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INFLUENCE OF VIBRATION ON SUB-BALLAST LAYER INDUCED BY LOADING APPLICATION ON A FOULED TRACK BALLAST

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Abstract
The railway track's sub-ballast layer is important, but it is often neglected, leading to the contamination and blockage of voids, as well as track deformation and degradation. These issues occur when fouling materials infiltrate the sub-ballast due to load-induced vibration. The purposes of this paper are to investigate the influence of vibration on the sub-ballast layer when loads are applied to a fouled ballast and to determine whether sub-ballast saturation should be ignored. A ballast box was fabricated to represent actual railway conditions and filled with 100 kg of ballast aggregates containing fouling materials (crushed ballast, sand, clay, and coal) proportional to the ballast weight. In addition, a vibratory compactor plate machine was used to simulate load on the fouled ballast, inducing vibrations that caused fouling materials to migrate into the sub-ballast. The results indicate that 18% of crushed ballast, 20% of sand, 20.7% of clay, and 15% of coal infiltrated the sub-ballast due to loading-induced vibration, and fouling infiltration percentages rose as vibration from loading increased. These percentages exceeded the standard 10% weight of fouling infiltration into the sub-ballast, indicating an unfavourable sub-ballast condition and showing that sub-ballast saturation should not be ignored. These findings have significant implications for maintenance engineers, as they underscore the need for continuous monitoring and upkeep to ensure optimal sub-ballast performance.

1.0 INTRODUCTION
Ballasted railway tracks represent the most popular railway system in the world today, but they have been bedevilled by the prevalence of fouling materials that negatively affect track beds [1]. Railway track ballast breakdown is caused by the gradual degradation of the ballast aggregates resulting from the continuous train vibrations on the track due to loading. In railways, vibration and noise arise due to the forces generated at the wheel/rail contact point by the steady moving constant axle loads on the railway track [2 – 6]. Vibrations caused by train movement even propagate to the surrounding surface structures and down into the track structures [7, 8]. These vibrations also cause the movement of ballast particles in the ballast bed [9]. As the train loads come from the top, they are spread and distributed to the surrounding track component layers, significantly impacting the track components due to the vibration of the track during loading. Even at the constant axle loads, substructure deformations appear where they have not appeared before due to the increased load and speed of trains [3][10].

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Along with the stresses generated by environmental conditions, traffic load vibrations degrade and crush ballast aggregate stones, producing ballast fines that deform and degrade the track ballast [11, 12]. The fines produced fill and clog the ballast voids, which increase the settlement of ballast particles, reducing track bed elasticity [13, 14], which prevents the effective drainage of water from the ballast. Other fouling materials, such as sand, coal, clay and crushed ballast aggregates, degrade the ballast by affecting the bearing capacity and the permeability of the track ballast, which causes the ballast to settle, which impedes the required voids needed and the resiliency [15, 16]. During train load action, fouling material particles migrate between the ballast particles and enter the surrounding substructure layers [17], thereby fouling or contaminating the ballast aggregates in the sub-ballast.

The ballast layer is an important component that adds to the support and rigidity of the railway track system. It plays the role of draining water completely from the track to avoid track ballast pollution and other deformations of the ballast bed on the track. While the ballast plays a major role in keeping the track system healthy and functioning, the sub-ballast layer plays an even more important role as a construction component of the railroad track [18]. Specifically, it prevents the mixing and penetration of ballast and subgrade, mitigates subgrade attrition by the ballast, reduces subgrade stress, etc. [19, 20]. These functions underscore the importance of the sub-ballast layer in track substructure components in keeping a track at an optimum level of performance. In light of these functions carried out by the sub-ballast layer, it is crucial to ascertain the impact of vibration on this layer as a result of the application of loading on existing fouled ballasts in order for it to continue to function as a drainage ballast layer and an efficient filtration channel [21].

However, monitoring the condition of the sub-ballast is challenging, as the substructure remains hidden from view unless the main ballast is evacuated [22]. Non-destructive testing methods, such as visual testing, automatic visual testing, ultrasonic testing, and radiographic testing [23, 24], have been used to monitor the condition of the sub-ballast structure. However, these methods require heavy equipment and incur high costs, which disrupts and delays traffic operations [22]. Also, SmartRocks software (battery-powered, wireless sensors that physically resemble ballast particles in shape, size, and texture) has been employed effectively by maintenance engineers to monitor the real-time conditions of track substructures [22]. In addition, ground penetrating radar has also been used to monitor substructure conditions. In research by Bassey et al. [25], Benedetto et al. [26], and Liu et al. [27], ground penetrating radar was used to establish an accurate dataset to measure track deflection and give a better result on the condition of the track.

