Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – June 13-15, 2024
Paper No. 164
DOI: 10.11159/iccste24.164

Case Studies of Sandy Fouled Ballast and the Impact on the Hydraulic Behaviour

Ahmed Nabil Ramadan[1,*], Jinxi Zhang[1], Li Zhang[3], Yaqi Zhang[1], Peng Jing[2]
[1] College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China
ahmednabil@emails.bjut.edu.cn; zhangjinxi@bjut.edu.cn; Zhangyaqi@emails.bjut.edu.cn
[2] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
pengjing@bjtu.edu.cn
[3] Baotou Railway Vocational & Technical College, Inner Mongolia 014060, China
873510867@qq.com
[*] Author to whom correspondence should be addressed

Abstract **-** Sandy fouled ballast is a widespread challenge in railway engineering. The existence of sand particles within ballast layer substantially impacts track performance and stability. This paper aims to highlight the importance of studying the hydraulic behaviour of sandy fouled ballast as it is limited scope, while that will affect directly the mechanical behaviour of fouled ballast. Some case studies from the track sites in different countries have been presented showing the impact on track structure and safety operation. Besides, investigate the results of the current studies regarding the hydraulic behaviour of fouled ballast by clay and sand, separately. Finally, the impact of increasing the Fouling Index (FI) within the ballast layer has been discussed. And the influence of some soil parameters on the hydraulic behaviour has been investigated regardless the fouling material is clay or sand.

Keywords**:** Ballasted Track, Sand-Fouled Ballast, Clay-Fouled Ballast, Hydraulic behaviour, Soil Water Retention Curve (SWCC)

1. Introduction

Railway tracks have an effective use in transporting individuals and goods in large numbers and quantities over the world, where the ballast layer plays a pivotal role in ensuring stability and load distribution [1]-[2]. Ballasted railway tracks are a widespread system due to many advantages like: good drainage performance, easy to construct and modify the alignment, low cost of construction compared with ballastless tracks. Ballast layer is considered to be the biggest consumer element of track maintenance costs because of its deformation producing deterioration of track geometry and deterioration of track elements. There are several geotechnical issues leading to ballast deformation [3]-[9]. One of these issues is the phenomenon of ballast fouling due to existing of small particles lower than minimum size of ballast stones inside the ballast layer (e.g., sand particles, subgrade or subballast fine particles in ballast layer, organic materials, and contamination of stones fragmentations that clearly founded in old tracks) [10]. One of the important and widespread fouling materials is sand particles that considered as a particularly disruptive material due to its granular nature, wide range of grain sizes, and lower porosity compared to the ballast stones, which severely impact the hydraulic and mechanical behaviour of the ballast layer.

The presence of fouling materials within ballast layer has different ways to express the quantities regarding the characteristics of the fouling materials. Such as the fouling index (FI), it is a general parameter to describe ballast fouling while it's applicable for silt, clay, and sand contaminated particles [11]. As this index is containing the particles that pass through No. 4 sieve (4.75 mm) with particles pass through No. 200 sieve (0.075 mm) showing in Eq. (1) as follows:

$$FI = P_4 + P_{200} \tag{1}$$

where P_4 is the percentage passing No. 4 sieve and P_{200} is the percentage passing No. 200 sieve.

Contamination of ballast layer leads to have many problems. The track strength and its modulus of elasticity will be changed, affecting the suspension system of rolling stocks and wheel/rail contact. In case of fully submerged with fouling materials of sand, accidents could be happened because of losing the functionality of track elements (e.g., fixation of switches because of sand obstruction, displacement of wheel as sand particles submerged the track gauge, etc.). Many studies have been done to mitigate the impact of sand migration to the track by different ways (e.g., blocking fences, deviating boards, trees planet, large roughness elements, etc.) [12]-[13]. But that is only mitigation not totally preventing the ballasted tracks of sand particles. So understanding the hydraulic behaviour of sandy fouled ballast is essential as it is limited scope and about 33% of Earth's geography covered by deserts causing many problems for numerous railway tracks widely [14]. While some case studies in different countries are introduced to show the impact of sand migration to the railway tracks from field vision.

