Shear behavior and Permeability of rail track ballast fouled by the infiltration of finer particles

S. K. Navaratnarajah
Department of Civil Engineering
University of Peradeniya
Kandy, Sri Lanka
navask@eng.pdn.ac.lk

H. G. S. Mayuranga
Department of Civil Engineering
University of Peradeniya
Kandy, Sri Lanka
sushanm@eng.pdn.ac.lk

S. Venuja
Department of Civil Engineering
University of Peradeniya
Kandy, Sri Lanka
venujas@eng.pdn.ac.lk

***Abstract*— Ballasted track is the traditional and widely used railway track system in many countries due to its numerous benefits. The ballast layer consists of uniformly distributed coarse granular material that acts as the main load-bearing component of the track while facilitating better drainage. The ballast fouling is one of the major issues in ballasted tracks where the voids of the ballast layer fill with fine particles generated from ballast degradation under repetitive train load and from various other sources. Ballast fouling affects the shear strength and drainage properties of the ballast layer which finally leads to track instability. A better understanding of the effect of fouling material on shear, degradation and permeability behaviour of railway ballast is imperative to maintain track performance. Also, the full-scale simulation of large-size granular materials at the laboratory through large-scale testing facilities is important to capture the real behaviour of railway ballast. Therefore, this paper explores the results of large-scale direct shear and permeability tests carried out at the laboratory to analyze the shear, degradation and permeability behavior of railway ballast fouled with finer particles.**

Keywords—ballast fouling, large-scale testing, shear, permeability

I. Introduction

Rail transport is one of the most popular modes of transport as it carries a large number of passengers and bulk freights at a single time with comparatively low cost and high efficiency [1]. Ballasted rail tracks are a highly used track type all over the world due to the low initial construction cost and ease of construction [2]. The ballast layer is the primary load-bearing layer and it transfers the loads from moving trains to the underlying layer at a reduced level [3-5]. The uniformly graded ballast layer with large void spaces ensures the proper drainage of the railway track [6]. However, during the track operation, ballast is fouled and degraded due to the repetitive cyclic loads exerted by train movements which affect the performance of the ballast layer [7-9].

Ballast fouling is also known as ballast contamination, where finer particles such as sand, clay, coal, and broken ballast fill the voids in the ballast layer [10, 11]. The major sources of ballast fouling include the fines generated from particle breakage, infiltration of fines from subgrade, subballast, and ballast surface as well as from sleeper wear [12]. Ballast fouling breaks the contact between ballast particles, reduces the resiliency, degrades the shear strength capacity and deters the drainage properties of ballast [13-15]. Thus, it affects the longevity and overall performance of rail tracks. Therefore, understanding the shear strength and permeability characteristics of fouled ballast at different stages of fouling is imperative.

Strength, deformation, and drainage properties of fine-grained materials can be obtained by conducting standard direct shear, triaxial, and permeability tests. But these testing facilities are not capable to carry out the tests on granular materials such as railway ballast where the particle size varies from 19 to 63 mm. When parallel gradation techniques are used in this case, it may lead to imprecise deformation, degradation, drainage behavior and failure modes. This is because of the inevitable size-dependent dilation and different mechanisms of particle crushing that occur in real-sized particles. Therefore, the load bearing capacity of ballast and its deformation, degradation, and drainage characteristics can only be studied using large-scale testing equipment.

The large-scale direct shear, triaxial, and permeability test facilities for testing railway ballast have been designed and built in-house at the Department of Civil Engineering of the University of Peradeniya. In this study, a series of large-scale direct shear and permeability tests were conducted to investigate the effect of fouling materials on shear, degradation and permeability

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behavior of railway ballast. No previous studies have been conducted on the shear and permeability behaviour of fouled ballast applicable to the Sri Lankan conditions. Therefore, the purpose of this research is to determine the shear and permeability behavior of fouled ballast with varying amounts of fouling encountered on Sri Lankan rail tracks. The findings of this study will help Sri Lankan railway authorities to make decisions on the most suitable maintenance period and that used to improve the performance of railway lines.