The current study considers the condition of the sub-ballast layer of a ballast track bed whose saturation was often ignored in previous studies. Also, neglecting its maintenance has contaminated and blocked voids, resulting in track deformation and degradation. The insights and findings presented in this study could aid railway engineers, track managers, and researchers in formulating a more precise means of monitoring the degree of fouling infiltrations within track sub-ballast layers during vibrational load applications.

The objective of this study is to assess the condition of the sub-ballast layer and determine whether the saturation with fouling infiltrations should be disregarded. Given that the sub-ballast layer remains hidden from direct observation, this research adopts a localised and non-disruptive approach known as the physical visual inspection and monitoring of fouling materials. This approach tracks the infiltration of fouling materials into the sub-ballast layer within the ballast box induced by vibrations during load application on fouled ballast. This technique assesses the extent of fouling infiltration into the substructure sub-ballast layer, a situation that has been overlooked in previous studies. Comparable methodologies were applied by Gu et al. [28] to gauge track ballast settlement levels. It is important to note that this study does not address the effects on the subgrade layer. Moreover, this study underscores the significance of continuously monitoring the condition of tracks' sub-ballasts, given their integral role in the railway track ballast bed systems.

2.0 METHODOLOGY

2.1 Test Apparatus

A track ballast bed encompassing both the main ballast and sub-ballast layers was constructed within a rectangular box (Figure 1). This box, known as the ballast box, has a total weight of approximately 24.5 kg. It was built from rectangular wooden sheets with a thickness of 15 mm. It also incorporated a hollow metal pipe with dimensions of 20 mm by 20 mm and a thickness of 2 mm. The ballast box, as illustrated in Figure 2, was partitioned into two layers, mirroring the arrangement of the main ballast and sub-ballast layers found within a track bed system. The upper layer,

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corresponding to the main ballast, had dimensions of 300 mm in depth, 450 mm in length, and 300 mm in width. The lower layer, representing the sub-ballast, had dimensions of 200 mm in depth, 450 mm in length, and 300 mm in width.

These chosen dimensions represented a section of the track and accurately replicated the actual depth of the layers within a track ballast bed along the Abuja-Kaduna standard gauge line. Between these two layers of the ballast box, a sieve with an aperture size of less than 12.7 mm was affixed to the underside of the main ballast layer. This design allowed fouling materials to pass into the sub-ballast layer below during periods of vibration induced by loading. Following Ocholi et al. [29] and NRC Lecture Note [30], a sieve size of 12.7 mm was selected, as any smaller materials are classified as fouling material in Nigeria.

Figure 1: Fabricated ballast box

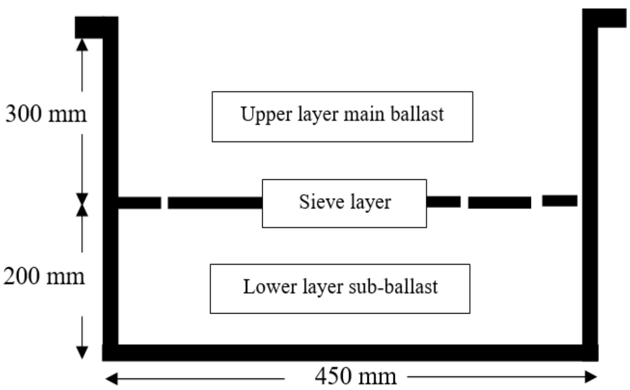

Figure 2: Ballast box layout

Additionally, this study utilised a vibrating plate compactor machine with an approximate weight of 200 pounds (91 kg/0.091 tonnes) and the ability to generate around 10,000 vibrations per minute. This machine was used owing to the need to replicate the vibrations induced by passing trains during the application of loads. The vibrating plate compactor machine simulated the behaviour of a 21-ton (21,000-kg) axle on the ballast based on the axle load observed on the Abuja-Kaduna Standard gauge line. This parameter was chosen because only a vibrator machine can mimic the vibration from the train dynamic axle load since it causes the percolation or infiltration of fouling materials into the voids of the ballast aggregates.

However, this behaviour was proportionally scaled down to a 1:231 ratio, with each kilogram of the vibratory machine corresponding to 231 kilograms of actual axle weight. In previous research, Rampersad et al. [15] determined the rate of ballast settlement using a hydraulic actuator to apply vibrations on a ballast box due to the continuous cyclic load on the ballast. Meanwhile, Huang et al. [31] used a vibratory compactor to compact ballast aggregates in a ballast box and prepared for a direct shearing test.

