dry density of the ballast was calculated using the mass of the ballast aggregate and the volume of each shear box. Other properties of the ballast aggregate are also presented in Table 2.

Table 2: Dry density and other Properties of sample ballast aggregate

Dry Density (g/cm^3)		Specific Gravity	Abrasion Value (%)
Top Shear Box	**Bottom Shear Box**		
1.85	1.59	2.55	24.6

For contaminated ballast, 50 kg of ballast aggregate was mixed with the weight of fouling

material according to the specified fouling percentage. The contaminated ballast was then prepared in six layers using a procedure similar to that of the clean ballast sample.

After compacting the sample within the shear box, the test was conducted under three simulated normal loads: 3.56 kN (800 lb), 4.46 kN (1000 lb), and 5.34 kN (1200 lb). These loads correspond to normal stresses of 135 kPa, 169 kPa, and 203 kPa, respectively, over a cross-sectional area of 0.3 m by 0.3 m. A hydraulic jack applied these loads through a rigid plate placed on the 20 mm-thick specimens. The shear test was conducted similarly to those by Danesh et al., (2018) and TolouKian et al., (2018) but with different parameters. The test maintained an average shearing rate of 19 mm per 30 seconds until a strain of 15% of the shear box length was reached. Using an electronic micrometer dial gauge tester, the maximum shear force at failure under the confining normal pressures was recorded for clean ballast and for ballast mixed with 12% and 25% different fouling materials. Shear displacement and shear stress were recorded at 30-second intervals throughout the test. The maximum shear strength is attained when 15% of the shear strain is reached.

The study employed the Mohr-Coulomb failure criterion to assess shear strength, which is influenced by two key factors: (i) the friction angle (φ) of the material at failure, and (ii) the cohesion (c) of the material. The relationship is expressed as:

$$\tau = c + \sigma n \tan(\varphi)$$

Where; τ = shear stress

c = cohesion (intercept of failure envelope)

σn = normal stress

φ = friction angle (slope of failure envelope)

These parameters are fundamental in geotechnical engineering for describing the shear strength of ballast aggregates.

RESULTS

Table 3 presents the average result of a total of 25 sample test of direct shear tests conducted repeatedly on both clean ballast and ballast contaminated with four different fouling materials at two levels of fouling: 12% and 25%. These tests were performed under three distinct normal confining stresses (135 kPa, 169 kPa, and 203 kPa) to determine the maximum shear stresses at failure for each normal stress and to establish the relationship between normal stress and shear stress.

Table 3: Direct shear box ballast strength test results

Normal Stress (kPa)	Maximum Shear Stress (kPa)								
	Clean Ballast	Clean Ballast with Fouling Material							
		Crushed Ballast		Sand		Clay		Coal	
		12%	25%	12%	25%	12%	25%	12%	25%
135	100	96	94	98	94	85	80	99	91
169	130	127	113	124	116	110	95	100	96
203	151	145	140	147	140	125	115	145	134

Figure 3 typically shows the effect of normal stress on reduction of shear strength with respect to the maximum shear strength of clean ballast.

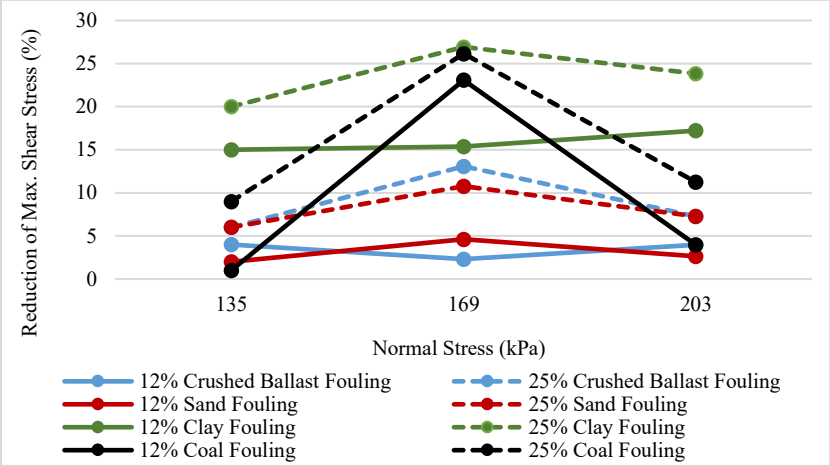


Figure 3: Shear strength reduction versus normal stress for fouled ballast samples
Source: Author's work (2025)

Further figure 4 illustrates the relationship between maximum shear stress and normal stress for both clean ballast and ballast containing fouling materials, with R^2 values ranging from 0.70 to 0.99.