II. Large Scale Direct Shear Test

A. *Test apparatus*

According to the standards, the shear plane can be either circular or square shape under direct shear testing. For undisturbed soil samples collected using a cylindrical tube sampler, a circular shape shear box is preferable. For disturbed samples, the shape of the shear area can be either circle or a square. An appropriate area correction factor is applied when calculating the shear stress. The large-scale direct shear test apparatus designated at the Geotechnical laboratory to test disturbed granular ballast has a circular shear plane which consists of two equal cylindrical parts as a top and bottom cylinder. The apparatus can accommodate a test specimen of 400 mm diameter and 300 mm height as shown in Fig. 1. Lateral load can be applied to the bottom cylinder using a hydraulic jack that is handled manually. The normal load can be applied using a lever arm method on the top loading plate. The shear resistance is obtained using the load cell attached to the top cylinder. Linear transducers connected to the bottom cylinder and top loading plate are used to obtain the shear and vertical displacements during the test, respectively. Datalogger is used to obtain the results digitally where dial gauges and load cell are connected.

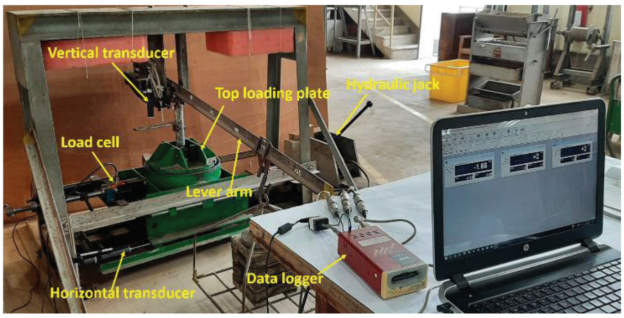

Fig. 1. Components of large-scale direct shear test apparatus

B. *Test procedure*

The materials used in this study are railway ballast and fouling material (sand and clay). Large-scale direct shear tests were conducted on fresh ballast and ballast fouled with sand and clay. Ballast was collected from the Gampola stockpile, clay material was collected from Digana area and available river sand in the Geotechnical laboratory was used. The ballast was sieved and washed thoroughly to remove adherences. Following the usual practice, the Indian Standard Gradation of ballast was adopted to prepare the test samples [16]. Fig. 2 depicts the particle size distribution (PSD) of the test sample and the limits of Indian standard gradation. The specific gravity and the void ratio of fresh ballast when compacted to the field density were 2.68 and 0.63, respectively.

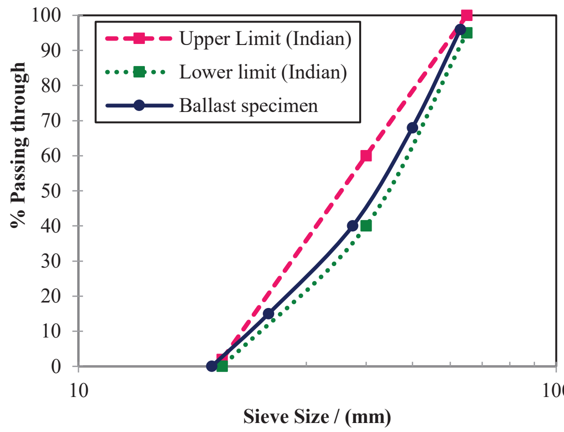

Fig. 2. Test ballast and limits of Indian standard gradation

Ballast was filled in three layers into the apparatus and each layer was compacted to obtain field unit weight. The amount of finer particles was determined by mass with respect to the fouling percentage. 5% of clay fouling and 10 and 15% of sand fouling were selected for this experimental study. Sand (C_u = 3.67 and C_c = 0.92) was poured on top of the ballast and a shutter vibrator was used to pack the sand into the voids in the ballast specimen. Clay (PL = 23 and LL = 37) was coated to the ballast particles using the wet mixing method and after drying the clay-coated ballast was filled into the apparatus.

All samples were tested under 30, 60, and 90 kPa normal stresses and a constant shearing rate of 4 mm/min. Tests were conducted up to 15% shear strain which is 60 mm of shear displacement. Shear displacement, vertical displacement, and shear resistance load were

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obtained using the data logger connected to the computer. Shear stress was calculated using the area correction factor suggested by Olson and Lai [17] for a circular shear plane. At the end of each test, the sample was collected carefully and a sieve analysis was carried out to quantify the breakage using Ballast Breakage Index (BBI) suggested by [18]. The BBI calculation method is illustrated in Fig. 3.