Figure 3: Ballast aggregates

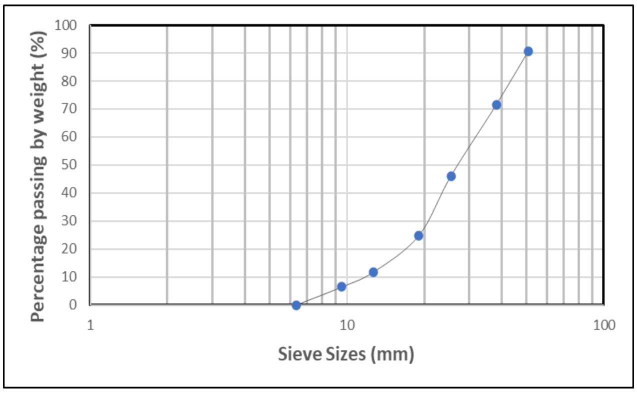

Figure 4: Particle size distribution of ballast aggregates

2.2 Sample Preparation

The ballast aggregates shown in Figure 3 below were selected in accordance with the aggregates employed on the Abuja-Kaduna standard gauge track. A total of 100 kg of clean aggregates were carefully sampled from the ballast dump at the rail site and subsequently sieved. This sieving process was employed for a combination of aggregates ranging from 12.7 mm to 50.8 mm according to British Standard (BS 812 Part

103.1-1985). The resulting particle size distribution curve is depicted in Figure 4.

Laboratory tests were conducted to determine the specific gravity (BS 812: Part 2: 1995 Part 2) and abrasion value (BS EN 1097-2:1998 Part 2) of ballast aggregates. Additionally, the material density was calculated by relating the mass of the aggregate to the volume of the ballast box [m/v]. The findings regarding the properties of the ballast aggregates are presented in Table 1.

Table 1: Properties of sample ballast aggregates

Material	Material density	Specific gravity	Abrasion value
Ballast aggregates	0.002469 kg/cm^3	2.55	24.6%

The ballast aggregates were investigated in relation to four types of fouling materials, encompassing crushed ballast stones, sand, clay, and coal (Figure 5). These four fouling materials were selected because they are the common type of fouling material along the selected track study area. The crushed ballast fouling was obtained from crushing ballast aggregates using an impact load machine. The sand fouling was obtained from surrounding track sides, which eventually entered the track bed through the wind effect as trains passed. The clay fouling was obtained from clay deposits not very far from the rail track, and the coal fouling was obtained from a coal mining company that freighted coal through the rail.

(a) Crushed ballast **(b)** Clay **(c)** Sand **(d)** Coal

Figure 5: Selected fouling materials

Table 2: Site test preparation samples

Fouling materials	Percentage Passing (%)	Weight of sample (kg)	Weight of fouling sample passing (kg)	Weight of fouling material for highly fouled ballast (kg)
Crushed ballast	82	100	82	33.62
Sand	98	100	98	40.18
Clay	87	100	87	35.67
Coal	97	100	97	39.77

Table 2 shows the aggregate weights and the fouling material weights for on-site testing purposes. The weight for the fouling materials used was obtained based on the percentage of fouling materials for highly fouled ballast, which is >40%, according to Selig and Waters [32]. This percentage is also based on the weight of fouling samples for all four fouling materials. This level of fouling was chosen to ensure the ballast aggregates were heavily fouled for the test.

2.3 Test Procedure

The test was conducted at a selected section of the Abuja-Kaduna Standard gauge track line at a time when traffic operations were not disrupted. The ballast box was located on the railway track because of the availability of and easy access to the ballast aggregate dump. Generally, the upper layer of the ballast box consists of aggregates and fouling material, whereas the lower layer is free of ballast materials. However, it was lined with a polythene bag, which facilitated the collection of infiltrated fouling materials that passed through the 12.7-mm sieve.

Figure 6: Ballast box filled with aggregates and specific types of fouling materials

Figure 7: Vibratory compactor machine mounted on ballast box

The 100 kg of clean aggregates were combined with a specific type of fouling material before being placed in the ballast box. The utilised quantity of fouling material is given in Table 2. This combination, known as a fouled ballast, was placed and compacted on the upper layer of the ballast box using a tamping rod. A ballast box filled with a combination of aggregates and selected fouling materials is shown in Figure 6. The vibratory plate compactor machine was mounted on the fouled ballast in the ballast box (Figure 7). The vibratory plate compactor machine was utilised in five-second intervals over a period of 30 seconds to facilitate the percolation of fouling materials into the sub-ballast through the voids in the ballast. The fouling materials that infiltrated the sieve with an aperture size of 12.7 mm were gathered every five seconds using a polythene bag laced on the sub-ballast layer. The collected materials were then removed from the ballast box, weighed (Figure 8), and recorded.