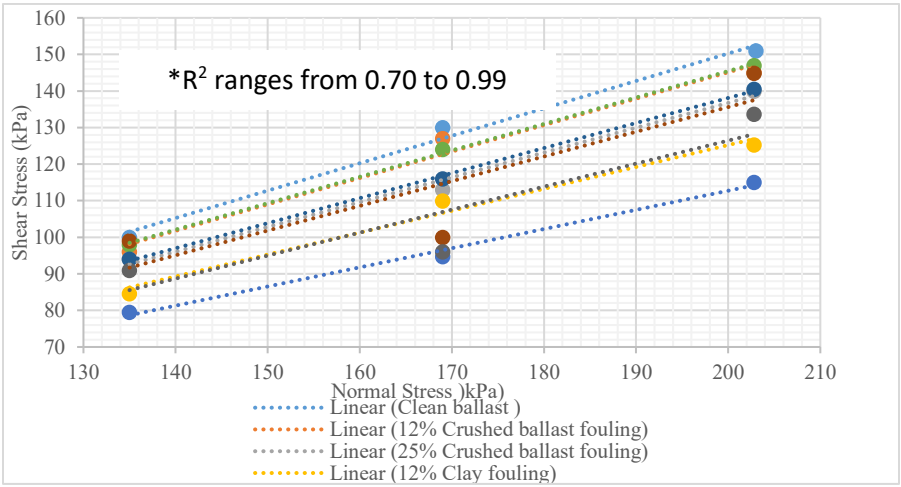


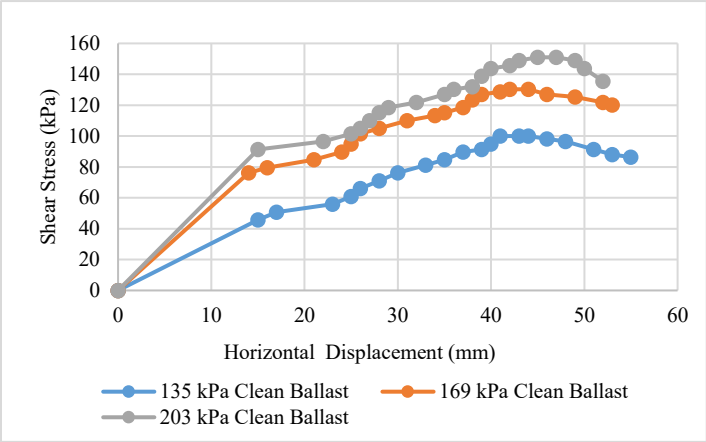
Figure 4: Maximum shear stress - normal stress relationship for clean and fouled ballast samples
Source: Author's work (2025)

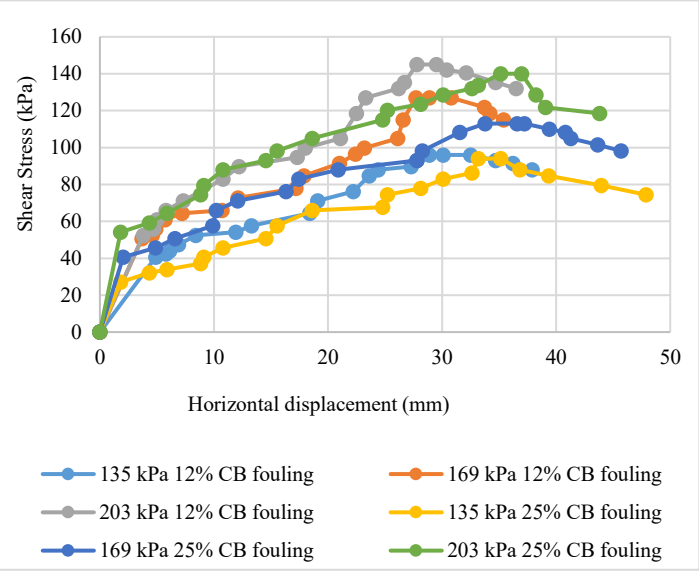
Table 4 presents the internal friction angles (φ) and cohesion intercepts (c) for both clean ballast and ballast mixed with varying amounts of fouling materials, under different combinations of shear and normal confining stresses.

