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INNOVATIVE GROUND IMPROVEMENT TECHNIQUES TO STABILISE UNSTABLE SUBGRADE

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Abstract: This paper presents two ground improvement techniques using geocomposite and granular waste to stablise unstable and expansive subgrade under rail tracks. The influence of geosynthetics in controlling and preventing mud pumping was investigated using the dynamic filtration test by assessing the variation of excess pore pressure, particle size distribution, and the water content of subgrade soil specimens. The experimental results were then used to evaluate the performance of selected geotextiles under heavy haul loading. For expansive subgrade soils, coal wash, a by-product of coal mining, was mixed with subgrade soil to obtain the optimum mixture to reduce the plasticity, susceptibility to shrinkage, and swell pressure of clay soil. The results of this study suggest that both techniques can be adopted to enhance the track performance, thereby reducing the maintenance budget.

Keywords: cyclic load, expansive soil, geocomposite, ground improvement, railway

1. INTRODUCTION

There has been an increasing demand for faster and more reliable railway transportation for moving passengers and goods. However, railway tracks often built on weak and expansive subgrade soil are vulnerable to instability due to the induced and repeated dynamic stress during heavy-haul and passenger trains' passage and moisture variation. The railway organisation spends hundreds of millions of dollars for maintenance, mainly for subgrade instability caused by poor drainage in railway tracks. The rapid accumulation of Excess Pore Water Pressure (EPWP) during repeated load induces a decrease in effective stress, and upward seepage drags the finer particles up toward the overlying layers under critical hydraulic conditions.

Generally, the capping/sub-ballast layer serves two primary purposes: (1) to reduce the transferred cyclic stress from the ballast and (2) to offer sufficient drainage, thereby preventing pumped fines from subgrade soil. If the subgrade becomes saturated, the hydraulic gradient induced by cyclic loading can create the onset of internal instability. Due to these reasons, conventional impermeable capping fails to perform its primary functions and leads to track instability, as reported in various sites, including NSW Australia (Indraratna et al. 2020a).

Nguyen et al. (2019) show that the instability can be exacerbated by Cyclic Stress Ratio (CSR), the frequency (f), and the characteristics of subgrade, such as the consistency and degree of compaction of the soil. To ensure the free drainage condition, several studies confirm that drainage offered by geotextiles may prevent subgrade migration and limit excessive deformation and mud pumping under heavy haul loading (Aw 2007; Kermani et al. 2018; Selig & Waters 1994). Different approaches used to assess soil, and geotextile filtration, retention, and clogging criteria were studied earlier (Bhatia & Huang 1995; Faure et al. 2006; Ghataora et al. 2006; Ghosh & Yasuhara 2004; Palmeira et al. 1997; Palmeira 2009; Xiao & Reddi 2000). Small specimens under cyclic triaxial conditions were employed to investigate the changes in the EPP and determine how geotextile in highway embankments can control the rate at which fine particles are pumped (Alobaidi & Hoare 1994; Alobaidi & Hoare 1998; Alobaidi & Hoare 1996). Further investigation is required to study the start of mud pumping and the role and efficiency of geocomposite using large-scale dynamic filtration tests under in-situ hydraulic conditions in railway tracks.

The concerns about the presence of expansive soils during the construction and post-construction phases of the rail tracks have been widely documented (Tang et al., 2009, Alazigha et al., 2018, Wang and Wei, 2014). Seasonal wetting and drying cycles with swelling and shrinkage can induce cracking that can lower the bearing capacity of subgrade. In rail tracks, this problem causes an intensified differential settlement creating the risk of instability and potential failure (Sánchez et al., 2014). For example, along the Wellcamp-Charlton alignment in Toowoomba, Australia, more than100 km of expansive clays were revealed and 248,600 m^3 out of 369,600 m3 needed to be excavated (AECOM, 2017). The need to mine appropriate replacement geo-materials significantly increased the construction cost, with the cost of maintaining tracks almost doubled. Coal wash (CW) is the discarded granular material after the processing/separation of coal. It usually contains approximately 30-40% gravel and 60-70% sand in NSW, Australia. CW requires an enormous area of landfill for storage (Indraratna et al., 2020b, Rujikiatkamjorn et al., 2013), posing a serious environmental issue in many parts of the world. The potential recycling of coal wash as an additive to improve the properties of expansive soil underneath railway track have significant benefits, both from financial and environmentally friendly perspectives. This study employed a mixture of CW and expansive clay to create a more resilient and environmentally friendly subgrade material for rail track construction. Expansive soil and CW mixtures are characterised using basic geotechnical tests and the shrinkage and swelling potential of the soil. A series of monotonic and cyclic triaxial tests also took place to examine the blended matrix under dynamic loading conditions.

