Effect of Coal Fines on the Shear Strength and Deformation Characteristics of Ballast

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ABSTRACT

Ballast is the most common material supporting the rail track structure due to its large shear strength, high load bearing capacity and free-drainage. However, the fouling of ballast effects deterioration of track performance, and eventually demands track cleaning. Fouling refers to the progressive intrusion of fines into the ballast layer and subsequently filling the voids. Coal spilling from wagons during transport, sleeper and ballast degradation and soil pumping from soft subgrade are the major factors contributing to ballast fouling. Queensland rail network suffers mainly due to ballast breakdown and intrusion of coal fines. The maintenance costs of ballasted tracks can be significantly reduced if an accurate estimation of the different types of fouling material and associated degradation mechanisms in the ballast layer can be quantified. Moreover, modern track design should be able to capture particle breakage and adjust the ballast type and gradation for improved performance. A series of large-scale triaxial tests were performed with the objective of studying the effects of coal fouling on the shear strength of ballast. The strength and deformation characteristics were investigated for fresh ballast mixed with different percentages of coal fines. In this study, the shear strength properties are linked to ballast fouling indices to better assess the effect of coal fouling on track degradation. The shear strength of ballast was found to reduce significantly with the increase in coal fines. Practical implications of coal-fouled ballast are discussed with reference to possible fouling mechanisms and associated degradation of the track substructure.

Keywords: Railway Ballast, Fouling material, Contamination, Breakage, Deformation, Degradation

1 INTRODUCTION

Ballast is the largest component of a rail track by weight and volume. It plays an important role in supporting heavy traffic loading, preventing track deformation, and providing adequate drainage of water in the track structure. In newly constructed track, the volume of voids constitutes approximately 45% of the total volume of ballast. The progressive intrusion of various types of fines into ballast layer fills the voids and causes ballast fouling. As a result, the void ratio of the ballast decreases which in turn reduces the shear strength and induces irrecoverable deformations. Thus the compressibility of the ballast layer becomes serious concern leading to track instability and frequent costly maintenance. Despite advancements in maintenance technology, railway industries annually invest millions of dollars in maintenance, including the removal and replacement of fouled ballast. One of the main causes of rail track maintenance is ballast fouling. Several potential sources of ballast fouling include: sleeper wear, breakdown of ballast particles under traffic loading (i.e. 'mineral fouling'), infiltration from underlying subballast and subgrade layers (e.g. clay fouling) and spillage during transport of wagons (e.g. coal fouling) (Selig and Waters 1994, Indraratna et al. 2011a).

Early research studies in USA reported that around 76% of ballast fouling originates from fracture and abrasion of ballast particles, followed by 13% of infiltration from subballast, 7% infiltration from surface ballast, 3% from subgrade intrusion, and 1% from sleeper wear (Collingwood 1988, Selig et al. 1992). However, In Australia, coal and ballast breakage are major sources of ballast fouling and contributes to 70-95% and 5-30% of ballast fouling respectively (Feldman and Nissen 2002). Therefore strength and deformation characteristics need to be studied for coal fouled ballast at various stages of fouling. Very few studies have been reported in the literature addressing the adverse effects of coal fouling on the strength of ballast (Han and Selig 1997, Budiono et al. 2004, Tutumluer et al. 2008, Dombrow et al. 2009, Indraratna et al. 2011b). This paper presents the findings of a series of isotropically consolidated monotonic triaxial shearing tests using large-scale cylindrical triaxial apparatus, to study the effects of coal fouling on the behaviour of railway ballast.