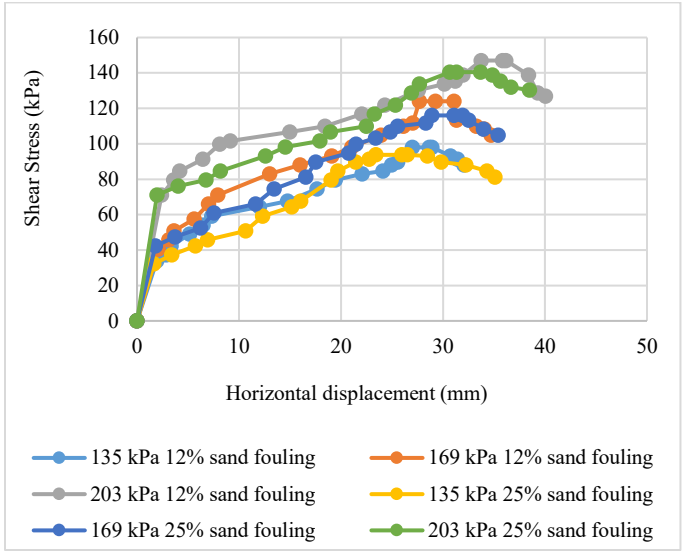
Table 4: Ballast internal friction angles and cohesion intercepts

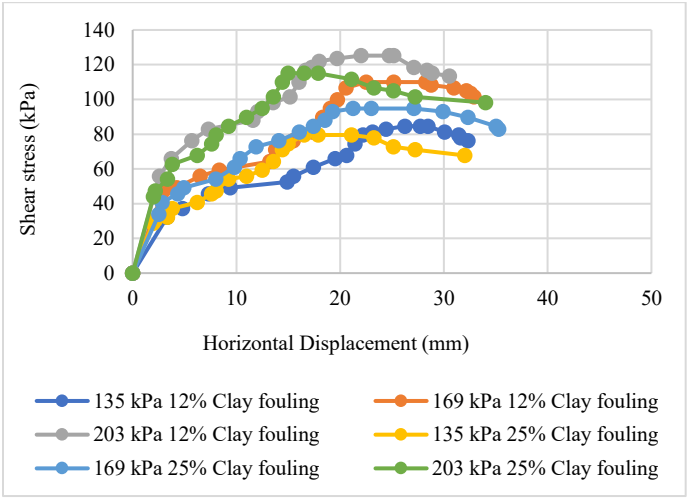
Materials	Fouling (%)	Relationship $\tau = c + \sigma_n \tan(\varphi)$	Cohesion, c (kPa)	Friction angle, φ (degree)
Clean ballast	0	$\tau = 0.75\sigma_n + 0.25$	0.3	36.87
Clean ballast with crushed ballast fouling	12	$\tau = 0.7228\sigma_n + 0.567$	0.6	35.86
	25	$\tau = 0.6782\sigma_n + 1.0887$	1.1	34.15
Clean ballast with sand fouling	12	$\tau = 0.7226\sigma_n + 0.9232$	0.9	35.85
	25	$\tau = 0.685\sigma_n + 1.0942$	1.1	34.41
Clean ballast with clay fouling	12	$\tau = 0.599\sigma_n + 5.4099$	5.4	30.92
	25	$\tau = 0.524\sigma_n + 7.9386$	7.9	27.65
Clean ballast with coal fouling	12	$\tau = 0.6756\sigma_n + 0.4842$	0.5	34.04
	25	$\tau = 0.629\sigma_n + 0.6297$	0.6	32.17

Finally, figure 5 illustrates the relationship between shear stress and horizontal displacement for both clean and fouled ballast samples under varying normal confining stresses.









