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INFLUENCE OF FINE MATERIALS ON STRESS-STRAIN AND DEGRADATION BEHAVIOUR OF RAILWAY BALLAST UNDER STATIC LOADING CONDITIONS

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Abstract: Ballast is a selected, crushed, granular material used for supporting train load through sleepers and rail in a rail track foundation system. It is used highly because of the availability of low-cost raw materials and has many technical advantages such as free drainage and high lateral resistance among others. But fast and heavy haul train loads and with many external environmental factors foul the ballast material and change its load deformation and degradation behavior. Ballast fouling from the intrusion of foreign materials such as water-driven and wind-flown fine soil particles (predominately silt or very fine sand and clay) or mud pumping from underneath the subgrade layer is inevitable. These processes continuously contaminate the ballast particles and change their physical and mechanical property which leads to a change in shear strength and stability of the ballast layer. This study mainly focuses on the influence of different types of fine materials intrusion on shear and degradation behavior of railway ballast used in Sri Lankan rail tracks. Clay and fine sand were used as fouling materials in this study. A series of large scale direct shear testing was performed considering full-size ballast particles with and without ballast fouling for different loads. The findings show that when the sand fouling percentage increases, the shear strength tends to increase due to the increase of density of the material. When the ballast contaminated with clay material, the shear strength of the fouled ballast tends to decrease. Ballast breakage analysis shows that the breakage increasing with higher vertical stress, but decreasing with ballast fouling.

Keywords: Ballast; Sleepers; Fouling; Degradation; Fine Materials

1. Introduction

Ballasted rail tracks are extensively used in many countries due to the ease of construction, availability of ballast material, provision of lateral resistant and low initial construction costs (Chan and Johan, 2016; Kurukulasuriya *et.al.*, 2015; Navaratnarajah and Indraratna, 2017). The efficiency of the ballasted track depends on the combined performance of various track components such as rails, fastening system, sleepers, ballast, capping layer and subgrade. Open-graded crushed aggregates are widely used as ballast material due to the optimum resiliency, effectively transfer the loads exerted by moving trains to the subgrade at a reduced level, good drainage and lesser plastic deformations in vertical, lateral and longitudinal directions (Indraratna, 2016; Selig and Waters, 1994).

A general problem with the ballast is filling the voids with finer particles such as broken ballast particles, sand, clay, coal, mineral fillers and mud (Huang *et.al.*, 2009). This ballast contamination can be caused by self-degradation of ballast, external fines intrusion and subgrade pumping (Koohmishi, 2019). Ballast particles undergo fragmentation due to the heavy cyclic loading. Breakage of angular corners and crushing of smaller particles are higher in stiff subgrade conditions due to the large impact loads. These fragmentations affect the strength and drainage of the track substructure (Indraratna *et.al.*, 2014). Ballast layer solidification which assembles the finer windy sand into the voids of the ballast layer thus increases the track modulus and the vibration-induced on the ground is a major issue in desert areas due to wind-blown sand accumulation (Esmaeili *et.al.*, 2013).

This ballast fouling leads to poor drainage, reduction in shear strength, load-bearing capacity and stiffness, and increased track settlement (Indraratna, 2016). The Void Contaminant Index (VCI) is simply the ratio between the volume of finer material and the volume of voids within the ballast that provides a gesture of how much volume of the ballast is inhabited with the fines.

Fouled ballast should be replaced with fresh ballast or cleaned to maintain the performance and safety of the track system. This leads to a large amount of waste ballast in stockpiles and the necessity for quarrying fresh ballast. Therefore, fouled ballast can be cleaned, sieved and reused in the track structure. Also, under ballast mats stabilizing hard base condition such as rail track on bridges and under sleeper pads at the base of concrete sleepers are adaptable to minimize the self-degradation at stiffer ballast interfaces (Navaratnarajah *et.al.*, 2018).

In this study, the effect of the intrusion of fine materials on stress-strain and degradation behavior of ballast under static loads was studied by conducting a series of large scale direct shear tests. River sand and clay were used as fouling materials. A series of direct shear tests were conducted on fresh ballast, sand and clay fouled ballast with various normal stresses such as 30, 60 and 90 kPa. The ballast breakage index for each sample after direct shear testing was calculated and degradation behavior was analyzed.