2 BALLAST FOULING MEASUREMENTS

Fouling material is defined as the material passing the 9.5 mm sieve (Selig and Waters 1994). Several fouling indices are used in practice for measurement of fouling. Selig and Waters (1994) have defined the fouling index as a summation of percentage (by weight) of fouled ballast sample passing the 4.75 mm (No. 4) sieve and 0.075 mm (No. 200) sieve:

$$FI = P_{0.075} + P_{4.75} \quad (1)$$

They also proposed percentage of fouling (% fouling), which is the ratio of the dry weight of fouled material passing 9.5 mm sieve to the dry weight of total fouled ballast sample. An earlier study by Tutumluer et al. (2008) reported an empirical linear relationship between the % fouling and FI. North American Railway systems use typical ballast sizes ranging from 4.76 mm to 51 mm and Australian Railways (AS 2758.7: 1996, TS 3402: 2001) uses ballast sizes varying from 13.2 mm to 63 mm. In view of this, Ionescu (2004) defined the Fouling Index as a summation of percentage (by weight) passing the 13.2 mm sieve and 0.075 mm sieve to suit the Australian Rail Track conditions:

$$FI_P = P_{0.075} + P_{13.2} \quad (2)$$

Based on the particle size distribution analysis of fouled ballast samples, it was observed that intrusion of fines caused significant variation in D_{10} in contrast to that in D_{90}. Therefore, Ionescu (2004) modified the Fouling Index as:

$$FI_D = \frac{D_{90}}{D_{10}} \quad (3)$$

Jeffs and Martin (1994) carried out assessment of ballast fouling for Queensland Railways using D-bar ($\overline{D}$) test. It is geometrical mean particle size based on the particle size distribution of fouled ballast sample. However, all the above mass based indices give a false measurement of fouling, when the fouling material has a different specific gravity. Therefore, Feldman and Nissen (2002) defined the Percentage Void Contamination (PVC) as the ratio of bulk volume of fouling material to the volume of voids of ballast when it is clean.

$$PVC = \frac{V_2}{V_1} \times 100 \quad (4)$$

where, V_1 is volume of voids in the ballast, and V_2 is the total volume of re-compacted fouling material (particles passing 9.5 mm sieve). They recommended undertaking ballast cleaning process once PVC reaches to 30%. However, PVC does not consider the effect of void ratio, gradation and specific gravity of fouling material. Therefore, a new parameter, Void Contaminant Index (VCI) is proposed to incorporate effects of void ratio, specific gravity and gradation of fouling material and ballast (Indraratna et al. 2010).

$$VCI = \frac{(1+e_f)}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \quad (5)$$

where, e_b is void ratio of clean ballast, e_f is void ratio of fouling material, G_{sb} is specific gravity of ballast material, G_{sf} is specific gravity of fouling material, M_b is dry mass of clean ballast, and M_f is dry mass of fouling material. The specifications of clean ballast vary widely for different railway organizations throughout the world. Therefore the changes in void ratio, specific gravity and gradation of clean ballast are always expected. However, all ballast specifications generally demand a uniform gradation (uniformity coefficient, C_u = 1.5 - 3.0) to fulfil the requirements of rapid track drainage. Also, void ratio of clean ballast (e_b) will not change significantly. However, there is significant variation in the void ratio, specific gravity and gradation characteristics of fouling material such as sand, silt, clay and coal fines, and VCI can take into account all such variations. In the current study, VCI is used to measure the amount of coal fouling.

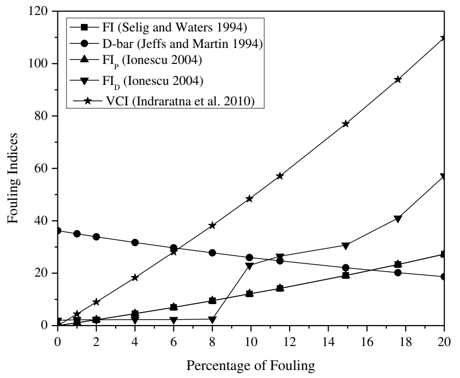

Figure 1. Correlation between fouling indices and VCI for various percentages of coal fouling