2. EXPERIMENTAL PROGRAM

2.1 Filtration test

Arivalagan et al. (2021) employed the filtration apparatus developed by Israr et al. (2016) was altered to monitor the local EPP, and deformation during cyclic load application (Fig. 1). A vertical monotonic or cyclic load up to 40 kN with a frequency up to 40 Hz can be applied through the piston connected to the loading plate. The cell had a 240 mm diameter and 300 mm high. Subgrade soil experiencing mud pumping was obtained from a rail track near Wollongong (NSW, Australia). The liquid and plastic limits were 42% and 26%, respectively. The soil could be categorized as inorganic clay with medium plasticity. An in-situ soil density of 1600 kg/m^3 was adopted, where its permeability was 8.9x10^{-7} m/s. The geocomposite G1 had a filter media between nonwoven geotextile layers with an aperture opening size of <1 µm, whereas those of G2 and G3 were 60 and 75 µm, respectively (Fig. 2).

A total vertical pressure of 30 kPa was applied for two days. The cyclic load was applied to the specimen through a circular loading plate to ensure constant pressure. Constant normal stress was applied to simulate an axle load of 35 tonnes with frequency varied between 1.0 and 5.0 Hz (train speeds of 45-225 km/h.

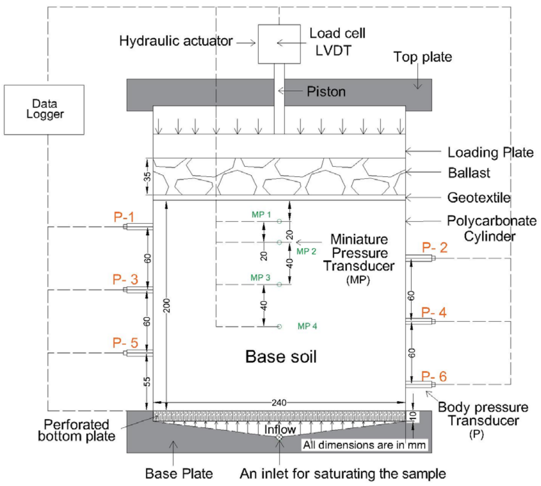


Figure 1: Dynamic filtration apparatus (Arivalagan et al. (2021)

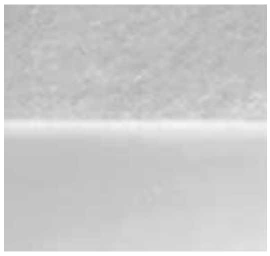
The test program consisted of two distinct phases.

Phase 1 (specimen without geotextiles): the aim is to investigate the soil behvaiour under (a) undrained conditions and (b) free drainage at the ballast and subgrade interface. Vertical stress of 40 kPa was applied under the frequency of 5 Hz.

Phase 2: The aim is to assess the performance of different geotextiles in controlling EPP and delaying the subgrade fluidisation. The cyclic loading was applied as described in Phase 1.

(a)

(b)



(c)

Figure 2: Geotextiles G1, G2 and G3

2.2 Testing program for CW mixtures

Dzaklo et al. (2021) adopted CW from Illawarra Coal Wollongong, NSW, where CW particles were angular and mainly in the sand-size particles (0.075mm to 9.5mm). The content of up to 50% CW by weight increased the proportion of sand-size particles and changed the associated PSD curves towards that of CW (Fig. 3a). The liquid limit and plasticity index reduced from 90% to 45% and from 49% to 26%, after adding 50% CW (Fig. 3b). Mixtures of CW and clay could be classified as High plasticity soil (CH), nevertheless, the 50% CW mixtured could be described as low plasticity soil (CL). Linear shrinkage reduces as the content of CW increases (Fig. 3c). Fig. 3d shows the addition of 30% CW reduced a a swell pressure by almost 40%. The specimens for monotonic and cyclic triaxial tests were compacted to their respective dry density and optimum moisture content. Table 1 summarises a total of 31 consolidated-undrained monotonic and cyclic triaxial tests.