2. Materials and Experimental Procedure

2.1 Materials

Ballast materials were collected from Gampola railway stockpile and clay material was collected from Digana area, Sri Lanka. The properties of the ballast materials are available elsewhere (Dissanayake *et.al.*, 2016). Initially, sieve analysis was conducted using the BS 410 standard sieve series to separate ballast materials with various sizes. After that, the ballast was cleaned with water and air-dried to remove the dust and adhered soil particles. River sand was dried and sieved to get the material properties. Clay was dried and crushed to remove unwanted larger particles from it such as roots, small stones, etc.

2.2 Sample preparation and Test Apparatus

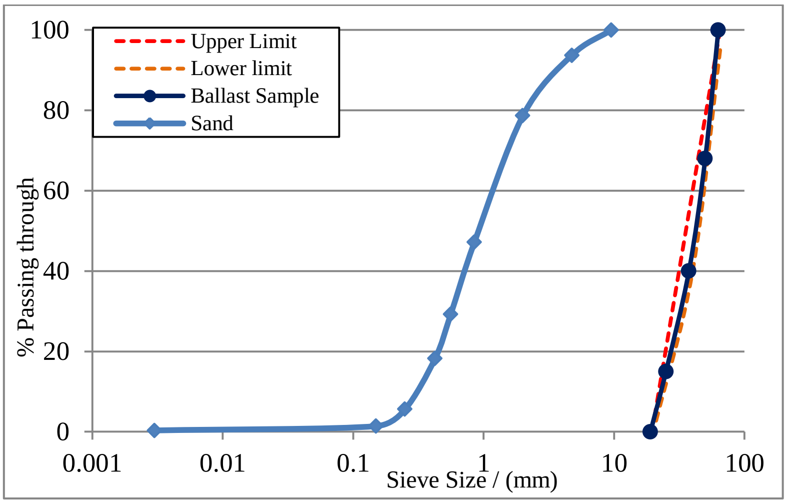
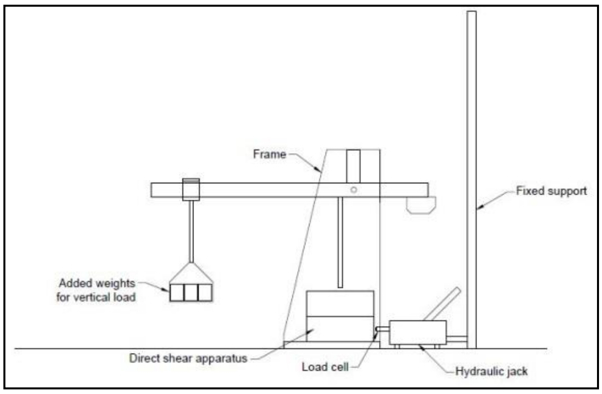


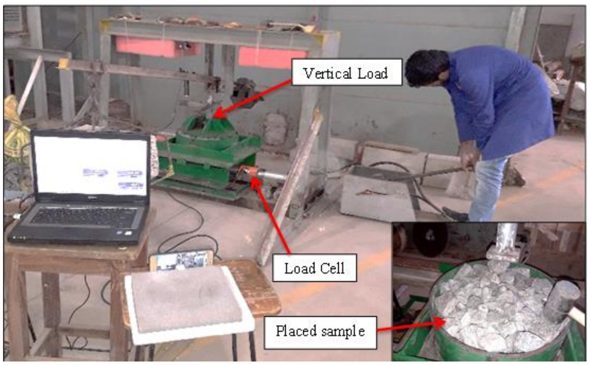
Figure 1: Particle size distribution (PSD) of ballast and sand samples

The ballast material was prepared according to the Indian standard (adapted in Sri Lanka) for the direct shear test. The particle size distributions (PSD) of fresh ballast and sand are shown in Figure 1.