Figure 8: Weighing infiltrated fouling materials

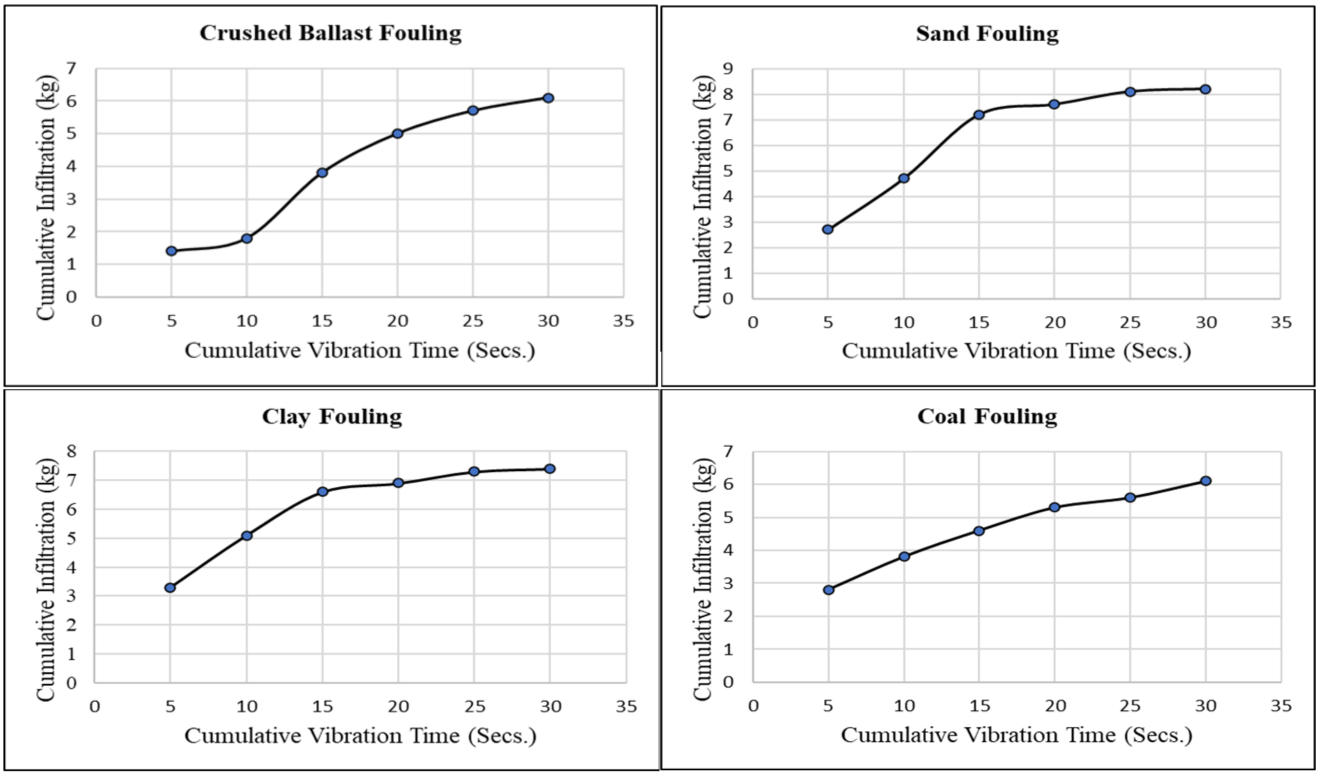

Figure 9: Fouling infiltration into sub-ballast during 30 seconds of vibration

3.0 RESULTS AND DISCUSSION

Figure 9 illustrates the cumulative infiltration of various fouling materials into the sub-ballast layer during a 30-second vibration period. The data clearly demonstrates that the cumulative infiltrations for each fouling material progressively increase with the duration of vibration. This observation aligns with the finding of Esmaeili et al. [33] that the ballast fouling percentage increases with an increase in environmental vibration due to train passing assessed by acceleration and displacement. Track vibrations caused by acceleration are another contributing factor to the downward movement of particles in the ballast layer, as stated by Bian et al. [9]. Thus, as vibration intensity increases, the amount of fouling particle material that infiltrates the sub-ballast layer also increases. At five seconds of vibration time, clay fouling exhibited the highest cumulative infiltration (3.3 kg), followed by coal (2.8 kg), sand (2.7 kg), and crushed ballast (1.4 kg).

Similarly, at 10 seconds, clay fouling continued to lead in terms of cumulative infiltration (5.1 kg), followed by sand (4.7 kg), coal (3.8 kg), and crushed ballast (1.8 kg). Notably, at five and 10 seconds of cumulative vibration time, clay fouling infiltrated more than the other three fouling materials. Clay fouling led to more cumulative infiltration in the first five and 10 seconds compared to others at the initial stage due to its fine nature. The fine clay particles had more space in between the ballast voids to pass through; they served as a lubricating agent and reduced particle interlocking. Particle movement and behaviour due to vibration are forms of translational motion because these particles move downward since the vibration emanates from the top main fouled ballast [34].