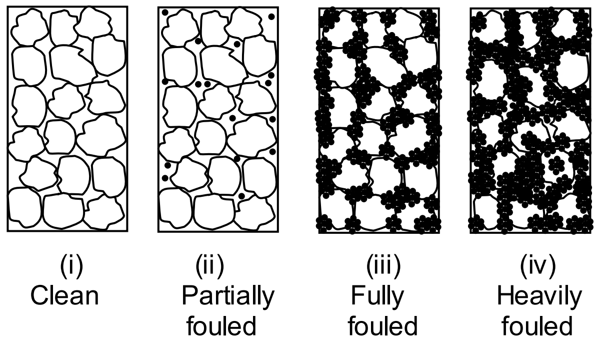

Figure 2. Ballast fouling classification

It is evident from Figure 1 that the conventional or commonly used fouling indices seriously misinterpret the fouling of ballast when fouled material contains more than one type of material having different specific gravities (i.e. coal and clay). It also highlights the significance of VCI which incorporates effects of void ratio, specific gravity and gradation of fouling material and ballast. The VCI predicts well the fouling of ballast due to coal fines and can be termed as more suitable fouling index compared to other fouling indices prevalent in the practice.

3 BALLAST FOULING CLASSIFICATION

For railway ballast, four possible states of fouling can be identified (see Figure 2). Case (i) shows a clean ballast sample (VCI = 0) with well established contacts between aggregates sufficiently to carry the load. In Case (ii), fouled ballast exhibits partial fouling (100 > VCI > 0) whereas in Case (iii), fouling material completely fill the voids (VCI = 100). During Cases (ii) and (iii), it is believed that coarse grain contacts play a primary role in the soil's shear response and coal fines offer a secondary contribution. During case (iv), due to the excessive amount of fouling, the fine grains actively participate in the internal force chain by separating the coarse grains and supporting the coarse grain skeleton (VCI > 100). In normal railway practice, case (iv) is expected to be rare, while cases (ii) and (iii) are common.

4 EXPERIMENTAL WORK

4.1 Testing Apparatus

A large scale triaxial apparatus designed and built at the University of Wollongong that accommodates a specimen of height 600 mm and diameter 300 mm was used in the current study (Figure 3). As the ratio of test specimen to maximum particle size (d_{max} = 63 mm) approaches 6, the sample size effect becomes negligible. Also a length to diameter ratio of 2 ensures minimum influence of end constraints on test results (Marachi et al. 1972, Indraratna et al. 1998). The triaxial test apparatus consists of six main components: the cylindrical triaxial chamber, the vertical loading unit (actuator), the air pressure and water control units, the pore pressure measurement device, the axial and volume change measurement systems and the data acquisition system connected to computer.

4.2 Material Characteristics

The fresh ballast used in the present investigation is latite basalt, a common volcanic igneous rock in the south coast of New South Wales. The ballast particles represent sharp angular coarse aggregates, and their physical properties were evaluated using the standard test procedures as per AS 2758.7 (1996) [Indraratna et al. 1998]. It is a fine-grained, dense and very dark aggregate, with the essential minerals being feldspar, plagioclase and augite. Figure 4 shows the particle size distribution of fresh ballast and coal fines, within the given range of ballast specifications (AS 2758.7: 1996). Table 1 shows the particle size characteristics of fresh ballast and the coal materials used in the current study.

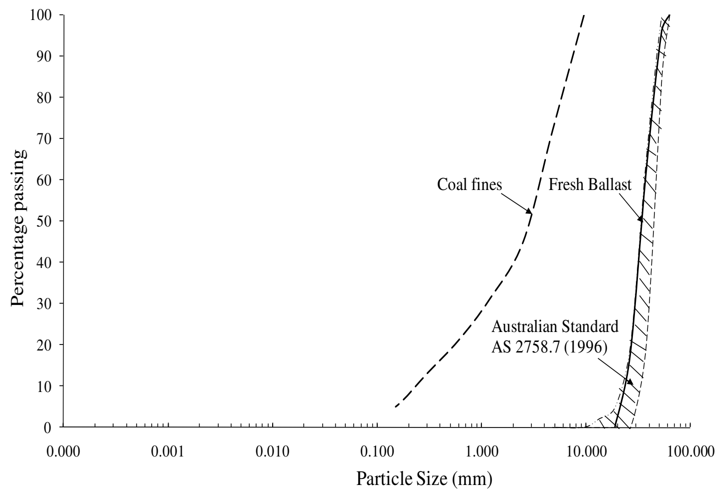

Figure 3. Large-scale cylindrical triaxial apparatus.	Figure 4. Grain size characteristics of fresh ballast and pulverised coal fines.