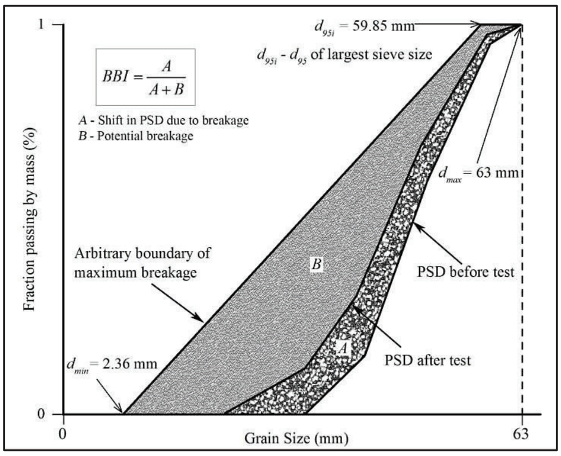

Fig. 3. Ballast Breakage Index (BBI) calculation method

III. Large Scale Permeability Test

A. *Test apparatus*

The large-scale permeability apparatus which was designed and built at the Geotechnical laboratory was used to conduct a series of large-scale constant head permeability tests on clay fouled railway ballast. A drawing and a photograph of the test apparatus are shown in Fig. 4(a) and (b), respectively. The apparatus consists of a cylindrical steel chamber, constant head tank, piezometer, water storage tank and measuring cylinder. The diameter of the steel chamber is 400 mm and that can accommodate a full-scale ballast specimen up to a height of 800 mm. The dimensions of the steel chamber were selected to maintain the sample size ratio (the ratio between test specimen diameter and mean diameter of maximum particle size) greater than 6 to avoid the sample size effect. The height of the ballast specimen should be greater than 5 times the maximum particle size. To fulfil that, a 400 mm high ballast specimen was used during the experiment. A filter layer was used at the base of the ballast specimen, and underneath that, a larger size (> 63 mm) ballast aggregate layer having 200 mm thickness was placed to avoid washing out of fine particles during the experiment.

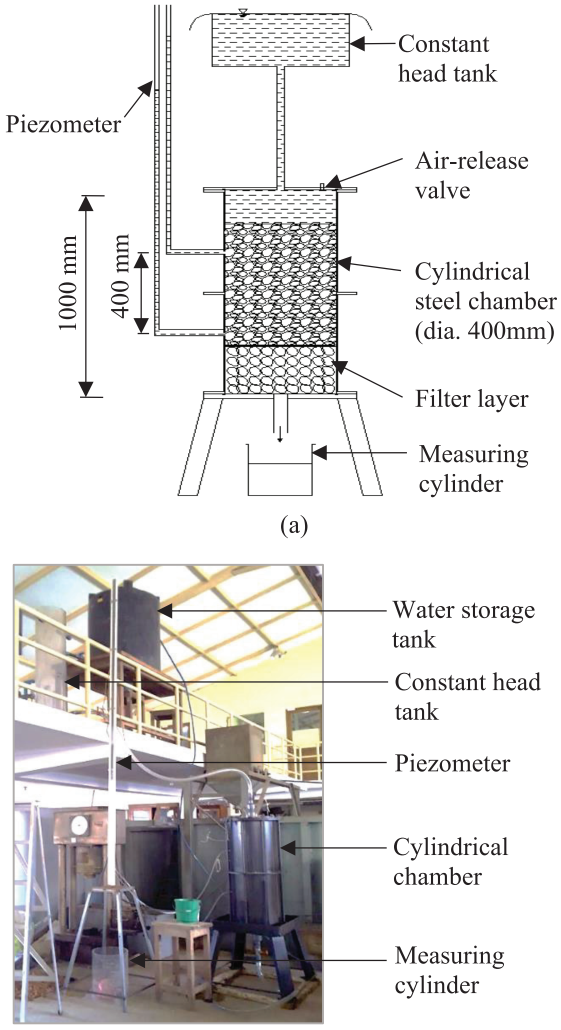

Fig. 4. Large-scale permeability apparatus (a) Drawing and (b) Photograph

B. *Test procedure*

The materials used in this study were railway ballast and fouling material. The fresh ballast material identified as biotite gneiss was collected from the Gampola stockpile. The fresh ballast samples were prepared following the same procedure explained under section II-B above. Sandy clay with 48% fines was used as the fouling material which was collected from Matale area. Liquid limit (LL), average plastic limit (PL), and plasticity index (PI) of sandy clay material were obtained as 47%, 24%, and 23%, respectively. The optimum moisture content (OMC) and the maximum dry density (MDD) of sandy clay material were 16.5 and 1674 kg/m^3, respectively. Further, the specific gravity and the void ratio of fouling material were found as 2.64 and 0.58, respectively.