2. Different Countries and Actual Situation of Fouling Tracks

The fouling phenomenon is widely existed in different countries as it depends on the conditions of ballasted tracks and the different types of fouling materials. The impact of fouling materials varies across countries, leading to have substantial challenges and implications for railway infrastructure and safety operation of the track. Sand is a widespread fouling material and different case studies introduced by countries as follow.

1- Egypt: Passing parallel to the North coastal, there is a single ballasted track connecting the cities of Alexandria with Marsa Matruh with length of 296 km. The track superstructure is not unified along the line. As the ballast layer is containing basalt and dolomite stones, where sleepers are wooden with K-type fasteners (direct fastening system) and concrete sleepers with vossloh fastening system of renovated tracks. While all rails are 54E1 connected with rail joints and welding in renewed zones. The track is suffering from two problems. The first one is the sand moving from the desert to the track, and the second is exposing the track to different levels of precipitations. As illustrated in Fig. 1, the wind direction (U) is controlling the sand traveling to the track with distinct quantities depending on the obstacles faced the movement of sand particles and wind force.

Fig. 1: Sand sedimentation induced by track line as an obstacle for wind direction [20].

Moreover, the construction works beside the track is also be another main reason of fouling the ballasted tracks. As the construction associated with the High Speed Rail (HSR) project/ Green Line in Egypt is directly beside the line of Alexandria and Marsa Matruh line without adequate protection, causing immigration of sand particles to the existed line and sandy fouled ballast as shown in Fig. (2).

Fig. 2: Sand immigration particles to the existed track cause of construction works beside it.

2- China: Exactly in Gansu province there is a ballastless track with length of 1,776 km linking Xinjiang's capital Urumqi with Lanzhou that is along the Gobi Desert. The design speed is 350 km/hr; however, the top speed was operated at 200 km/h or below because of windblown sand effects and saline soil as shown in Fig. 3 [15]-[16].

Fig. 3: Lanzhou-Xinjiang high-speed railway [17].

3- Saudi Arabia: From Mecca to Medina in parallel with the Red sea coastal region, there is a ballastless track with length of 450 km as the design speed is 300 km/hr. The track passed in desert with around 220 km along sandy zones where 20 km of it across dune fields. As shown in Fig. 4, during the construction phase of the project there are some reports about sand migration problems. Accordingly, it is supposed to reduce the operation speed due to sand moving to the track; besides, the track operation could be frozen if it is submerged with sand.

Fig. 4: Track under construction from Medina to Mecca [18].

4- United Arabs of Emirates (UAE): Linking the seven emirates of UAE, a ballasted track of 900 km was constructed mainly for freight transportation.

As presented in Fig. 5, the track is totally suffering from sand immigration from desert to the railway tracks. As the track is passing by more than 50 km of sensitive desert parts where the height of sand dunes could reach to 150 m [19].

Fig. 5: Sand moving to the network of Etihad Rail Network [20].

3. Impact of Fouling Materials on the Hydraulic Behaviour

The hydraulic behaviour of ballast layer could be altered by the intrusion of fouling material like sand or clay, affecting water drainage and the permeability of ballast layer. The hydraulic conductivity of the fouled ballast can be derived from the soil water retention curve (SWCC), as the SWCC is influenced by the grain size distribution, density, and mineralogical composition of the fouling material.

Due to changing the hydraulic conductivity the track strength will be affected, developing settlement and degradation of track elements. So it is necessary to understand the hydraulic behaviour of contaminated ballast with different fouling materials. In general, contamination characteristics affect the hydraulic conductivity as follows.

- Particle size: decreasing the size of particles ensuring decreasing the hydraulic conductivity as the pore sizes is reducing.
- Level of saturation: increasing the water content within the fouled ballast leading to increase the hydraulic conductivity as the pores within the fouled ballast are already connected so water movement is easier than in unsaturated state.
- Contamination percentage: contamination has main impact on the water conductivity through the fouled ballast layer. As by increasing its percentage, the particles prevent water connections beside water transferring out of the track, resulting in decreasing the hydraulic conductivity.