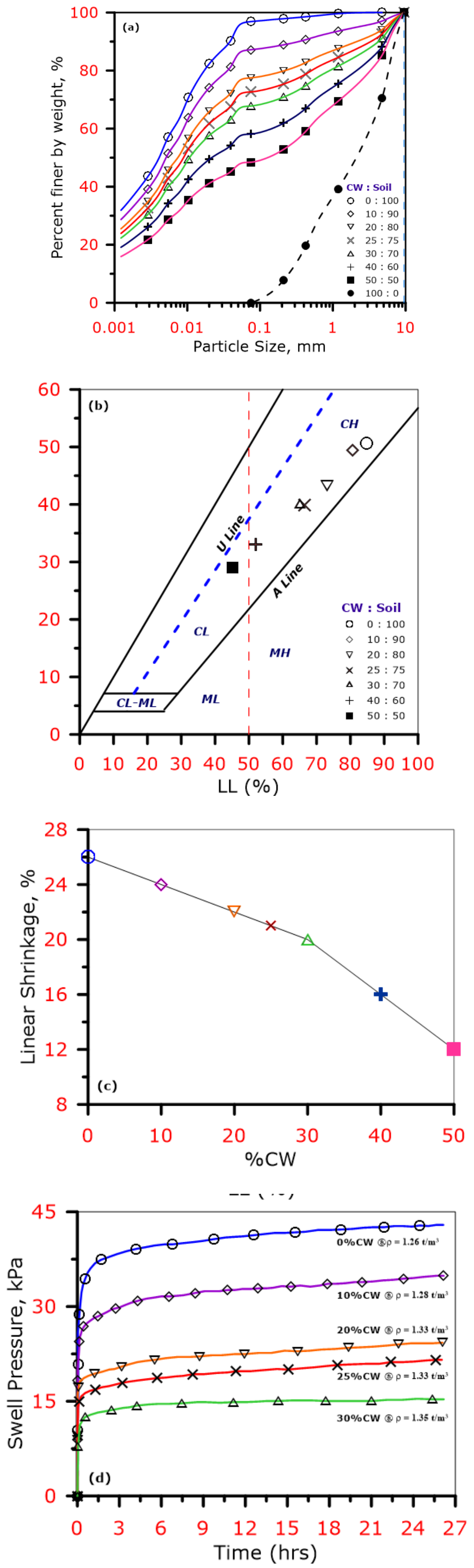


Fig. 3: Soil, and CW-Soil mixtures (a) Particle Size Distribution curves, (b) Soil classification according to plasticity chart, (c) Linear shrinkage, and (d) Swell pressures (Dzaklo et al. 2021)

A consolidated-undrained condition was applied for cyclic loading under a relatively low effective confining pressure (30kPa) and a frequency of 8 Hz to represent a train speed of 55km/hr. All the tests were designed to reach 20,000 cycles unless either an axial strain of 4% was reached or there was a rapid increase in axial strain. The cyclic stress ratio (CSR) is the ratio of applied cyclic stress to twice the effective confining pressure. A CSR from 0.4 to 0.95 represents axle loads between 16 and 38 tonnes at the subgrade levels.

Table 1: Triaxial tests (Dzaklo et al. 2021)

Monotonic Triaxial Test		
Test ID	***%CW***	***Confining Pressure, kPa***
CS1	0	30
CS2		50
CS3		80
CS4	10	30
CS5		50
CS6		80
CS7	20	30
CS8		50
CS9		80
CS10	25	30
CS11		50
CS12		80
CS13	30	30
CS14		50
CS15		80

Cyclic Triaxial Test				
Test ID	***%CW***	***q_{cyc}, kPa***	***Cyclic stress ratio, CSR***	***Maximum No. of cycles before failure, N******
CC1	0	24	0.4	20,000
CC2		36	0.6	20,000
CC3		48	0.8	3,620
CC4		57	0.95	305
CC5	10	24	0.4	20,000
CC6		36	0.6	20,000
CC7		48	0.8	5,280
CC8		57	0.95	315
CC9	20	24	0.4	20,000
CC10		36	0.6	20,000
CC11		48	0.8	20,000
CC12		57	0.95	995
CC13	30	24	0.4	20,000
CC14		36	0.6	20,000
CC15		48	0.8	20,000
CC16		57	0.95	3,333