Large scale direct shear test apparatus shown in Figure 2 is capable of conducting prototype experiments without downsizing the ballast material. This apparatus has dimensions of 400 mm diameter and 300 mm height. It has equal halves of the fixed top part and movable bottom part. The top-loading plate is free to move vertically and normal load is applicable through a static weight lever arm method. The schematic diagram of the test apparatus is illustrated in Figure 2a and a photograph of the test apparatus is shown in Figure 2b.



(a)



(b)

Figure 2: (a) Schematic diagram of large scale direct shear test apparatus; (b) Test setup

ASTM D3080-03 limits the maximum particle size to 10 % of the diameter of the test apparatus for direct shear testing. But, Fakhimi and Hosseinpour (2008) recommended this limit to 20 % for cohesionless materials. Therefore, tests can be carried out for ballast materials under Indian Standard where the maximum particle size is 65 mm. The weights of ballast samples by sizes according to ballast PSD were calculated and mixed properly using a shovel before placing it into the test apparatus. The ballast was placed in three layers and each layer was compacted using a rubber hammer in order to achieve its field unit weight of 16 kN/m^3, this field density was maintained throughout the all tests. The rubber hammer has been used to minimize ballast breakages during sample compaction.

Sample preparation for sand fouled ballast was similar to fresh ballast at the initial stage. After placing the fresh ballast in three layers, the calculated amount of sand with respect to 10 % and 15 % fouling by mass was poured on top of the ballast sample. After that, a small vibration was applied using a shutter vibrator to fill the sand particles into the voids of ballast material.

When testing for clay fouled ballast, after mixing the desired amount of various sized ballast, 5% clay (LL=37, PI=14) by mass was wet-mixed with the ballast to create a clay coating and left to dry. Then, the clay mixed ballast was placed into the test apparatus in three layers and compacted to appropriate field density.

2.3 Test Procedure

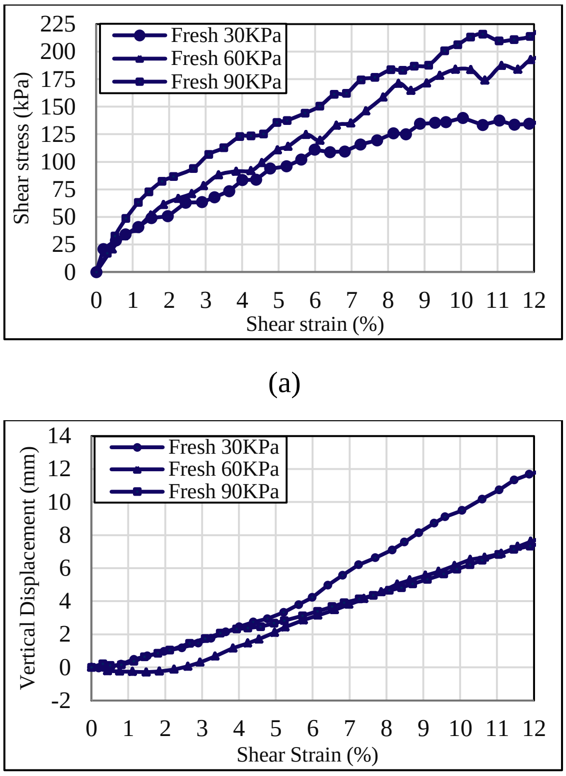
Table 1 shows the tests conducted in this study. The direct shear tests were conducted with three vertical load combinations of 30, 60 and 90 kPa. The lateral load was applied at a constant loading rate of 4 mm/min using a hydraulic loading system. All tests were conducted up to 15 % shear strain. Vertical and horizontal displacement gauges and load cell were used to measure the displacements and load, respectively. The horizontal displacement, vertical displacement and horizontal load readings were obtained by a data logger connected to a computer.