4.3 Sample Preparation and Test Procedure

The ballast was thoroughly cleaned, dried, sieved through a set of standard sieves (aperture size 63: 19 mm). The ballast was placed inside a 7 mm thick Neoprene rubber membrane in six separate layers, and then each layer was compacted with a handheld vibrator to simulate in-situ density (γ_b = 15.3 kN/m^3; e_b = 0.72 - 0.74) representative of a typical heavy haul track in Australia. The pulverised wet coal fines were added at the top of each layer ensuring uniform distribution within the ballast specimen with an aid of vibration. A rubber pad (4 mm thick) was used to minimise the risk of breaking sharp corners and edges of ballast during compaction produced by a vibrator. An internal suction of 0.3 kPa was sufficient to ensure stability during the transfer of the specimen to the interior of the triaxial chamber. Ballast specimens were saturated using a back-pressure of 50 kPa to obtain sample saturation (Skempton's B value > 0.95). These specimens were then isotropically consolidated to a net confining pressure of 30 and 60 kPa. For monotonic loading the strain controlled test condition was adopted. Triaxial drained compression tests were conducted at an axial strain rate of 0.6% per minute, which allowed dissipation of excess pore water pressure. Upon completion of a test, the sieving procedure was repeated and the extent of breakage was evaluated. Considering an axial strain of 28%, the necessary membrane correction was calculated using the ASTM D4767-04 (2002) method using the membrane properties and dimensions.

Table 1: Grain size characteristics of fresh ballast and pulverised coal

Material	d_{max} (mm)	d_{min} (mm)	d_{50} (mm)	C_u	C_c	Gradation
Fresh Ballast	63.0	19.0	35.0	1.6	1.0	Very Uniform
Pulverised Coal	9.5	0.075	3.0	14.6	1.7	Well-graded

5 RESULTS AND DISCUSSION

The strength and deformation characteristics were investigated for both clean and coal fouled ballast at various stages of fouling.

5.1 Deviator Stress-strain Behaviour

During monotonic triaxial testing of ballast, it is customary for loading to continue until a certain predetermined value of axial strain (ε_a = 28%) has been obtained. In large granular specimens, no distinct failure plane is observed; instead, failure is usually accompanied by specimen 'bulging' (Indraratna et al. 1998). As expected, the highest peak deviator stresses are obtained for the clean ballast at all confining pressures (see Figure 5). The stress-strain behaviour of the clean ballast is similar to that of various clean ballast samples reported in earlier studies (Indraratna et al. 2011a). As expected, when the confining pressure (σ′3) is increased from 30 to 60 kPa, the peak deviator stress and the initial deformation modulus increased for clean ballast and coal-fouled ballast. The coal-fouled ballast that contains both coarse gravel-sized rock (ballast) particles and fine-grained (coal) particles exhibited reduced shear strength (i.e. peak deviator stress) with the increase in VCI. Moreover, the stress-strain curve of clean ballast (VCI = 0%) indicates a distinctly prominent strain-softening behaviour, whereby significant coal fouling (VCI = 50%) shows an increasingly more ductile post-peak response.

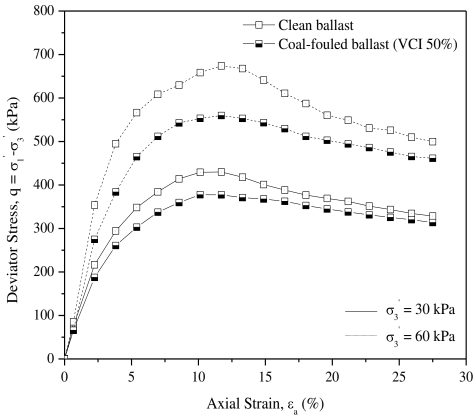

Figure 5. Stress-strain behaviour of coal fouled ballast at effective confining pressure of 30kPa