3. TEST RESULTS AND DISCUSSION

3.1 Performance of Geotextiles under Cyclic Load

Phase 1:

As reported by Arivalagan et al., (2021), Test T1 was under undrained condition, whereas Test T2 mimics the common condition where ballast is compacted above the subgrade soil. Test T1 shows a swift increase in EPP (>22kPa) within 500 cycles without any noticeable reduction later (Fig. 4a). The EPPs at 40 and 80 mm below the surface are higher than the EPP near the top of subgrade soil. Under free drainage in Test T2, the maximum EPPs is 20 kPa after 500 cycles and reduces to 10-15 kPa. Regarding the settlement, the maximum vertical strains for T1 and T2 at the end of tests are about 2% and 9%, respectively (Figure 4b). As confinement near the surface is insignificant, the subgrade particles can easily migrate upwards, and ballast particles can infiltrate the subgrade layer. This implies that the specimen can experience fluidisation when the axial strain is more than 6%

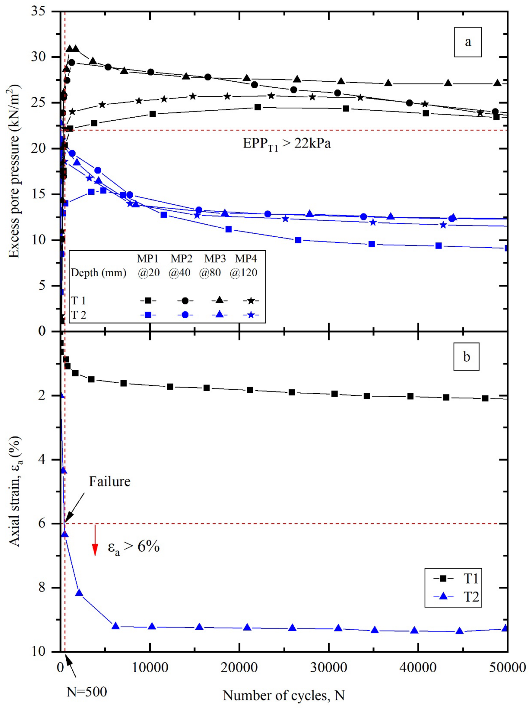


Figure 4: Tests T1 and T2 (a) Excess pore water pressure and (b) Axial strain (Arivalagan et al., 2021)

Figure 5 shows the variations of the liquidity index (LI) with depth at 100,000 cycles. When LI reaches unity, the water content is its liquid limit representing the fluidised state of soil (slurry). The LI decreases linearly from unity to 0.2. Particle migration and interlayer creation were observed using a rapid increase in axial strain in Test T2. Using the Malvern particle size analyser, migrated fines (< 75μm) accumulated near the interface of the specimen T1 (≈ 52%), which is more than at the middle region (≈ 48%), which previously had approximately 50% of fines. Increased water content can enable the formation of a slurry at the interface.

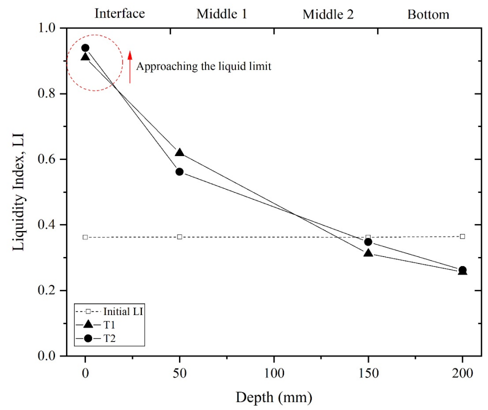


Figure 5: Liquidity Index after cyclic load along depths (Arivalagan et al., 2021)

Phase 2:

The performance of geotextiles (G1, G2, and G3) was assessed by Arivalagan et al. (2021), as shown in Fig. 6. In contrast to other geotextiles (G2 and G3), G1 could reduce the EPP at a faster rate by over 85% and 60%, at 20 and 40 mm depth, respectively. G1 can control the development of axial strain and prevent the formation of an interlayer through additional confinement at the interface. There was a constant increase in axial deformation in G2 and G3 due to the dissipation of EPP and particle movement through the pore openings. The accumulation of fines at the interface with the inclusion of G2 and G3 could not be prevented. The fines trapped in G1 was 35% less than G3, which confirms its effectiveness. Geotextiles also helped reduce the water content of the soil, unlike the undrained (T1) and free drainage (T2) tests. The presence of G1 could decrease the water content by 5%, unlike G2 and G3. The geotextile inclusion with an effective filter (G1) can inhibit excessive particle migration and provide adequate drainage by dissipating the excess pore water pressure (EPP).