However, at 15, 20, 25, and 30 seconds of cumulative vibration time, the cumulative infiltration for sand fouling became higher than that for the other three fouling materials. Sand fouling showed cumulative infiltrations of 7.2 kg, 7.6 kg, 8.1 kg, and 8.2 kg at 15 seconds, 20 seconds, 25 seconds, and 30 seconds, respectively. This is because the sand utilised for the study had a small amount of silt content (7.5%). The silt acted as a lubricant that strengthened the sand particles, thus enabling more of it to pass through more voids than the other three types of particles [35][36]. The amounts of cumulative infiltration for other fouling materials after 30 seconds of vibration were 6.1 kg for both coal and crushed ballast and 7.4 kg for clay.

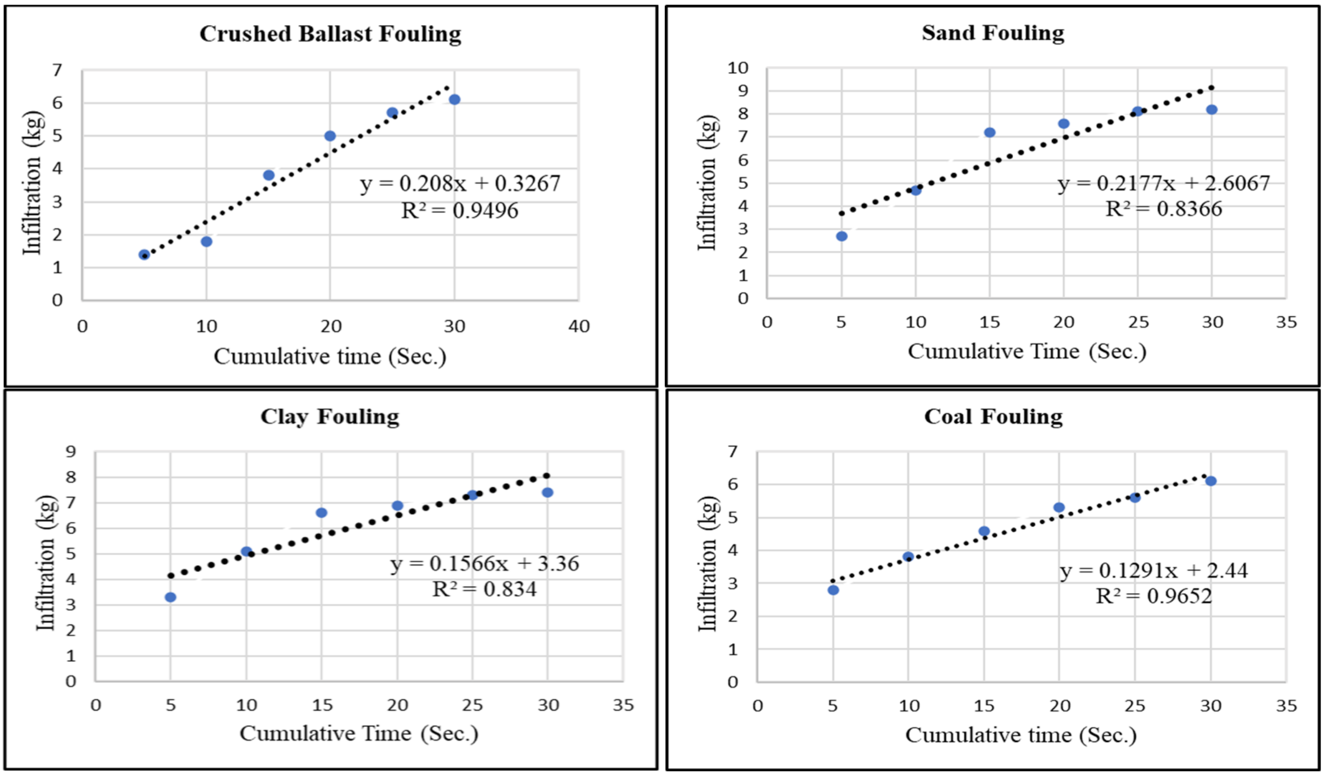

Figure 10: Relationship between vibration time and fouling infiltration

Table 3 presents the cumulative percentages of infiltration into the sub-ballast layer resulting from vibrations during loading application. For ballast particle fouling, the cumulative infiltration was 18% of the original fouling weight. Sand fouling demonstrated a cumulative infiltration of 20%, while clay fouling and coal fouling exhibited percentages of 20.7% and 15%, respectively. According to Li and Wick [20], infiltration into the sub-ballast layer exceeding 10% fines content makes the sub-ballast vulnerable to excessive deformation under loading and could cause water to be retained through capillary tension.