It was found that the hydraulic conductivity could be affected by the changing in the contamination percentage within the fouled ballast. As presented in Fig. 6 by increasing the percentage of Void Contamination Index (VCI) of clay particles, the hydraulic conductivity was decreased because of less void spaces that clogging the water passage [21].

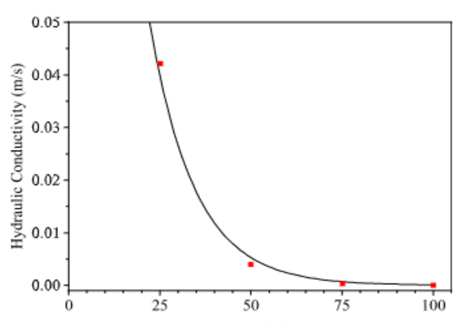

Fig. 6: The impact of changing the VCI on the hydraulic conductivity of fouled ballast [21].

Normally the percentage of fouling materials has a positive relationship with the matric suction. However on the other side the matric suction has a negative relationship with the hydraulic conductivity. In Fig. 7, it can be found that the suction increased by decreasing the volumetric water content or the degree of saturation when the ballast fouled by clay particles that is for measured and modelled data [22] as its dry density equals 2.01g/cm^3. Particle size distribution of fouled ballast sample with clay is shown in Fig. 8 as the graph contains the distribution of the fouled ballast and the fouling material.

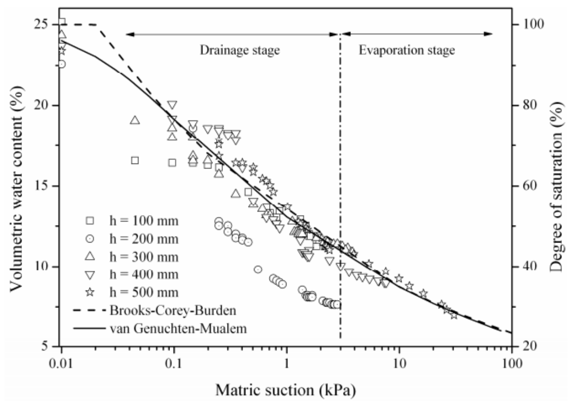

Fig. 7: Relation between volumetric water content and matric suction of fouled ballast [22].

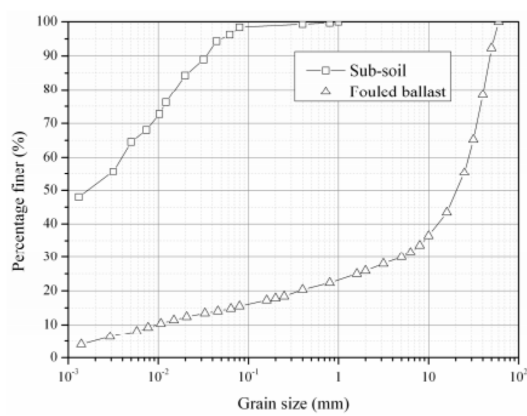

Fig. 8: Particle size distribution of fouled ballast and the fouling material [22].

The same relationship between the hydraulic conductivity and the matric suction was found of sandy fouled ballast as illustrated in Fig 9, where the particle size distribution is presented in Fig. 10. As the relationship has been investigated using large-scale of the transient water release and imbibition method (TRIM) [23]. SP large is the pore graded sand classified regarding to ASTM D2487 by using Large-scale test, where SP 50 and SP 22 are the fouling percentage of the fouled ballast with 50 % and 22%, respectively. It is obviously found the impact of the fouling percentage on the suction of fouled ballast. Whither the suction is increased by increasing the FI at the same level of unsaturation. In addition, the by increasing the level of saturation or the water content inside the sandy fouled ballast the suction will be decreased. The saturated volumetric water content of SP 50 has the same value of SP 22; although, the residual volumetric water content of SP 50 is higher than SP large. That could be because of the samples of SP 50 and SP 20 have the same properties of density, porosity, and the dry density as in Table 1.