3.1 Cyclic Behaviour of Compacted Black Soil-Coal Wash Matrix

As reported by Dzaklo et al. (2021), Fig. 5 presents the rate of variation of maximum dry density (MDD) and optimum moisture content (OMC) with the CW content. The noticeable change in the MDD and OMC due to 10% CW is followed by a gentle change between 20% and 30% of CW, but there is a significant variation from 40% to 50% of CW. The two variations intersect at 32% CW, corresponding to an MDD and OMC of 1.4t/m^3 and 28%, respectively. The point is considered as the point of optimum, outside this it is dominated by either CW or soil. The Breakage Index (Bg) for samples compacted at OMC increases from 0.34 to 2.49 with CW content up to 30%.

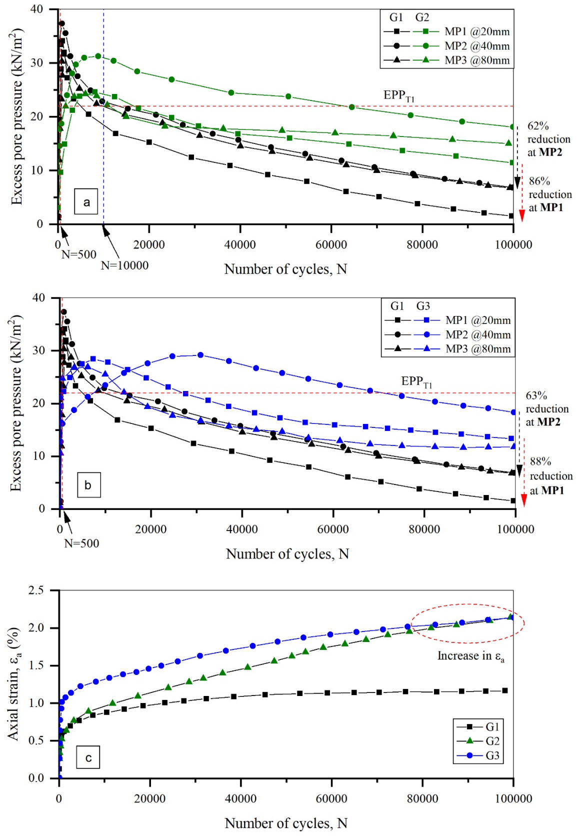


Figure 6: Excess pore water pressures and axial strains (Arivalagan et al., 2021)

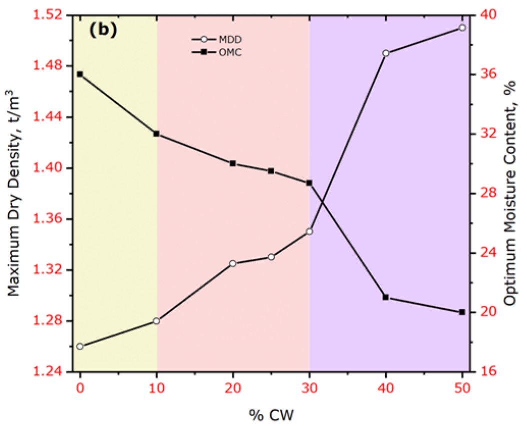


Figure 7: Effects of CW contents on maximum dry density and optimum moisture content (Dzaklo et al. 2021)

The axial strains (ε_a) of CW-soil mixtures under cyclic loading are plotted in Fig. 8. When q_{cyc} exceeds 48kPa, a swift increase in axial strain is observed. In contrast, specimens subjected to q_{cyc} below 36kPa show stable axial strain after 1250 cycles (Fig. 8a). For specimens with 10%CW, axial strain reaches 1.5% before failing (Fig. 8b). For 20% CW specimens, the axial strains remain constant after N=1250 for q_{cyc} <48kPa, but failure can be observed when q_{cyc} =57 kPa (Fig. 8c). Fig. 8d shows that the axial strain curves for the stable specimens gradually developed into steady values, unlike the specimens with less CW (< 30% CW) where the turning point is abrupt. Overall, the addition of CW increased the cyclic resistance of expansive soil.