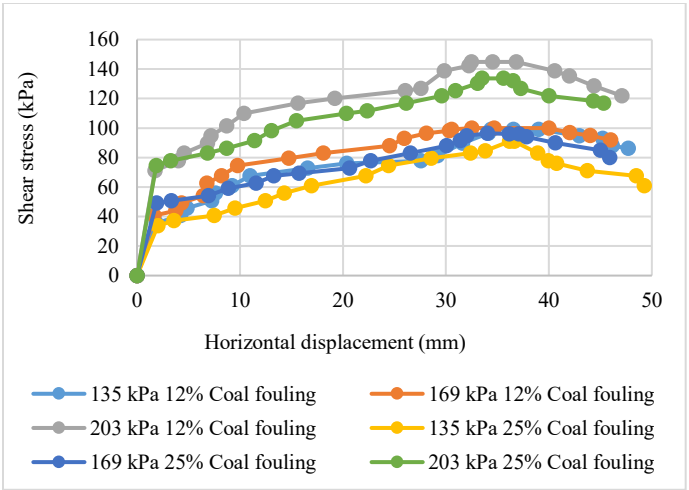


Figure 5: Shear stress vs. displacement behavior for clean and fouled samples
Source: Author's work (2025)

DISCUSSIONS

Table 3 shows the average of 25 total repeated sample test conducted. The maximum shear stresses for clean ballast were found to be 100 kPa, 130 kPa, and 151 kPa under the normal confining stresses of 135 kPa, 169 kPa, and 203 kPa, respectively. However, when the ballast is contaminated with any of the four fouling materials at 12% and 25% levels, a reduction in shear stress is observed. Notably, clay fouling has a pronounced degrading effect on ballast shear strength, with significant decreases in shear stress at both 12% and 25% contamination levels. These findings indicate that the shear strength of ballast is highly influenced by the type and amount of fouling material, with increasing levels of contamination leading to a marked reduction in both shear strength of the ballast aggregates. This trend aligns with previous studies of (Chen et al., 2022, Danesh et al., 2018, Tennakoon & Indraratna, 2014), which also reported that fouled ballast aggregates exhibit lower shear stresses.

It is very clear from figure 3 that there is significant percentage reduction in the shear strength for all fouled samples indicated by gentle and steep slopes on the graph. However, for 25% clay fouled sample and 12% and 25% coal fouled samples under 169 kPa normal stress, the reduction in shear strength with respect to the maximum shear strength of clean ballast are very obvious as they indicate 27%, 23% and 26% reduction in shear strength respectively. The 27% reduction in shear strength for the 25% clay fouling sample under 169 kPa normal stress is attributed to the cohesive strength of the clay fouling material. Also, the 23% and 26% reduction in shear strength for the 12% and 25% coal fouling cohesionless samples respectively under the 169 kPa normal stress indicates a reduce influence of normal stress (Danesh et al., 2018) on the shear strength reduction indicated by the steep slope on the graph as compared with percentage reduction values under 135 kPa and 203 kPa normal stresses.

In figure 4, these R^2 values indicates a strong correlation between the normal stress and the maximum shear stress. As expected, the results indicate that maximum shear stress at failure increases with higher normal stresses. The highest shear strength values were consistently observed in clean ballast across all normal stress levels, while fouled ballast samples exhibited a noticeable decrease in shear strength.

The results in table 4 indicate that clean ballast exhibits a significantly high friction angle of 36.87°, which is attributed to the strong interlocking effect of its angular particles. This finding is consistent with Shi et al., (2023), who noted that freshly crushed ballast particles tend to provide higher inter-particle friction due to their angularity. Cohesion values for clean ballast remain low, typically around 0 kPa, with only a slight cohesion (0.3 kPa) detected, likely due to minor interparticle forces. Previous studies by Selig and Waters, (1994) and Anbazhagan, (2012) suggest that as ballast becomes increasingly fouled with fines, its shear strength diminishes. This degradation occurs because, over time, the degree of fouling increases, causing aggregate particles to become more separated while the fines act as a lubricant, leading to a weaker ballast structure with reduced shear strength (Dissanayake et al., 2016). In addition, simulations and laboratory tests by Gong et al., (20219) indicate that fouling also affects both cohesion and internal friction angles of ballast aggregates, contributing to overall

structural weakness.