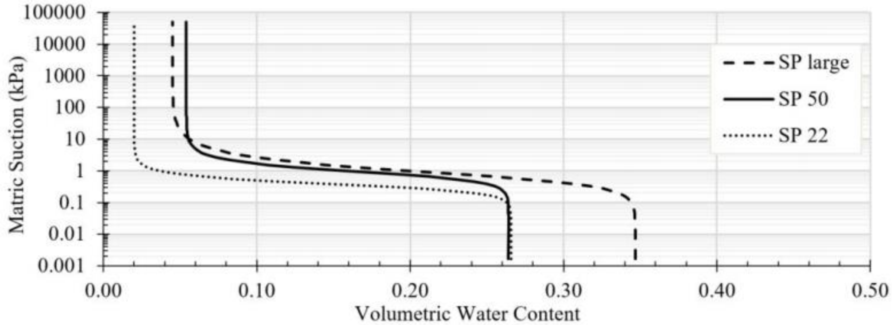

Fig. 9: Soil water characteristic curve of sand and sandy fouled ballast [23].

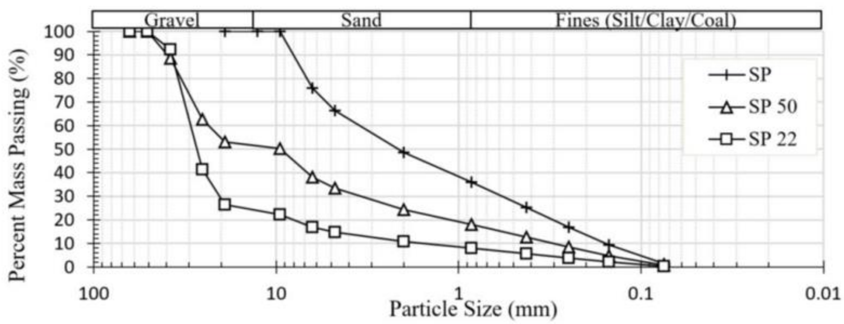

Fig. 10: Particle size distribution of sandy fouled ballast and fouling material [23].

Table 1: sandy fouled ballast and fouling material specimens properties [23].

Sample ID	FI	ρ_d(g/cm^3)	Porosity (%)	Gs
SP	-	1.74	34	2.64
SP 50	36	1.94	26	2.64
SP 22	15	1.94	27	2.64

4. Analysis and Discussion

From the last particle size distributions of fouled ballast with clay and sand particles, it can be found that the FI of fouled ballast with clay is about 46% (where, P_4= 33% and P_{200}= 15%). However, the FI of the fouled ballast with sand particles (SP 50) is about 36% (where, P_4= 36% and P_{200}= 0%). The values of P_4 in both samples are close to each other, but the values of P_{200} are totally different. Volumetric water content in saturation stage of fouled ballast with clay is 25%, where, the volumetric water content in fouled ballast with sand of the same stage is 26%.The residual water content in fouled ballast with clay is up to 6%, where the residual water content in fouled ballast with sand is 5.8%. The air entry pressure equals 0.02 kPa in fouled ballast with clay; however, it equals 0.1 kPa in fouled ballast with sand. Coefficient of uniformity (C_u) and coefficient of curvature (C_c) are main parameters used for size particle analysis for granular materials as introduced in Eq. (2) and Eq. (3), respectively.

$$C_u = {}^{D_{60}}\!/_{D_{10}} \tag{2}$$

$$C_c = {}^{D_{30}^2}\!\Big/_{D_{60} * D_{10}} \tag{3}$$

where D_{60} is the corresponding size of particles with cumulative passing 60 % , D_{30} is the corresponding size of particles with cumulative passing 30 % , and D_{10} is the corresponding size of particles with cumulative passing 10 %

In clay-fouled ballast, D_{60} is 30 mm, D_{10} is 0.01, and D_{30} is 4 mm. So, C_u of clay fouled ballast equals 3000 and C_c equals 53.3. In sand-fouled ballast, D_{60} is 23 mm, D_{10} is 2 mm, and D_{30} is 3.3 mm. So, C_u of sand fouled equals 11.5. and C_c equals 0.23.