Table 1: Direct shear test with various conditions

Normal Load / (kPa)	Fresh Ballast	Fouled Ballast		
		Sand Fouling		Clay Fouling
		10%	15%	5%
30	√	√	√	√
60	√	√	√	√
90	√	√	√	√

3. Results and Discussion

3.1 Effects of Normal Stress on Fresh Ballast Behavior



(a)

(b)

Figure 4: Variation of (a) Shear stress and (b) Vertical displacement with the shear strain of fresh ballast with various normal loads

Figure 4 exhibits the stress-strain behavior and volumetric behavior of fresh ballast under various normal loads. Shear stress showed a gradual increase with shear strain for a certain normal load and reached nearly a steady stage after attaining peak shear stress. As expected, shear stress increased with higher normal loads as illustrated in Figure 4(a). The higher interlocking between the angular particles and the rise in the frictional resistance provided by the rough surface of the ballast have significantly contributed for the increased shear strength. The increment in applied normal stress increased the compression. Therefore, a reduction in dilation occurred with the increase in normal stress as shown in Figure 4(b).

3.2 Effects of the Intrusion of Sand Particles on Ballast Shear Behavior

Figure 5 exhibits the shear stress variation of sand fouled ballast with shear strain for various normal stresses (30, 60 and 90 kPa) and two different fouling percentages (10% and 15% sand by weight).

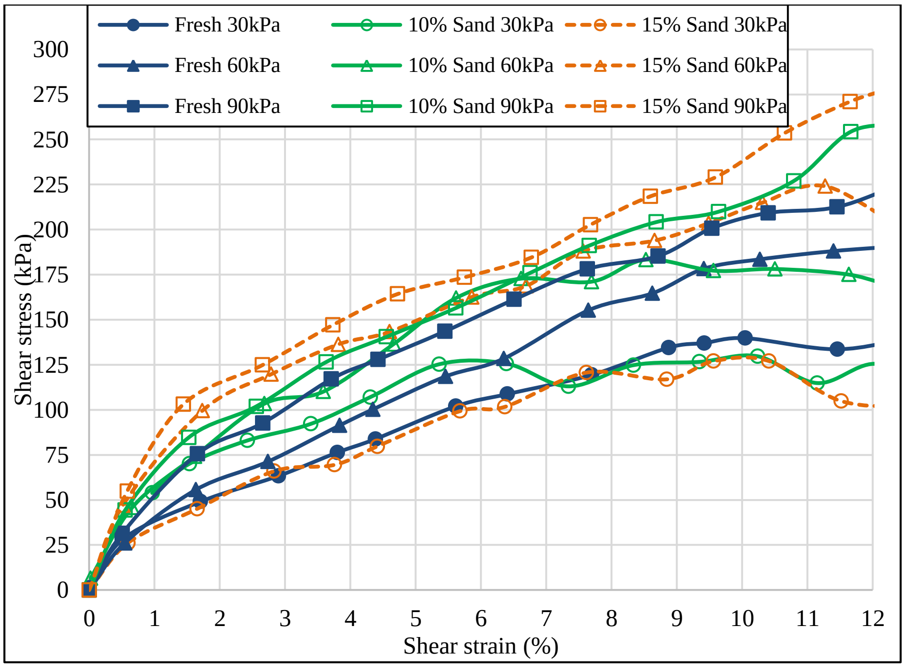


Figure 5: Variation of shear stress with the shear strain of sand fouled ballast

There is significant volume of sand particles filled in the voids of ballast materials. However, at lower normal load, there is a slight reduction of shear strength when ballast is fouled with sand materials and the reduction is very marginal. The slight reduction could be due to the lubricant action of sand particles within the ballast layer. However, when normal stress is increased, the shear strength increased with percentage of sand fouling due to the overall increase in the density of the sample which prevents the free movement of ballast compared to fresh ballast and also the overall increase of contact is at the shear plane leads to more frictional resistance. Thus, 15 % of sand inclusion gives higher shear stress compared to 10 % sand inclusion as shown in Figure 5.

3.3 Effects of the Intrusion of Clay Particles on Ballast Behavior

The shear behavior of clay fouled ballast with various normal loads was elaborated in Figure 6.