In this study, the data show that as fouling levels rise from 12% to 25%, the friction angle of the ballast decreases, while cohesion values exceed 0.3 kPa. Specifically, clean ballast with 12% fouling exhibits a cohesion value of 0.6 kPa and a friction angle of 35.86°, while ballast with 25% fouling shows a cohesion value of 1.1 kPa and a friction angle of 34.15°. At 12% fouling, the ballast retains much of its interlocking capability, resulting in a relatively high friction angle of 35.86°. The introduction of fines begins to fill some voids, slightly increasing cohesion to 0.6 kPa, but the structure is still predominantly governed by particle interlocking. However, at 25% fouling, more fines fill the voids between larger particles, leading to a higher cohesion value of 1.1 kPa. The friction angle decreases to 34.15°, reflecting a reduction in interlocking efficiency. While the increase in cohesion is not too much different from clean ballast because the fines primarily act to fill voids rather than create strong cohesive bonds. The cohesion and friction angle observed in clean ballast with 12% and 25% sand fouling are comparable to those found in ballast fouled with crushed ballast. This similarity is likely due to the low silt content in the sand from the study region, which influences fouling behavior.
In contrast, clay fouling material demonstrated higher cohesion but lower friction angles. At 12% clay fouling, the cohesion reached 5.4 kPa, while the friction angle dropped to 30.92°. With 25% clay fouling, cohesion further increased to 7.9 kPa, and the friction angle decreased to 27.65°. These results indicate that ballast contaminated with clay fouling becomes highly cohesive, which significantly reduces its shear strength. This makes clay fouling the most detrimental among the tested fouling materials and has a greater negative impact on ballast shear strength (Danesh et al., 2018). Finally, ballast mixed with coal fouling materials showed cohesion values of 0.5 kPa and 0.6 kPa at 12% and 25% fouling, respectively. Except for the clay fouling mixture, the friction angles for coal fouling were generally lower than those for other fouling material mixtures.
Finally, in figure 5, as normal confining stress increases from 135 kPa to 169 kPa and 203 kPa, a corresponding increase in both shear stress and horizontal displacement is observed in both clean and fouled ballast samples. However, it is also observed that as the normal stress increases, the peak horizontal displacements also increase (Rujikiatkamjorn et al., 2012). Significantly, in the present study the horizontal displacement for clean ballast is seen to stretch beyond 50 mm while the horizontal displacement for ballast fouled with crushed ballast and coal stretches beyond 40 mm. This is attributed to the dryness and coarseness of these samples. In contrast, the horizontal displacement of ballast fouled with sand and clay does not stretch beyond 40 mm. This is attributed to the silt content in the sand and the high cohesiveness of the clay, which tends to bind the materials together.

CONCLUSION

The direct shear test of ballast aggregates is a vital procedure for evaluating the shear strength and mechanical performance of ballast materials. It provides critical insights that inform the

design, maintenance, and operational safety of railway track systems, thereby enhancing the overall efficiency of railway networks. This study assessed the impact of fouling on the shear strength of railway ballast in Nigeria. The results reveal that increasing fouling levels in ballast aggregates consistently reduces their shear strength and friction angle under various confining normal stresses. These findings highlight the detrimental effects of fouling on the mechanical stability of ballast, underscoring its significance for railway track performance and maintenance. To mitigate these impacts, a robust monitoring system should be established to continuously assess fouling levels in ballast beds. This proactive approach will help maintain the optimal mechanical properties of ballast aggregates, ensuring the stability, safety, and longevity of railway infrastructure. As railway networks continue to expand and play an increasingly critical role in global transportation, the insights gained from direct shear tests will remain indispensable for sustaining and improving the quality and reliability of railway systems worldwide.

RECOMMENDATIONS AND FUTURE RESEARCH

Based on the study's findings and conclusion, the following recommendations are made;

1. To establish a robust monitoring system to continuously assess fouling levels in ballast beds.
2. To adopt a more stringent and stricter methods for monitoring clay fouling interference with track aggregates to ensure minimal impact.
3. To implement a real-time monitoring system to detect faults and anomalies in ballast layers for continuous maintenance
4. To conduct future studies to understand ballast behaviour under wet conditions and assess the effect of load application on track subsidence.