So generally it can be found that the P_4 and dry density of fouled ballast can control holding water in case of saturation and dry, as these two parameters are close to each other in clay-fouled ballast and sand-fouled ballast. There is strong relation between P_4 and dry density with saturation and residual water content whatever the fouling material is sand or clay. Nevertheless, C_u and C_c of fouled ballast of different fouling materials can affect the air entry pressure and the hydraulic behaviour during the unsaturation state.

6. Conclusions

This paper seeks to focus on the impact of sand migration to the railway tracks. By demonstrating some case studies from the field in different countries, the importance of studying the behaviour of sandy fouled ballast is mandatory. Especially the hydraulic behaviour regarding changing in water content as this scope is limited. After investigating the hydraulic behaviour of fouled ballast with clay and sand fouling materials, the main findings can be summarized as follows:

- Both materials have the same principle of SWCC, meaning by decreasing the water content the suction increased and by increasing the Fouling Index the suction increased.
- The percentages of particles passing No. 4 sieve (4.75 mm) and the dry density of the fouled ballast are mainly controlling the values of water content in saturation and dry stages, despite the fouling material is clay or sand.
- Regardless the fouling material is sand or clay, coefficient of uniformity and coefficient of curvature of fouled ballast are affecting the air entry pressure and the hydraulic behaviour during the unsaturation stage.

Acknowledgements

Acknowledgments for the sponsorships from the National Natural Science Foundation of China (Grant No.51908011), Beijing Municipal Education Commission (No.KM202110005001) and Inner Mongolia Autonomous Region Natural Science Foundation (2023MS05039). Thanks also go to the International Research Cooperation Seed Fund of Beijing University of Technology (No.2021B08) and the Project of Baotou Railway Vocational & Technical College (BTZY202226).

References

[1] D. Li, J. Hyslip, T. Sussmann, and S. Chrismer, *Railway geotechnics*. 2002.

[2] C. Ngamkhanong, B. Feng, E. Tutumluer, Y. M.A. Hashash, and S. Kaewunruen, “Evaluation of lateral stability of railway tracks due to ballast degradation,” *Constr. Build. Mater.*, vol. 278, p. 122342, Apr. 2021, doi: 10.1016/j.conbuildmat.2021.122342.

[3] X. Han and E. T. Selig, “Effects of fouling on ballast settlement,” in *Proc., 6th International Heavy Haul Railway Conference*, 1997, pp. 6–10.

[4] M. M. Hasnayn, W. J. McCarter, P. K. Woodward, D. P. Connolly, and G. Starrs, “Railway subgrade performance during flooding and the post-flooding (recovery) period,” *Transp. Geotech.*, vol. 11, pp. 57–68, 2017.

[5] X. Bian, H. Jiang, and Y. Chen, “Preliminary testing on high-speed railway substructure due to water level changes,” *Procedia Eng.*, vol. 143, pp. 769–781, 2016.

[6] H. Jiang, X. Bian, J. Jiang, and Y. Chen, “Dynamic performance of high-speed railway formation with the rise of water table,” *Eng. Geol.*, vol. 206, pp. 18–32, 2016.

[7] M. Malawska and B. Wilkomirski, “Accumulation rate of polychlorinated biphenyls(PCBs) in dandelion(Taraxacum officinale) in the conditions of soil contamination with oil derivatives,” in *Annales of National Institute of Hygiene/Roczniki Panstwowego Zakladu Higieny*, 2001, vol. 52, no. 4, pp. 295–311.

