FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 6 No. 1, March, 2022, pp 210 - 215
DOI: https://doi.org/10.33003/fjs-2022-0601-871

EVALUATING THE INFLUENCE OF TRAIN AXLE LOAD ON RAILWAY BALLAST DEGRADATION AND AXIAL DEFORMATION

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ABSTRACT

Degradation and axial deformations of railway ballast bed are highly influenced by stresses induced by moving trains. Hence, this study evaluate the influence of train axle load on the rate of degradation and axial deformation of railway ballast bed. Series of cyclic loading test were conducted at intervals of 200,000 load cycles up to 1,000,000 cycles. Two trains with capacities of 30 ton and 24 tons for freight and passengers respectively were simulated at a typical moving speed of 120 km/hr which is equivalent to a frequency of 16.5 Hz. It was observed that with an increase in both axle load and number of load cycles, the degradation index and the axial deformation increased. It was also observed that ballast degradation has a strong influence on the ballast bed deformation. Hence, ballast degradation is highly influenced by train axle load and the axial deformation of the ballast bed has a strong correlation with the rate of ballast particles degradations.

Keywords: Ballast degradation; frequency, load cycle, breakage index, deformation

INTRODUCTION

With the accumulation of cyclic loading on ballasted railway track from train traffic, the ballast bed material undergoes degradation through breakage and attrition. Ballasted railway track system is divided into two components; the superstructure which consist of the sleepers, fasteners and the rail and the substructure which contain the subgrade, sub-ballast (if need be) and the ballast. The ballast bed provide support and stability to the superstructure, hence, it is an important component of the ballasted railway track. Generally, ballast degradation has a strong influence on the performance and mechanical behaviour of the railway track system. It is associated with excessive settlement (axial deformation) when it is high, as well as fouling of the railway ballast bed. During the degradation process, pulverised materials are produced through attrition of particles which reduce the particle-to-particle bond strength (angle of internal friction) due to cushioning effect caused by fines.

Ballast degradation refers to the change in the ballast initial gradation through attrition and breakage which lead to the ballast particles rearrangement, densification and result in axial deformation of the railway track. Ballast degrade under train cyclic loading due to the sliding actions between particle-to-particle contact (attrition) which results in abrasion of sharp edges and particle breakage into two or more pieces (Qian *et al.,* 2017; Danesh *et al.,* 2018 and Guo *et al.,* 2019). However, the studies on ballast behaviour under cyclic loading has been researched by numerous researchers. Sun *et al.,* (2016) conducted a cyclic loading test to evaluate the effect of loading frequency on ballast degradation and axial deformation, and concluded that loading frequency as well as train axle load has a strong influence on the rate of ballast degradation and its deformation mechanism. Indraratna *et al.* (2010) reported that ballast bed permanent deformation and particles degradation under train cyclic loading are influenced by loading frequency and confining pressure. Thakur *et al.,* (2013) performed a cyclic loading test on ballast sample at varying frequencies and confining pressure to evaluate the mechanical behaviour of railway ballast bed. The results revealed that both the confining pressure and the number of load cycle have significant influence on the ballast deformation and resilient modulus. Indraratna *et al.* (2015) and Lackenby *et al.* (2007) reported from their respective studies that the resilient modulus of railway ballast is greatly influenced by the number of load cycles, confining pressure and deviator stress while the ballast degradation is more profound at higher frequencies. It was also reported by Anderson and Fair (2008), Indraratna *et al.,* (2005) and Indraratna and Salim, (2005) that degradation and permanent deformation of a railway ballast are more profound at initial stage of service after which the ballast bed becomes stabilized and with an increase in the number of load cycles of train axles, the ballast bed degrade and deform continuously at lower phase which is due to the reduction in sharp edges and rough surfaces. Sun, (2017) stated that gradation and bulk density of ballast materials have a significant influence on its resilience modulus and the rate of its degradation.

During the degradation process, attrition between ballast aggregate produces pulverized ballast particle, which contributes immensely to the formation of ballast voids fouling (Danesh *et al.,* 2018; Ionescu, 2004). Fouling is the fundamental factor that causes loss of contact between ballast aggregates, which in turn reduce the track stability and affect the performance of the railway track system (Danesh *et al.,* 2018; Ionescu, 2004; Ngo *et al.,* 2014; Qian *et al.,* 2014b). Salig and waters, (1994) reported that 76% of ballast fouling is due to ballast particles degradation. Studies have been conducted to evaluate the effect of the ballast degradation and other fouling agent on the ballast bed mechanical properties. Qian et al. (2014a) conducted an experimental study to investigate the permanent deformation behaviour of a fouled ballast caused by ballast degradation through a series of large-scale triaxial tests. The results showed that the more the ballast degrades, the more the fouling index which led to higher ballast deformation. It was concluded that specimens with degraded ballast yielded higher deformation when compared to the specimen with fresh gradation. This was attributed to the loss of contact between larger particles due to the intrusion of the fine into the void space of the ballast.