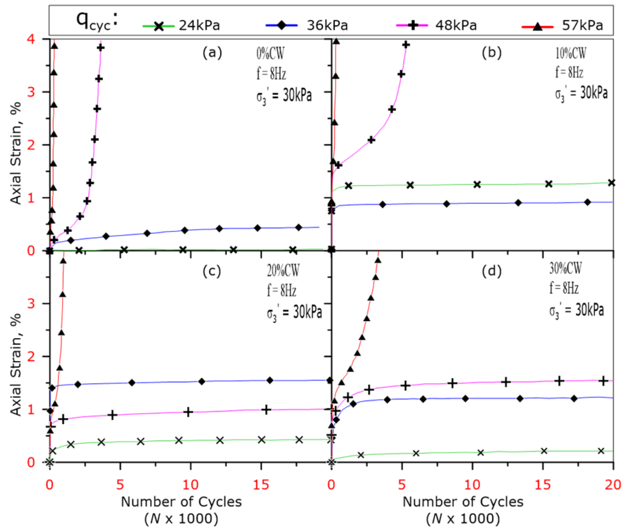


Fig. 8: Axial strain Variation of CW-Soil mixtures (Dzaklo et al. 2021)

4. CONCLUSION

The dynamic filtration tests were carried out to investigate the performance of geotextiles at the subgrade-subballast interface to prevent subgrade fluidisation. There are three conditions examined, (1) undrained, (2) partially drained, and (3) free drainage conditions subjected to heavy haul train loading. The role of geosynthetics as a drainage medium and filter to prevent particle migration and associated subgrade fluidization was discussed and explained. The inclusion of geosynthetics could minimise subgrade fluidisation as local excess pore pressures, excess pore pressure gradients, and upward fine and moisture migration reduced.

The geotextile (G1) could dissipate the EPP, reduce overall deformation, and prevent fine particle movement under cyclic loading. It kept the EPP at less than 10 kPa, which is approximately 55% of that in the Undrained Test, while the axial strain was within 1% for the same loading conditions. The EPPs under G2 and G3 were larger than that of T1 after 10,000 cycles, and the dissipation rate was not significant throughout the test. GI can still prevent particle migration and dissipate the EPP under cyclic loading. This proves that the G1 effectively reduces the increased EPP with time and inhibits particle migration through the interface.

Laboratory tests confirmed that when coal wash (CW) and expansive clay mixtures can provide improved geotechnical properties such as plasticity, shrinkage, and swell pressure, as well as the monotonic and cyclic strength parameters. The mixture with 30% CW-soil compacted at $1.35t/m_3$ was the optimal mix because it reduced the swell pressure and improved the strength of the mix. The shear strength of the mixture was higher than that of the original compacted clay because the change of PSD, and its overall plasticity and shrinkage. Expansive clays fail at a q_{cyc} between

48kPa and 57kPa on their own; however, adding 30% CW enhances the natural soil to withstand a much higher number of cycles

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6. REFERENCES

AECOM. 2017. Corridor Options Report. Australia: AECOM Australia Pty Ltd.

Arivalagan, J., Rujikiatkamjorn, C., Indraratna, B. & Warwick, A. 2021, 'The role of geosynthetics in reducing the fluidisation potential of soft subgrade under cyclic loading', Geotextiles and Geomembranes, vol. 49, no. 5, pp. 1324-38.

Alazigha, D. P., Indraratna, B., Vinod, J. S. & Heitor, A. 2018. Mechanisms of stabilization of expansive soil with lignosulfonate admixture. Transportation Geotechnics, 14, 81-92.

Alobaidi, I. & Hoare, D. 1994, 'Factors affecting the pumping of fines at the subgrade subbase interface of highway pavements: a laboratory study', Geosynthetics International, vol. 1, no. 2, pp. 221-59.

Alobaidi, I. & Hoare, D.J. 1996, 'The development of pore water pressure at the subgrade-subbase interface of a highway pavement and its effect on pumping of fines', Geotextiles and geomembranes, vol. 14, no. 2, pp. 111-35.