[8] M. Malawska and B. Wiłkomirski, “Soil and plant contamination with heavy metals in the area of the old railway junction Tarnowskie Góry and near two main railway routes.,” *Rocz. Panstw. Zakl. Hig.*, vol. 51, no. 3, pp. 259–

267, 2000.
[9] M. Malawska and B. Wilkomirski, "An analysis of polychlorinated biphenyls (PCBs) content in soil and plant leaves (Taraxacum officinale) in the area of the railway junction Iława Główna," *Toxicol. Environ. Chem.*, vol. 70, no. 3–4, pp. 509–515, 1999.
[10] D. Bassey, B. Ngene, I. Akinwumi, V. Akpan, and G. Bamigboye, "Ballast Contamination Mechanisms: A Criterial Review of Characterisation and Performance Indicators," *Infrastructures*, vol. 5, no. 11, p. 94, Nov. 2020, doi: 10.3390/infrastructures5110094.
[11] D. Ionescu, "Evaluation of the engineering behaviour of railway ballast," University of Wollongong, 2004.
[12] L. Bruno, M. Horvat, and L. Raffaele, "Windblown sand along railway infrastructures: A review of challenges and mitigation measures," *J. Wind Eng. Ind. Aerodyn.*, vol. 177, pp. 340–365, Jun. 2018, doi: 10.1016/j.jweia.2018.04.021.
[13] K. Zhang, J. Qu, K. Liao, Q. Niu, and Q. Han, "Damage by wind-blown sand and its control along Qinghai-Tibet Railway in China," *Aeolian Res.*, vol. 1, no. 3–4, pp. 143–146, Jan. 2010, doi: 10.1016/j.aeolia.2009.10.001.
[14] W. Alsharif, M. M. Saad, and H. Hirt, "Desert Microbes for Boosting Sustainable Agriculture in Extreme Environments," *Front. Microbiol.*, vol. 11, Jul. 2020, doi: 10.3389/fmicb.2020.01666.
[15] S. Chen, "Why China's longest high-speed railway is slowing down," 2021. https://www.scmp.com/news/china/science/article/3156416/why-chinas-longest-high-speed-railway-slowing-down.
[16] "Lanzhou–Xinjiang high-speed railway." https://en.wikipedia.org/wiki/Lanzhou–Xinjiang_high-speed_railway.
[17] W. Tao *et al.*, "Aerodynamic Properties and Shelter Effects of a Concrete Plate-Insert Sand Fence Along the Lanzhou-Xinjiang High-Speed Railway in Gobi Regions Under Strong Winds," 2022, [Online]. Available: https://www.frontiersin.org/articles/10.3389/fenvs.2022.861063/full.
[18] L. GÓMEZ and R. MÉNDEZ, "Saudis kick up storm over Spanish group's high-speed desert rail project," 2015. https://english.elpais.com/elpais/2015/02/04/inenglish/1423052376_326956.html.
[19] Saipem, "ETIHAD RAIL STAGE 1." https://www.saipem.com/en/saipem-worldwide-projects/etihad-railway-line.
[20] D. Bulmer, A. Durham, K. Williamson, and S. Lytherao, "Sand Mitigation Report for Etihad Rail," 2012.
[21] H. G. S. Mayuranga and S. K. Navaratnarajah, "Effect of clay fouling on track drainage capacity of railway Ballast: Experimental and numerical study," *Constr. Build. Mater.*, vol. 364, no. August 2022, p. 129987, 2023, doi: 10.1016/j.conbuildmat.2022.129987.
[22] L. D. Suits, T. C. Sheahan, A.-M. Tang, A.-N. Ta, Y.-J. Cui, and J. Thiriat, "Development of a Large-Scale Infiltration Tank for Determination of the Hydraulic Properties of Expansive Clays," *Geotech. Test. J.*, vol. 32, no. 5, p. 102187, 2009, doi: 10.1520/GTJ102187.
[23] S. E. Kulesza, L. B. Michelle, R. S. Robert, and S. Anibal, "Unsaturated Characteristics of Fouled Ballast to Support In Situ Identification of Fouling Using Ground Penetrating Radar – Phase I," 2022.