However, with an increase in demand for railway transport across the globe, the existing rail track system has been exposed to an increase in the frequency of operations, axle loads and speeds (Indraratna et al., 2020; Ngo et al., 2019). Hence, the ballast deteriorates progressively due to increasing load cycles (Indraratna et al., 2016). However, quite a number of researches have conducted to evaluate the effect of ballast degradation on the performance of railway ballast bed and was found to be inevitable. Hence, it is of utmost importance to develop a relationship that can be used to evaluate the rate of ballast degradation with number of load cycles. Therefore, this study aim at evaluating the effect of train axle load on the rate of ballast particles degradations and its corresponding axial deformation, which can be used to predict the time at which the railway ballast bed will be due for maintenance.

MATERIAL AND METHODS

Material

The b1allast material used for this study was 100% crushed granite and the specimens were prepared in accordance with Chinese standard gradation requirements (TB/T 2328.14-2008) for new railway lines as shown in Figure 1. The Chinese code was chosen due to the fact that the new Nigerian standard gauge rail lines are designed and constructed by Chinese companies.

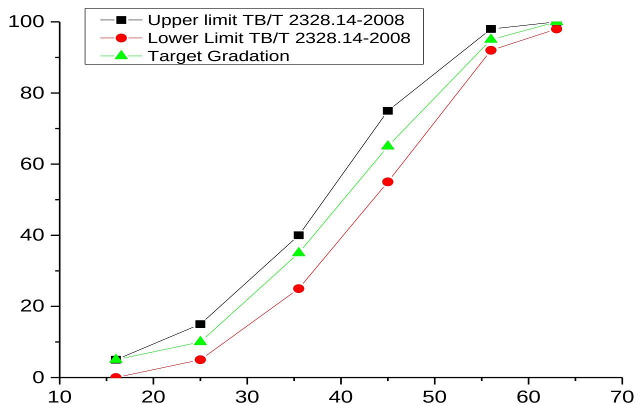

Figure 1. Gradation of crushed granite ballast material (TB/T 2328.14-2008).

Methods

Cyclic loading test

The specimens for the cyclic loading tests were prepared in accordance with the gradation requirement and compacted to a field density of 1512 kg/m$^{2.}$ Typical heavy haul freight and passenger trains with speeds of 120 km/h corresponding to frequency of 16.5 Hz. The load capacity for the heavy haul freight and passenger trains were 30 tons and 24 tons, corresponding to 288 kPa and 231 kPa, respectively were simulated. The cyclic loading tests were conducted at varying load cycles of 200000, 400,000, 600,000, 800,000 and 1,000,000 cycles. The Maximum deviator stresses used for the test is the summation of stresses induced by moving train and 45 kPa due to stress from the railway track superstructure (Esveld and Esveld, 2001), which are equivalent to 333 kPa and 276 kPa respectively and a minimum stress of 45 kPa for all tests. The specimens were sieved after each of the test run using standard sieves. Material retained on each sieve were collected and recorded.

Evaluation of Ballast degradation

Marsal's Breakage index (B_g) proposed by (Marsal, 1967), was used to estimate the ballast degradation index. It was determined as the summation of positive values of the difference in mass of material retained on same sieve size before and after the test. The differences in percentage retained on each sieve size (ΔW_k) were determined as follows;

$$\Delta W_k = W_{ki} - W_{kf} \tag{1}$$

where; W_{ki} and W_{kf} ; are the percentages by mass retained on sieve size *k* before and after the test respectively.

RESULTS AND DISCUSSION

Ballast material characterisation

The preliminary tests results for the physical properties of the ballast material are as presented in table 1. Based on the results obtained, it is evident that the material satisfied all code requirements for used as ballast material.

Table 1: of Preliminary Test Results conducted on Ballast Aggregates

Tests	Code Used	Test Result	Code requirements
Aggregate Crushing Value (%)	BS 812 Part 112 (1990)	21.0	Max. 25
Aggregate Impact Value (%)	BS 812 Part 111 (1990)	20.6	Max. 25

Specific Gravity Of Coarse Aggregate	ASTM C127 (2009)	2.66	2.55 – 2.75
Density of Coarse Aggregate (kg/m^3)	ASTM C127 (2009)	1512	>1450
LAA value (%)	ASTM C535 (2015)	15.52	Max.25

Degradation

The results for the ballast degradation is as presented in Figure 2. The figure presents the pattern of changes in gradation after the cyclic loading test at an interval of 200000 load cycles. It can be clearly observed that, as the number of load cycles increases, the particle size distribution curves keep shifting to the left and becoming well graded. The changes in particles size distribution of ballast sample is attributed to the wearing and abrasion of the particles' sharp edges and continuous breaking of larger particles into two or more with an increase in the number of load cycles. Therefore, ballast degradation in the field is strongly link to the breakage of sharp edges and breakage of larger aggregate particles during service. This is in line with the finding of Qian *et al.*, (2017) and Indraratna *et al.*, (2014; 2013).