Table 3: Cumulative fouling infiltrations into sub-ballast over a 30-second cumulative vibration time

Fouling Material	Original Fouling Weight (kg)	Cumulative Infiltration (kg)	Cumulative Infiltration (%)
Crushed ballast	33.6	6.1	18
Sand	40.2	8.2	20
Clay	35.7	7.4	20.7
Coal	39.8	6.1	15

The current findings indicate an average of 18.4% infiltration into the sub-ballast for all fine content, which is more than the result from existing data. Such high levels of infiltration will immediately deform the layer and render its performance inadequate. Thus, if these percentages of infiltration into the sub-ballast occur within 30 seconds, then the entire amount of each fouling material, when subjected to vibration during loading application, would infiltrate the sub-ballast layer within 180 seconds (around 30,060 vibrations).

These findings clearly indicate that the sub-ballast layer will be at risk of contamination and saturation with pollutants if the main ballast layer is highly fouled and subjected to vibration on load applications.

Therefore, since sub-ballast saturation is a common but often ignored problem [19], this study has demonstrated that ignoring sub-ballast saturation, whether it be with water trapped within it [37], crushed ballast aggregates, or other fouling materials, will make the sub-ballast layer inadequately permeable.

This situation cannot be ignored because the levels of fouling infiltration reported in this study can clog a sub-ballast layer's void, preventing it from performing optimally by distributing applied loads and reducing subgrade stresses over time. Thus, the sub-ballast layer's ability to drain will be impeded, causing it to fail quickly. Mayuranga and Navaratnarajah [38] stated that fouling affects sub-ballasts because it deforms and deteriorates the sub-ballast layer, which prevents appropriate drainage and results in track ballast settlement.

Figure 10 shows the relationship between vibration time and fouling infiltration for each type of fouling material. The regression line represents a strong positive linear relationship between vibration time and fouling infiltration. It indicates that vibration time due to loading impacts the weight of fouling infiltration into the sub-ballast layer. Under actual operating conditions, trains continuously pass over the track and generate vibrations that consequently impact fouled ballasts [3]. Consequently, all the fouling materials on the fouled ballast will become percolated and will infiltrate the sub-ballast layer. When this happens without maintenance, sub-ballast layer saturation occurs, which compromises the integrity of the sub-ballast and minimises its ability to perform optimally. Therefore, sub-ballast layer saturation should not be ignored. It should be managed with immediate and continuous maintenance to keep the sub-ballast layer in an operational state.

4.0 CONCLUSIONS

The railway track sub-ballast layer is a critical track ballast component which should be continuously free-draining with little or no fine fouling material content. Continuous train loading applications vibrate the entire track system, causing fouling materials from the top to migrate downwards and fill the voids in the sub-ballast with fouling materials. This study investigates the cumulative infiltration of various fouling materials into the sub-ballast layer during a 30-second vibration period. The findings indicate that the cumulative infiltration of fouling materials into the sub-ballast layer increases with the duration of vibration. Clay fouling initially exhibits the highest cumulative infiltration due to its fine nature, while sand fouling surpasses others in later stages, facilitated by silt content acting as a lubricant. All fouling materials subjected to 30 seconds of vibrations resulted in a cumulative infiltration of more than 15% of the original fouling weight, exceeding the 10% fines content threshold, thus rendering the sub-ballast vulnerable to excessive deformation. The strong positive linear relationship between vibration time and fouling infiltration demonstrates the continuous impact of train-induced vibrations on fouled ballasts.
Therefore, maintenance engineers should constantly monitor and maintain this layer to ensure that the sub-ballast layer performs optimally. Moreover, moisture should be avoided by discouraging high fines content within the sub-ballast and encouraging high permeability and low or no water retention within the sub-ballast layer. Furthermore, a geosynthetic membrane of an aperture with a diameter smaller than the smallest fouling particle size should be laid between the main ballast and the sub-ballast layer to avoid or reduce the level of fouling infiltration into the sub-ballast layer during loading application.

5.0 ACKNOWLEDGEMENT

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REFERENCES

[1] Mayuranga, H. G. S., Navaratnarajah, S. K., Gimhani, M. N., and Karunarathne, J. M. M. Y. "The Effect of Fouling Materials on Permeability Behaviour of Large Size Granular Materials".

[2] Connolly, D. P., Kouroussis, G., Laghrouche, O., Ho, C. L., and Forde, M. C. "Benchmarking railway vibrations - Track, vehicle, ground and building effects", *Constr. Build. Mater.*, vol. 92, pp. 64–81, 2015, doi: 10.1016/j.conbuildmat.2014.07.042.

[3] Kolos, A., Petriaev, A., and Konon, A. "Study on railway elastic substructure vibration under heavy axle load", in *AIP Conference Proceedings*, American Institute of Physics Inc., 2021. doi: 10.1063/5.0063961.