REFERENCES

Anbazhagan, P., Bharatha, T. P., & Amarajeevi, G. (2012). Study of Ballast Fouling in Railway Track Formations. Indian Geotechnical Journal, 42(2), 87–99. https://doi.org/10.1007/s40098-012-0006-6

Chen, J., Gao, R., Liu, Y., Zhang, R., & Shi, Z. (2022). Influence of Various Fouling Materials on Geogrid-Reinforced Ballast Performance. Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 57(1), 200–206. https://doi.org/10.3969/j.issn.0258-2724.20200307

Committee, R. L. P., Han, J., & Glavinich, T. (2013). Permeability , Resistivity and Strength of Fouled Railroad Ballast By : AJ Rahman B . S ., University of Kansas , Lawrence , Spring 2013 Submitted to the Department of Civil , Environmental , and Architectural Engineering and the Graduate Faculty of the U.

Danesh, A., Palassi, M., & Mirghasemi, A. A. (2017). Evaluating the influence of ballast degradation on its shear behaviour. International Journal of Rail Transportation, 00(00), 1–18. https://doi.org/10.1080/23248378.2017.1411212

Danesh, A., Palassi, M., & Mirghasemi, A. A. (2018). Effect of sand and clay fouling on the shear strength of railway ballast for different ballast gradations. Granular Matter, 20(3). https://doi.org/10.1007/s10035-018-0824-z

Dissanayake, D. M. A. G. B., Kurukulasuriya, L. C., & Dissanayake, P. B. R. (2016). Evaluation of shear strength parameters of rail track ballast in Sri Lanka. Journal of the National Science Foundation of Sri Lanka, 44(1), 61–67. https://doi.org/10.4038/jnsfsr.v44i1.7982

Esmaeili, M., Heydari, H., Mokhtari, M., & Darvishi, S. "Shear strength characteristics of mixing slag-stone ballast reinforcement with tire geo-scrap using large-scale direct shear tests", *Railway Engineering Science*, 2024, *0123456789*. https://doi.org/10.1007/s40534-024-00356-2

Gong, H., Song, W., Huang, B., Shu, X., Han, B., Wu, H., & Zou, J. “Direct shear properties of railway ballast mixed with tire derived aggregates : Experimental and numerical investigations”, Construction and Building Materials, 200, 2019, pp. 465–473. https://doi.org/10.1016/j.conbuildmat.2018.11.284

Guo, Y., Xie, J., Fan, Z., Markine, V., Connolly, D. P., & Jing, G. (2022). Railway ballast material selection and evaluation: A review. In Construction and Building Materials (Vol. 344). Elsevier Ltd. https://doi.org/10.1016/j.conbuildmat.2022.128218

Heydari, H., Naseri, R., & Khanie, N. (n.d.). Investigating the Effect of Ballast Contamination in Vertical and Shear Interlocking Stiffness; Experimental and Numerical Study 1 Investigating the Effect of Ballast Contamination in Vertical and Shear Interlocking Stiffness; Experimental and Numerical Study.

Huang, H., Tutumluer, E., & Dombrow, W. "Laboratory characterization of fouled railroad ballast behavior", *Transportation Research Record*, *2117*, 2009, pp. 93–101. https://doi.org/10.3141/2117-12

Indraratna, B., Tennakoon, N., Nimbalkar, S., & Rujikiatkamjorn, C. (2013). Behaviour of clay-fouled ballast under drained triaxial testing. Geotechnique, 63(5), 410–419. https://doi.org/10.1680/geot.11.P.086

Ishikawa, T., Fuku, S., Nakamura, T., Momoya, Y., & Tokoro, T. (2016). Influence of Water Content on Shear Behavior of Unsaturated Fouled Ballast. Procedia Engineering, 143, 268–275. https://doi.org/10.1016/j.proeng.2016.06.034

Juhasz, E., & Fischer, S. “Investigation of railroad ballast particle breakage”, Pollack Periodica, 14(2), 2019, pp. 3–14. https://doi.org/10.1556/606.2019.14.2.1

Li, D., Hyslip, J., Sussmann, T., & Chrismer, S. (2002). Railway geotechnics. In Railway Geotechnics (Issue May). https://doi.org/10.1201/b18982

Mayuranga, H. G. S., & Navaratnarajah, S. K. (2023). Effect of clay fouling on track drainage capacity of railway Ballast: Experimental and numerical study. Construction and Building Materials, 364. https://doi.org/10.1016/j.conbuildmat.2022.129987

Nigerian Railway Corporation (NRC) Lecture Note. (n.d.).