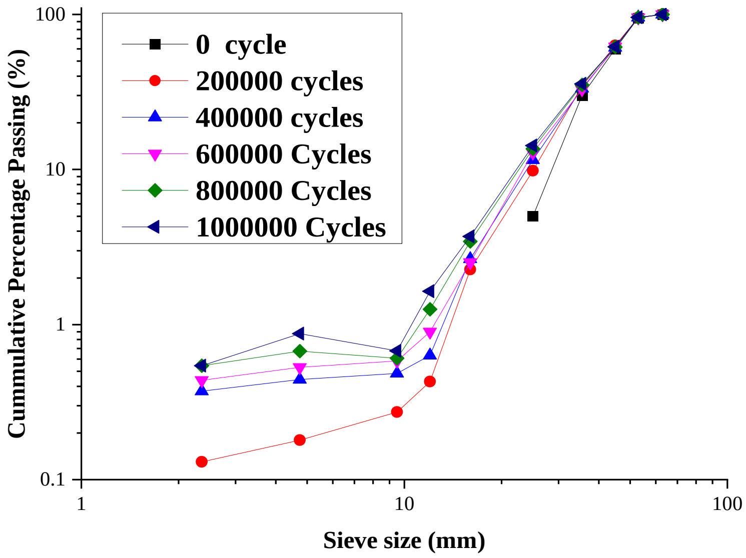

Figure 2. Gradation evolution of ballast specimen with number cyclic loading.

Development of Relationship between degradation and number of load cycles.

Figures 3 present the ballast degradation trends in terms of breakage index (B_g) values against the number of load cycles at loading frequencies of 16.5Hz. Figure 3 presents the relationship between the breakage index (B_g) and the number of turns of load cycles (C_{Cyc}) at varying train axle load with loading frequency of 16.5Hz (120km/h). It can be observed that with an increase in axle load from 24 tons to 30 tons, the degradation values significantly increased. The increase is an indication that train axle load has a strong influence on the rate of ballast material degradation. Based on the result obtained, the best-fit equations were found to be logarithmic with coefficient of determination (R^2) of 99.64% and 97.57% for the 30tons and 24tons respectively. The data can be represented in equations (1) and (2) respectively.

$$\mathrm{B_{g30t}} = 2.941\ln(\mathrm{N_{cyc}}) - 31.346 \quad (1)$$

$$\mathrm{B_{g\,24t}} = 2.180\ln(\mathrm{N_{cyc}}) - 22.755 \quad (2)$$

Based on the models obtained as presented in equation (1) and (2), a generalized relationship between the ballast deration and the train axle load with number of load cycles is as presented in equation 2. The expression can be used to evaluate ballast degradation for a train with a specific axle load and number of load cycles.

$$\mathrm{B_g} = 0.0918P_a\ln(\mathrm{N_{cyc}}) - 0.958P_a \quad (3)$$

Where: P_a is the axle load capacity of train in tons, $\mathrm{N_{cyc}}$ is the number of load cycles

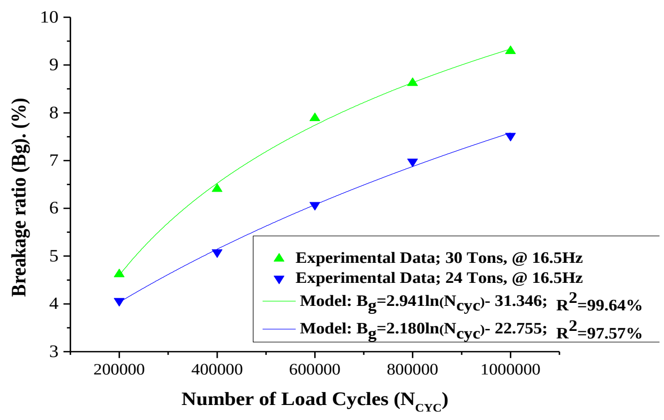

Figure 3: Relation between the Breakage Index and the number of Load Cycles

Deformations

The axial deformation of the ballast specimens under different train axle loads (30tons and 24tons) and varying number of load cycles is as presented in Figure 4. The presents the axial deformation for 30 and 24 ton at a loading frequency of 16.5Hz which simulates a train speed of 120km/h. It is observed that with an increase in train axle load, the axial deformation increases. The results also indicate that the ballast specimens deform rapidly at the initial stages of cyclic loading, which could be due to reduction in voids between the aggregate particles. Deformation of the ballast specimens stabilizes after about 100,000 load cycles, after which it increases at a slower rate. The reduction in rate of the axial deformation is an indication that the ballast specimen becomes denser, packed and the voids between the aggregates have significantly reduced. This deduction is in agreement with the findings of Anderson and Fair, (2008); Indraratna *et al.*, (2005); Indraratna and Salim, (2005).