[4] Milne, D. R. M., Le Pen, L. M., Thompson, D. J., and Powrie, W. "Properties of train load frequencies and their applications", *J. Sound Vib.*, vol. 397, pp. 123–140, 2017, doi: 10.1016/j.jsv.2017.03.006.

[5] Paul de Vos, S., and de Ferrocarriles, U. I. "Railway induced vibration - State of the art report", UIC-ETC (Railway Technical Publications), 2017.

[6] heng Zhang, Y., dong Qian, Z., lei Chen, L.,

Liu, Y., Zhang, H., and Zhang, X. "Impact of train vibration on physical and mechanical properties of epoxy asphalt concrete in the road-railway bridge", *Constr. Build. Mater.*, vol. 317, no. December 2021, p. 125637, 2022, doi: 10.1016/j.conbuildmat.2021.125637.

[7] Beena, K. S., Sandeep, M. N., Indraratna, B., and Malisetty, R. S. "Near-field vibrations in railway track on soft subgrades for semi high-speed trains", *Transp. Eng.*, vol. 12, no. November 2022, p. 100176, 2023, doi: 10.1016/j.treng.2023.100176.

[8] Qiu, Y., Zou, C., Wu, J., Shen, Z., and Zhong, Z. "Building vibration measurements induced by train operation on concrete floor", *Constr. Build. Mater.*, vol. 394, no. April, p. 132283, 2023, doi: 10.1016/j.conbuildmat.2023.132283.

[9] Bian, X., Cai, W., Luo, Z., Zhao, C., and Chen, Y. "Image-aided analysis of ballast particle movement along a high-speed railway", *Engineering*, 2022, doi: 10.1016/j.eng.2022.08.006.

[10] Tucho, A., Indraratna, B., and Ngo, T. "Stress-deformation analysis of rail substructure under moving wheel load", *Transp. Geotech.*, vol. 36, no. May, p. 100805, 2022, doi: 10.1016/j.trgeo.2022.100805.

[11] Al-Saoudi, N. K. S., and Hassan, K. H. "Behaviour of Track Ballast Under Repeated Loading", *Geotech. Geol. Eng.*, vol. 32, no. 1, pp. 167–178, 2014, doi: 10.1007/s10706-013-9701-z.

[12] Matias, S. R., and Ferreira, P. A. "The role of railway traffic and extreme weather on slab track long-term performance", *Constr. Build. Mater.*, vol. 322, no. December 2021, p. 126445, 2022, doi: 10.1016/j.conbuildmat.2022.126445.

[13] Gu, Q., Liu, H., Wu, Y., Luo, Z., and Bian, X. "Evolution of trackbed performance and ballast degradation due to passages of million train wheel axle loads", *Transp. Geotech.*, vol. 34, no. January, p. 100753, 2022, doi: 10.1016/j.trgeo.2022.100753.

[14] Shu, J. I., Wang, Y., Qian, Y., and Khan, J. A. "Analysis of the effect of shoulder cleaning on particle migration within ballast based on a coupled CFD-DEM approach", *Transp. Geotech.*, vol. 37, no. September, p. 100855, 2022, doi: 10.1016/j.trgeo.2022.100855.

[15] Rampersad, A. *et al.*, "The Influence of Ballast Fouling on Track Settlement Metrology of Mesoscale Ballast Particle Dynamics Using Kli-Pi View project Identifying opportunities for a more circular South African economy View project THE INFLUENCE OF BALLAST FOULING ON TRACK SETTLEMENT", 2018. [Online]. Available: https://www.researchgate.net/publication/350459208

[16] Tennakoon, N., Indraratna, B., and Nimbalkar, S. "Impact of ballast fouling on rail tracks", Civil-Comp Press, 2014. [Online]. Available: https://ro.uow.edu.au/eispapershttps://ro.uow.edu.au/eispapers/2466

[17] Cui, X., Xiao, H., and Ling, X. "Macro and Micro Analysis of Effect of Ballast Fouling on Dynamic Characteristics of Ballast Bed", *Tiedao Xuebao/Journal China Railw. Soc.*, vol. 44, no. 9, pp. 120–127, 2022, doi: 10.3969/j.issn.1001-8360.2022.09.016.

[18] Yavna, V., Shapovalov, V., Okost, M., Morozov, A., Ermolov, Y., and Kochur, A. "Modeling of long-term train loads impacts on subgrade soils: a review", *Int. J. Transp. Sci. Technol.*, no. xxxx, 2022, doi: 10.1016/j.ijtst.2022.06.005.

[19] Li, D., Hyslip, J., Sussmann, T., and Chrismer, S. *Railway geotechnics*, no. May. 2002. doi: 10.1201/b18982.

[20] Li, D., and Wilk, S. "Recent studies on railway-Track substructure at TTCI", *Transp. Saf. Environ.*, vol. 3, no. 1, pp. 36–49, 2021, doi: 10.1093/tse/tdaa031.