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The Void Contamination Index (VCI) [7] was adopted in this study to quantify the level of ballast fouling. The VCI is given by,

$$VCI = \frac{(1+e_f)}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \qquad (1)$$

where, e , G_s and M represent specific gravity, dry mass, and void ratio, respectively while subscripts f and b denote fouling material and ballast, respectively.

In this study, 5 different ballast samples were prepared including one fresh ballast sample and 4 clay fouled ballast samples with 25, 50, 75, and 100% VCI levels. The fouled ballast samples were prepared by uniformly mixing sandy clay material with fresh ballast aggregates. For each test, the test sample was placed inside the cylindrical chamber in 4 equal layers and each layer was compacted using a rubber padded compactor to achieve the field density. Initially, the test specimen inside the chamber was completely filled with water and kept for 24 hours to saturate. During the test, a constant water head was maintained using the constant head tank and the water was allowed to flow through the cylindrical chamber. To ensure a laminar flow condition, the hydraulic gradient of the apparatus was maintained below 4. In each test, the head differences were obtained from the piezometer at 5 different flow rates and the variation in flow rate was plotted against the head difference. Based on the gradient of the graph (m), the hydraulic conductivity (k) was calculated in each case following Darcy's flow using Eq. 2.

$$k = ml / A \qquad (2)$$

where, l and A denote the height of the sample between tapping points of the piezometer outlets and the cross-sectional area of the cylindrical test specimen, respectively.

IV. Results and Discussion

A. *Shear, dilation, and breakage behavior*

For coarse granular materials, the failure plane is not predefined but a shear band is formed diagonally due to the rolling of angular particles. When the ballast is fouled with fines, fine particles control the rolling over of ballast particles as it fills the voids and influences the direct contact between ballast particles. Therefore, fine particle intrusion contributes to the change in the shear behavior of ballast after fouling. Shear stress gradually increased with shear strain and no marginal increase was observed after attaining a peak value between 12-14% of shear strain as shown in Fig. 5. Regardless of the type of specimen, shear stress increased with normal stress increment due to the higher interlocking between angular particles. At lower normal stresses like 30 and 60 kPa, the shear stress of fresh ballast is significantly higher than the fouled ballast because of the lubricant behavior of fouled soil particles (both sand and clay) within the ballast void spaces. At higher normal stress, the shear stress of fresh ballast was less than that of sand fouled ballast. This is 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 at the shear plane leads to more frictional resistance. Using peak shear stresses corresponding to each normal stress were obtained and Mohr-Coulomb failure envelopes were developed for all types of samples. The friction angle of clean ballast 70° increased to 71° and 73° when fouled with 10 and 15 % sand by weight. On the other hand, the friction angle was reduced to 67° for 5 % clay fouled ballast.

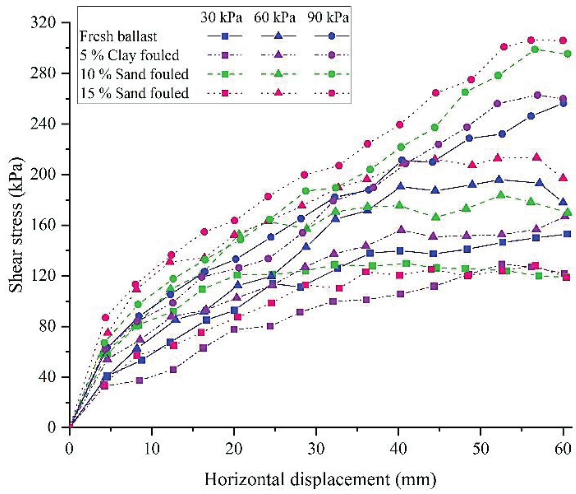

Fig. 5. Shear stress variation of tested samples

The volumetric behavior of all samples is plotted in Fig. 6. A small compression followed by dilation was observed at higher normal stresses. Dilation is reduced with higher normal stresses due to the limitation of particle movements. No definite variation in volumetric behavior with fouling was observed here.