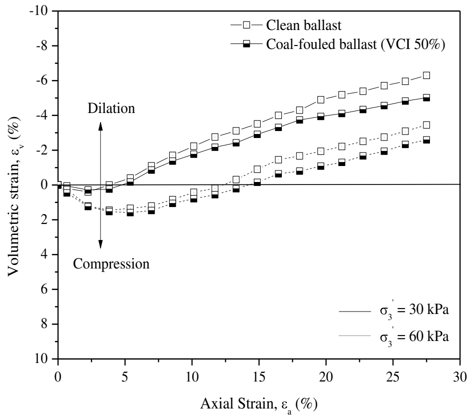

Figure 6. Volumetric strain behaviour of coal fouled ballast

5.2 Volumetric Strain Behaviour

Figure 6 shows the variation of volumetric strain with the axial strain for varying VCI and increasing confining pressure. As expected, the increase in σ′3 from 30 to 60 kPa significantly suppresses dilation of all specimens. The measured response of coal-fouled ballast specimen is best interpreted by looking at the compression zone and the dilation zone separately. In the compression zone, the increasing VCI generally shows an increased compression compared to the clean ballast. This may be attributed partly to the wet coal fines those are coating the ballast particles as a lubricant, thereby facilitating the specimens to attain a slightly higher compression and partly to compressibility of coal matrix achieved as a result of crumbling of soft crushable coal particles during monotonic shearing. In the dilation zone, the highly fouled specimen shows a decrease in the rate and magnitude of dilation at axial strain exceeding @ 15%. Intuitively, it may be argued that the addition of pulverised coal fines in sufficient quantities may contribute to a ‘lubricating’ effect that diminishes the tendency of the ballast aggregates to dilate.

5.3 Particle Breakage

The effect of ballast breakage on the performance of track has been studied (Indraratna et al. 1997, 1998, Indraratna et al., 2011a). The extent of ballast breakage was analysed by carrying out pre-test and post-test PSD analyses. In this study, breakage was evaluated using Ballast Breakage Index (BBI) proposed by Indraratna et al., 2005. It is evident from Table 2 that small size coal particles trapped between coarse ballast aggregates would have a cushioning effect to thwart the harsh attrition between rough and angular particles thereby reducing high contact stresses and associated degradation. The ballast particles experience less breakage at higher values of VCI. Nevertheless, the benefits of reduced ballast degradation are offset by the drop in shear strength as the degree of fouling increases.

Table 2: Assessment of ballast breakage during monotonic loading

Test no.	Description	Ballast breakage index (BBI)
1	Clean ballast (VCI = 0, σ_3' = 30 kPa)	0.048
2	Clean ballast (VCI = 0, σ_3' = 60 kPa)	0.068
3	Coal-fouled ballast (VCI = 50, σ_3' = 30 kPa)	0.030
4	Coal-fouled ballast (VCI = 50, σ_3' = 60 kPa)	0.045

6 CONCLUSION

Fouling of ballast due to intrusion of coal fines is one of the major concerns of ballasted rail tracks and often leads to diminished performance. The intrusion of coal fines into ballast bed significantly reduces its shear strength, and causes rapid deterioration of the track demanding regular maintenance. In this paper, a series of isotropically consolidated drained monotonic triaxial tests using a large scale cylindrical triaxial apparatus were conducted on coal-fouled ballast for various levels of coal fouling and confining pressures.

It was observed that the increased VCI would cause considerable decrease in the shear strength (peak deviator stress) of ballast. It was shown in this study that the increase in confining pressure, σ'_3 from 30 to 60 kPa, suppressed the dilation considerably. The overall volumetric response of the fouled specimens remained compressive which could be attributed to the lubrication effect induced by pulverised coal. It was also observed that excessive fouling (VCI = 50%) decreased both the rate and magnitude of dilation. With the increase of fouling, the ballast particles experienced less breakage. This could be attributed to the 'cushioning' effect of coal particles that assists in the reduction of very high inter-particle contact stresses. Although reduced breakage is beneficial, excessive reduction in shear strength due to fouling can have serious implications on track stability.

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