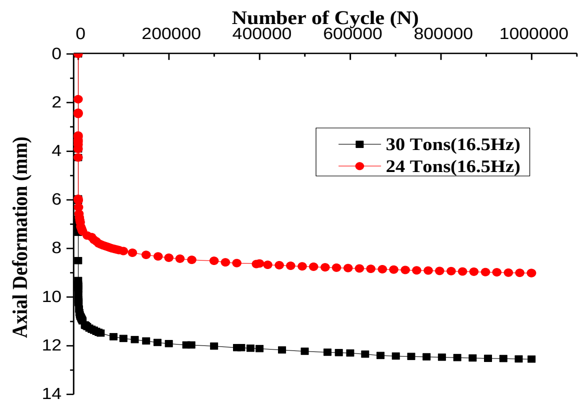

Figure 4: Relation between Axial deformation and the number of Load Cycles

Relationship between Axial deformation and degradation

The relationship between the ballast bed axial deformation and the particles degradation index in terms of breakage ratio is as presented in figure 5. It can be observed that the more the degradation (breakage ration) the higher the axial deformation, this is a clear indication that the deformation of ballast bed is adversely influenced by how much the aggregate particles degrade. Based on the experimental results data the relationship between the axial deformation and the ballast particles degradation were developed. The relationships were found to be linear with coefficient of correlation of 98.42% and 96.47% under train axle load of 30 tons and 24 tons respectively as presented in equation (4) and (5). The increase in the ballast bed axial deformation with an increase in ballast degradation value is attributed to the continue reduction in the initial void ratio between the aggregate particles due to the production finer particles through the breakage of larger particles and attrition of sharp corner edges of the ballast particles. This deduction agrees with the findings of Sun et al., (2016) and Indraratna et al., (2011). Hence a constitutive model is proposed for the evaluation of the ballast bed axial deformation with the ballast particles degradations.

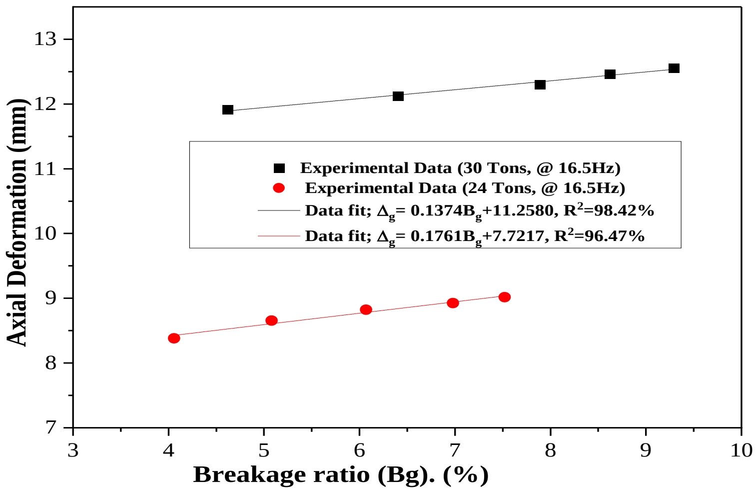

Figure 5. Relation between Axial deformation and breakage ratio

$$Sg_{30\,t} = 0.1374Bg+11.2580,\ R^2=98.42\% \quad (4)$$

$$Sg_{24\,t} = 0.1761Bg+7.7217,\ R^2=96.47\% \quad (5)$$

CONCLUSIONS

This study evaluated the influence of train axle load on ballast degradation and axial deformation under cyclic loading tests. Two typical heavy haul freight train and passenger train with 30-tons and 24 tons capacity respectively, at a speeds of 120km/h which correspond to loading frequency of 16.5 Hz were simulated for the test. At the end of the study, the following conclusions were derived.

The preliminary test results showed that the material satisfied all the relevant code requirements and hence, the material is suitable for use as ballast material.

The ballast degradation in terms of breakage index (B_g) increases with an increase in the number of load cycles. The increase in the ballast degradation is attributed to the chopping off of sharp edges, surface attrition, and breakage of larger particles into smaller sizes. The train axle load has a strong influence on the rate of ballast degradation and axial deformation.

Relationship between ballast breakage indexes(B_g) and the number of load cycles (N_{Cyc}) is proposed. Based on the results obtained, it can be concluded that ballast degradation can be estimated using the proposed relationship.

Relationship between ballast breakage indexes(B_g) and axial deformation **Sg**) is also proposed. The data obtained using the proposed relationships correlate well with the experimental data, hence the model can be used to estimate the axial deformation using the degradation index

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