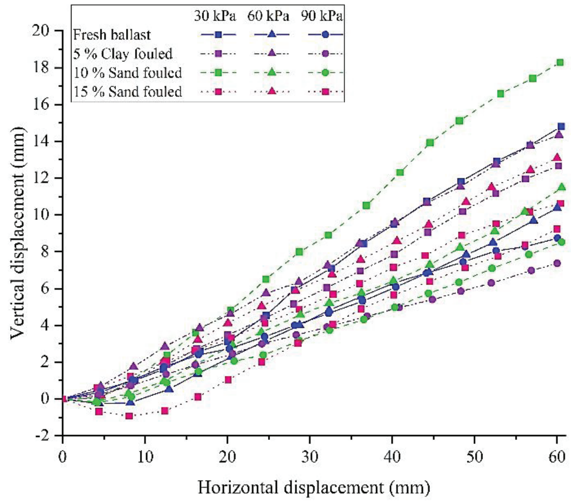

Fig. 6. Dilation variation of tested samples

BBI of different samples are tabulated in Table I. BBI increased with high normal stresses as the load on ballast increased and the free movement is reduced. When the ballast is fouled with sand and clay materials, the BBI was reduced. This is because of the densification of the sample by sand intrusion and reduction in frictional resistance by clay intrusion.

TABLE I. BBI OF DIFFERENT SAMPLES

Sample	Normal stress (kPa)		
	30	***60***	***90***
Fresh ballast	0.099	0.146	0.194
5 % clay fouled	0.061	0.088	0.126
10 % sand fouled	0.085	0.118	0.142
15 % sand fouled	0.017	0.109	0.124

B. Permeability behavior

The variation of flow rate with the variation of head differences for each test sample is shown in Fig. 7. Based on that, the calculated hydraulic conductivity values for each test sample are given in Table II. According to that, the fresh ballast sample exhibited a hydraulic conductivity of 0.43 m/s. The presence of fouling material has drastically reduced the hydraulic conductivity of fresh ballast exhibiting 90.72% and 99.96% reductions for 25% and 100% VCI values, respectively. The results of the permeability test can be used to understand the track drainage condition and thereby initiate the track maintenance operations. For that, the fouling level of a particular track section should be obtained by analyzing a field sample and the corresponding hydraulic conductivity can be estimated from the experimental data presented here. This will help railway authorities to decide the requirement on track maintenance operations such as undercutting operation, replacing existing ballast, and cleaning shoulder ballast.

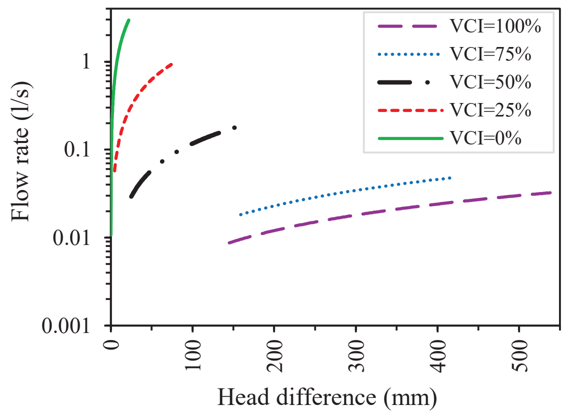

Fig. 7. Variation of flow rate with head difference under different VCI%

TABLE II. HYDRAULIC CONDUCTIVITY OF BALLAST AT DIFFERENT VCI LEVELS

VCI (%)	**Hydraulic conductivity, k (m/s)**
0	4.30×10^{-1}
25	3.99×10^{-2}
50	3.82×10^{-3}
75	3.18×10^{-4}
100	1.91×10^{-4}

V. CONCLUSIONS

In this study, large-scale direct shear and permeability tests were carried out to investigate the effect of fouling materials on shear, degradation and permeability behaviour of railway ballast. The effect of fouling material, fouling percentage, and normal stress on the shear, dilation, and breakage behavior of ballast was observed from the large-scale direct shear tests. Based on the study, shear stress increased and dilation decreased for all samples when normal stress increases. At higher normal stress, the densification effect of sand fouled ballast resulted in higher shear stress than that for fresh ballast. But, as the friction between clay-coated particles is lessen by the lubricant behavior of clay, lesser shear stress was observed. Ballast breakage increased with normal loads and decreased with fouling agents.

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The effect of clay fouling on the hydraulic conductivity of ballast at different VCI levels was studied through large-scale permeability tests. The results clearly exhibited that the presence of fouling materials has significantly reduced the hydraulic conductivity of fresh ballast. Therefore, it is important to initiate mitigating measures such as undercutting operation, cleaning shoulder ballast layer, etc. to recover the hydraulic conductivity of railway ballast to facilitate better drainage. Further, this study only analyzed the effect of two types of fines such as clay and sand fouling on the rail track ballast shear and permeability behavior. Further extending this same work for other types of fine intrusions such as broken ballast and quarry dust are in progress.

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