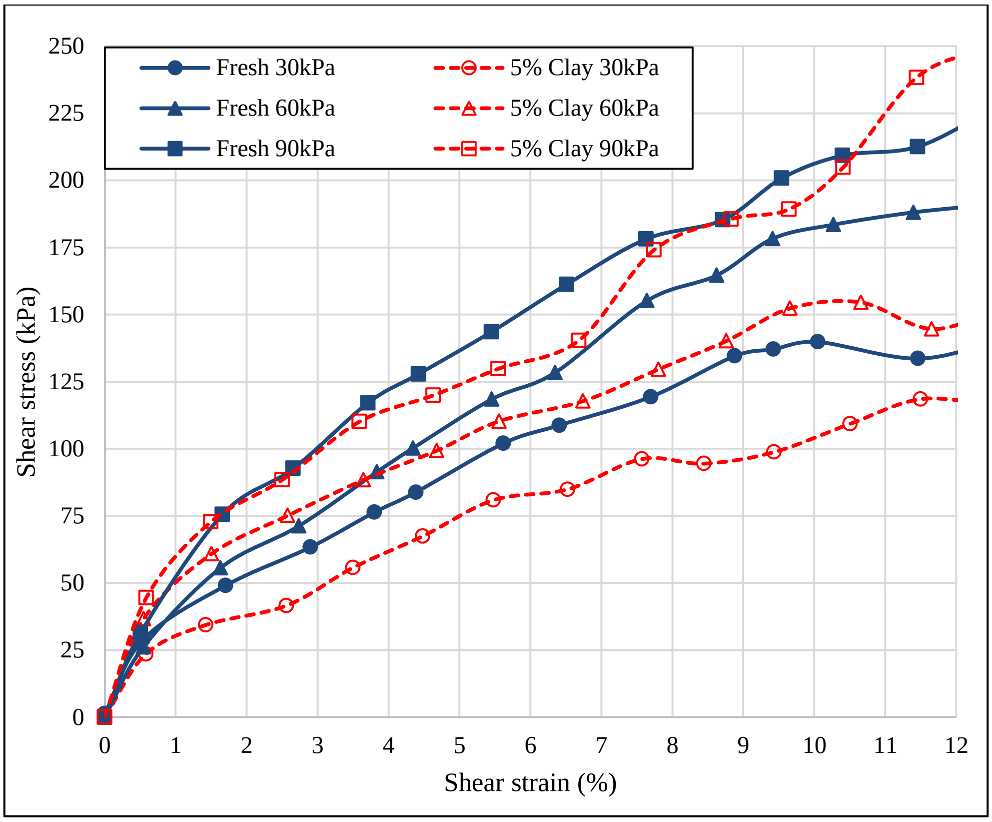


Figure 6: Variation of shear stress with the shear strain of clay fouled ballast

The shear stress of clay fouled ballast was lesser than the fresh ballast at a certain applied normal load, because of the reduction in the surface friction as clay served as a lubricant. However, for the higher normal load (90 kPa) the particles make batter interparticle contacts and the lubrication behavior by clay is not playing any significant role in reducing the shear resistance as per the results shown in Figure 6.

3.4 Effects of Fines Intrusion on Ballast Breakage Behavior

The Ballast Breakage Index (BBI) was calculated using the method proposed by Indraratna *et.al.* (2005). The particle size distributions of each type of sample before and after the testing were obtained by conducting sieve analysis before and after each test. Table 2 shows the BBI of fresh and fouled ballast under various normal loads. The BBI for fresh ballast increased with the increase in the normal load. This was due to the increase of load on ballast and reduction in dilation that leads to ballast breakage. BBI reduced with the inclusion of sand and clay, because of densification and lubricant behavior, respectively.

Table 2: Ballast Breakage Index of fresh and fouled ballast with different normal loads

Normal Load	Ballast Breakage Index (BBI)			
	Fresh	10% Sand Fouled	15% Sand Fouled	5% Clay Fouled
30 kPa	0.099	0.085	0.017	0.061
60 kPa	0.146	0.118	0.109	0.088
90 kPa	0.194	0.142	0.124	0.126

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. Conclusions and Recommendations

The results from the large scale direct shear tests clearly indicated that the shear stress, compressibility, and ballast breakage depend on the applied normal stress, fouling material as well as fouling percentage under static loading conditions. The increase in normal load leads to an increase in shear stress and a decrease in the dilation of fresh ballast. The intrusion of sand particles densified the sample, hence the shear stress was higher than the fresh ballast. Clay particles acted as a lubricant and reduced the surface friction, so a reduction in shear stress was observed. Further, ballast breakage is higher at high normal loads and reduces with the fouling materials intrusion.