Parsons, R. L., Rahman, A. J., Han, J., & Glavinich, T. E. (2014). Track ballast fouling and permeability characterization by using resistivity. In Transportation Research Record (Vol. 2448, pp. 133–141). National Research Council. https://doi.org/10.3141/2448-16

Parsons, R., Han, J., Glavinich, T. E. and Rahman, A.J. *Permeability, Resistivity and Strength of Fouled Railroad Ballast*, Report Number : MATC-UK: 148;25-1121-0003-148, 2014, https://rosap.ntl.bts.gov/view/dot/28308

Qian, Y., Tutumluer, E., & Hashash, Y. M. A. (2016). Moisture Effects On Degraded Ballast Shear Strength Behavior. http://www.asme.org/about-asme/terms-of-use

Qian, Y., Tutumluer, E., Hashash, Y. M. A., & Ghaboussi, J. (n.d.). Effects of Ballast Degradation on Shear Strength Behavior from Large-scale Triaxial Tests.

Rahman, M. H., Bhuyan, M. H., & Hayano, K. (2024). Fouling conditions and associated deformation characteristics of railway ballast. International Journal of Rail Transportation. https://doi.org/10.1080/23248378.2024.2363919

Ramadan, A. N., Zhang, J., Li, T., Xu, B., & Jing, P. (2024). The Impact of Sandy Fouled Ballast Properties on Its Mechanical Behavior. International Journal of Civil Infrastructure, 07. https://doi.org/10.11159/ijci.2024.015

Rampersad, A., George, T. B., Mokoena, R., Mgangira, M. B., & Gräbe, P. J. (2018). The influence of ballast fouling on track settlement. 37th Annual Southern African Transport Conference (SATC 2018), 27(July), 508–520. https://www.researchgate.net/publication/350459208

Rohrman, A. K., & Ho, C. L. (2019). Effects of fouling containing plastic fines on abraded ballast strength and deformation properties. Transportation Geotechnics, 21, 100278. https://doi.org/10.1016/j.trgeo.2019.100278

Rohrrnan, A. K., Kashani, H. F., & Ho, C. L. (2017). Influence of fouling and water content of ballast on railway substructure bearing capacity. 2017 Joint Rail Conference, JRC 2017, 1–5. https://doi.org/10.1115/JRC2017-2286

Rujikiatkamjorn, C., B. Indraratna, B., Ngo, N. T. and Coop, M. “A laboratory study of railway ballast behaviour under various fouling degree”, 5th Asian Regional Conference on Geosynthetics (GEOSYNTHETICS ASIA 2012), Bangkok, Thailand, 2012. https://ro.uow.edu.au/engpapershttps://ro.uow.edu.au/engpapers/5262https://ro.uow.edu.au/engpapers/5262

Selig, E.T. and Waters, J.M. *Track Geotechnology and Substructure Management*. Thomas Telford Publications, London, 1994. https://doi.org/10.1680/tgasm.20139

Shi, C., Fan, Z., Connolly, D. P., Jing, G., Markine, V., & Guo, Y. (2023). Railway ballast performance: Recent advances in the understanding of geometry, distribution and degradation. In Transportation Geotechnics (Vol. 41). Elsevier Ltd. https://doi.org/10.1016/j.trgeo.2023.101042

Tennakoon, N., & Indraratna, B. (2014). Behaviour of clay-fouled ballast under cyclic loading. Geotechnique, 64(6), 502–506. https://doi.org/10.1680/geot.13.T.033

TolouKian, A. R., Zakeri, J. A., & Sadeghi, J. "Large-scale direct shear tests on sand-contaminated ballast", *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, *171*(5), 2018, pp. 451–461. https://doi.org/10.1680/jgeen.17.00107

Wang, L., Meguid, M., & Mitri, H. S. "Impact of ballast fouling on the mechanical properties of railway ballast: Insights from discrete element analysis", Processes, 9(8), 2021. https://doi.org/10.3390/pr9081331