[21] Indraratna, B., Ngo, N. T., and Rujikiatkamjorn, C. "Behavior of geogrid-reinforced ballast under various levels of fouling", *Geotext. Geomembranes*, vol. 29, no. 3, pp. 313–322, 2011, doi: 10.1016/j.geotexmem.2011.01.015.

[22] Palese, M., Zarembski, A. M., Huang, H., and Palese, J. "Ballast particle dynamic response as a function of subgrade support using statistical methods", *Constr. Build. Mater.*, vol. 325, no. February, p. 126772, 2022, doi: 10.1016/j.conbuildmat.2022.126772.

[23] Gholizadeh, S. "A review of non-destructive testing methods of composite materials". *Procedia Struct. Integr.*, vol. 1, pp. 50–57, 2016, doi: 10.1016/j.prostr.2016.02.008.

[24] Mićić, M., Brajović, L., Lazarević, L., and Popović, Z. "Inspection of RCF rail defects – Review of NDT methods", *Mech. Syst. Signal Process.*, vol. 182, no. June 2022, pp. 1–24, 2023, doi: 10.1016/j.ymssp.2022.109568.

[25] Bassey, D., Ngene, B., Akinwumi, I., Akpan, V., and Bamigboye, G. "Ballast contamination mechanisms: A criterial review of characterisation and performance indicators",

Infrastructures, vol. 5, no. 11. MDPI AG, pp. 1–24, 2020. doi: 10.3390/infrastructures5110094.

[26] Benedetto, A., Tosti, F., Ciampoli, L. B., Calvi, A., Brancadoro, M. G., and Alani, A. M. "Railway ballast condition assessment using ground-penetrating radar-an experimental, numerical simulation and modelling development".

[27] Liu, G., Peng, Z., Jing, G., Wang, S., Li, Y., and Guo, Y. "Railway ballast layer inspection with different GPR antennas and frequencies", *Transp. Geotech.*, vol. 36, 2022, doi: 10.1016/j.trgeo.2022.100823.

[28] Gu, Q., Zhao, C., Bian, X., Morrissey, J. P., and Ooi, J. Y. "Trackbed settlement and associated ballast degradation due to repeated train moving loads", *Soil Dyn. Earthq. Eng.*, vol. 153, 2022, doi: 10.1016/j.soildyn.2021.107109.

[29] Ocholi, A., Samuel, A., Sunday, A., Danladi, E., and Ibu, T. A. "Physical and mechanical evaluation of ballast aggregates from selected quarry sites in mpape, abuja, nigeria for railway track construction", doi: 10.46654/ij.24889849.

[30] "NRC Lecture Note".

[31] Huang, H., Tutumluer, E., and Dombrow, W. "Laboratory characterization of fouled railroad ballast behavior", *Transp. Res. Rec.*, no. 2117, pp. 93–101, 2009, doi: 10.3141/2117-12.

[32] Selig, E. T., "Track geotechnology and substructure management".

[33] Esmaeili, M., Zakeri, J. A., and Mosayebi, S. A. "Effect of sand-fouled ballast on train-induced vibration", *Int. J. Pavement Eng.*, vol. 15, no. 7, pp. 635–644, 2014, doi: 10.1080/10298436.2013.818146.

[34] Indraratna, B., Tennakoon, N., Nimbalkar, S., and Rujikiatkamjorn, C. "Behaviour of clay-fouled ballast under drained triaxial testing", *Geotechnique*, vol. 63, no. 5, pp. 410–419, 2013, doi: 10.1680/geot.11.P.086.

[35] Hsiao, D. H., and Phan, V. T. A. "Effects of silt contents on the static and dynamic properties of sand-silt mixtures", *Geomech. Eng.*, vol. 7, no. 3, pp. 297–316, 2014, doi: 10.12989/gae.2014.7.3.297.

[36] Kaufman, L. P. "Percentage silt content in sands and its effect on liquefaction potential", Kaufman, L. P., U.S. Bureau of Reclamation, Denver, Colorado N.-Y. Chang, University of Colorado, Denver, Colorado," 1982.

[37] Wu, Y., Fu, H., Bian, X., and Chen, Y. "Impact of extreme climate and train traffic loads on the performance of high-speed railway geotechnical infrastructures", *Journal of Zhejiang University: Science A*, vol. 24, no. 3. Zhejiang University, pp. 189–205, 2023. doi: 10.1631/jzus.A2200341.

[38] Mayuranga, H. G. S., and Navaratnarajah, S. K. "Effect of clay fouling on track drainage capacity of railway Ballast: Experimental and numerical study", *Constr. Build. Mater.*, vol. 364, 2023, doi: 10.1016/j.conbuildmat.2022.129987