Aw, E.S. 2007, 'Low cost monitoring system to diagnose problematic rail bed: case study of mud pumping site', Massachusetts Institute of Technology.

Bhatia, S.K. & Huang, Q. 1995, 'Geotextile filters for internally stable/unstable soils', Geosynthetics International, vol. 2, no. 3, pp. 537-65

Dzaklo, C., Rujikiatkamjorn, C., Indraratna, B. & Kelly, R. (2021). Cyclic behaviour of compacted black soil-coal wash matrix. Engineering Geology. 294. 106385. 10.1016/j.enggeo.2021.106385.

Faure, Y.-H., Baudoin, A., Pierson, P. & Ple, O. 2006, 'A contribution for predicting geotextile clogging during filtration of suspended solids', Geotextiles and Geomembranes, vol. 24, no. 1, pp. 11-20.

Ghataora, G., Burns, B., Burrow, M. & Evdorides, H. 2006, 'Development of an index test for assessing anti-pumping materials in railway track foundations', Proceedings of the First International Conference on Railway Foundations, Railfound06, University of Birmingham, UK, pp. 355-66.

Ghosh, C. & Yasuhara, K. 2004, 'Clogging and flow characteristics of a geosynthetic drain confined in soils undergoing consolidation', Geosynthetics International, vol. 11, no. 1, pp. 19-34.

Indraratna, B., Singh, M., Nguyen, T.T., Leroueil, S., Abeywickrama, A., Kelly, R. & Neville, T. 2020a, 'Laboratory study on subgrade fluidization under undrained cyclic triaxial loading', Canadian Geotechnical Journal, vol. 57, no. 11, pp. 1767-79.

Indraratna, B., Qi, Y., Tawk, M., Heitor, A., Rujikiatkamjorn, C. & Navaratnarajah, S. K. 2020b. Advances in Ground Improvement Using Waste Materials for Transportation Infrastructure. 0, 1-44.

Israr, J., Indraratna, B. & Rujikiatkamjorn, C. 2016, 'Laboratory investigation of the seepage induced response of granular soils under static and cyclic loading', Geotechnical Testing Journal, vol. 39, no. 5, pp. 795-812.

Kermani, B., Stoffels, S. & Xiao, M. 2020, 'Evaluation of effectiveness of geotextile in reducing subgrade migration in rigid pavement', Geosynthetics International, vol. 27, no. 1, pp. 97-109.

Nguyen, T.T., Indraratna, B., Kelly, R., Phan, N.M. & Haryono, F. 2019, 'Mud pumping under railtracks: mechanisms, assessments and solutions', Aust Geomech J, vol. 54, no. 4, pp. 59-80.

Palmeira, E., Fannin, R. & Vaid, Y. 1997, 'A study on the behaviour of soil geotextile systems in filtration tests', Canadian Geotechnical Journal, vol. 33, no. 6, pp. 899-912.

Palmeira, E.M. 2009, 'Soil–geosynthetic interaction: Modelling and analysis', Geotextiles and geomembranes, vol. 27, no. 5, pp. 368-90.

Rujikiatkamjorn, C., Indraratna, B. & Chiaro, G. 2013. Compaction of coal wash to optimise its utilisation as water-front reclamation fill. Geomechanics and Geoengineering, 8, 36-45.

Sánchez, M., Wang, D., Briaud, J. L. & Douglas, C. 2014. Typical geomechanical problems associated with railroads on shrink-swell soils. Transportation Geotechnics, 1, 257-274.

Selig, E.T. & Waters, J.M. 1994, Track geotechnology and substructure management, Thomas Telford.

Tang, A.-M., Cui, Y.-J., Trinh, V.-N., Szerman, Y. & Marchadier, G. 2009. Analysis of the railway heave induced by soil swelling at a site in southern France. Engineering geology, 106, 68-77.

Wang, G. & Wei, X. 2014. Modeling swelling–shrinkage behavior of compacted expansive soils during wetting–drying cycles. Canadian Geotechnical Journal, 52, 783-794.

Xiao, M. & Reddi, L.N. 2000, 'Comparison of fine particle clogging in soil and geotextile filters', Advances in Transportation and Geoenvironmental Systems Using Geosynthetics, pp. 176-85.