The following recommendations are suggested for future studies: (i) Even though the intrusion of sand increases the strength parameters and reduces the ballast breakage, the fouling index or void contaminant index was not analyzed in this study. Thus, the effect of the fouling in the drainage properties of the ballast layer could be examined with various fouling percentages. (ii) In actual situations, the ballast layer experiences dynamic, cyclic and impact loadings. But, this research was carried out under static loads only. Therefore, experiments can be conducted under dynamic, cyclic and impact loadings to analyze the effects of fines intrusion under real field conditions. (iii) Ballast with various gradations could be tested to find out the effect of gradation on the shear strength and compressibility behavior of ballast. (iv) The effect of artificial inclusions can be studied which can lead to track longevity and reduce the track maintenance frequency.

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References

Chan, C.-M. and Johan, S. F. S. M. (2016) 'Performance enhancement of railtrack ballast with rubber inclusions: a laboratory simulation', *Japanese Geotechnical Society Special Publication*, 2(47), pp. 1640-1643.

Dissanayake, D., Kurukulasuriya, L. and Dissanayake, P. (2016) 'Evaluation of shear strength parameters of rail track ballast in Sri Lanka', *Journal of the National Science Foundation of Sri Lanka*, 44(1), pp. 61-67.

Esmaeili, M., Zakeri, J. A. and Mosayebi, S. A. (2013) 'Effect of sand- fouled ballast on train-induced vibration', *International*

Journal of Pavement Engineering, 15(7), pp. 635-644.

Fakhimi, A. and Hosseinpour, H. (2008) 'The role of oversize particles on the shear strength and deformational behavior of rock pile material', *The 42nd US Rock Mechanics Symposium (USRMS)*. San Francisco: American Rock Mechanics Association, pp. 1-7.

Huang, H., Tutumluer, E. and Dombrow, W. (2009) 'Laboratory Characterization of Fouled Railroad Ballast Behavior', *Transportation Research Record: Journal of the Transportation Research Board*, 2117(1), pp. 93-101.

Indraratna, B. (2016) '1st Proctor lecture of ISSMGE: Railroad performance with special reference to ballast and substructure characteristics', *Transportation Geotechnics*, 7, pp. 74-114.

Indraratna, B., Lackenby, J. and Christie, D. (2005) 'Effect of confining pressure on the degradation of ballast under cyclic loading', *Geotechnique, Institution of Civil Engineers*, 55(4), pp. 325-328.

Indraratna, B., Ngo, N., Rujikiatkamjorn, C. and Vinod, J. S. (2014) 'Behavior of fresh and fouled railway ballast subjected to direct shear testing: discrete element simulation', *International Journal of Geomechanics*, 14, pp. 34-44.

Koohmishi, M. (2019) 'Establishment of analytical-numerical method to determine the water level in the railway ballast layer contaminated with sandy material', *European Journal of Environmental and Civil Engineering*, pp. 1-17.

Kurukulasuriya, L., Dissanayake, D. and Dissanayake, P. (2015) 'Effect of fouling on shear strength characteristics of rail track ballast', *Instituion of Engineers, Sri Lanka*, pp. 53-60.

Navaratnarajah, S. K. and Indraratna, B. (2017) 'Use of rubber mats to improve the deformation and degradation behavior of rail ballast under cyclic loading', *Journal of geotechnical and geoenvironmental engineering*, 143(6), pp. 04017015 (1-15).

Navaratnarajah, S. K., Indraratna, B. and Ngo, N. T. (2018) 'Influence of under sleeper pads on ballast behavior under cyclic loading: experimental and numerical studies', *Journal of Geotechnical and Geoenvironmental Engineering*, 144(9), pp. 1-16.

Selig, E. T. and Waters, J. M. (1994) '*Track geotechnology and substructure management*, pp. 26-27.