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Experimental investigation of effects of sand contamination on strain modulus of railway ballast

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Abstract. Ballast layer has an important role in vertical stiffness and stability of railway track. In most of the Middle East countries and some of the Asian ones, significant parts of railway lines pass through desert areas where the track (particularly ballast layer) is contaminated with sands. Despite considerable number of derailments reported in the sand contaminated tracks, there is a lack of sufficient studies on the influences of sand contamination on the ballast vertical stiffness as the main indicator of track stability. Addressing this limitation, the effects of sand contamination on the mechanical behavior of ballast were experimentally investigated. For this purpose, laboratory tests (plate load test) on ballast samples with different levels of sand contamination were carried out. The results obtained were analyzed leading to derive mathematical expressions for the strain modulus (E_V) as a function of the ballast level of contamination. The E_V was used as an index for evaluation of the load-deformation characteristics and bearing capacity of track substructure. The critical limit of sand contamination, after which the E_V of the ballast reduces drastically, was obtained. It was shown that the obtained research results improve the current track maintenance approach by providing key guides for the optimization of ballast maintenance planning (the timing of ballast cleaning or renewal).

Keywords: railway ballast; sand; contamination; strain modulus; maintenance; laboratory test

1. Introduction

Railway ballast is composed of coarse aggregates in the size range of (20-60 mm) which are graded uniformly. Ballast transfers train loads to the sub-ballast layer and plays significant roles in the lateral and longitudinal stability of railway track systems. Ballast has sufficient voids in its structure which provide free and rapid draining condition and damp the track induced vibrations (Selig and Waters 1994, Esveld 2001, Sadeghi *et al.* 2016, Wang *et al*. 2016). It is fouled when fine particles infiltrate into the layer and consequently ballast voids are filled up with the fines.

In the majority of the Middle East countries and some of Asian ones, significant parts of railway lines pass through desert areas and get severely contaminated with sands due to frequent sand storms (Zakeri and Sadeghi 2007, Zakeri *et al*. 2011, Qin and Guo 2014). In addition to sand contamination, aggregate breakage and infiltration of fine particles from subgrade are generally the main sources of ballast contamination (Selig and Waters 1994, Salim 2004). However, in the desert and sandy areas, sand infiltration is the main cause of contamination. When ballast is contaminated with sand, it fails to perform its functions. Samples of ballast contamination with sands in the Iranian eastern railway network are presented in Fig. 1. The infiltration of sand into the tracks is one of the most serious concerns of railway industries in the Middle East and Asia.

Generally, as a result of contamination, the strength and stiffness of ballast reduces considerably and in turn the ballast plastic deformations increase (Tennakoon 2012, Rahman 2013, Kumara and Hayano 2016). Since ballast is the main source of differential settlement of railway track, reduction in the ballast strength due to the contamination is an important challenge of the railway industry in the desert areas. Non-uniform settlement of the ballast results in degradation of track geometry, and in turn possible derailments (Ebrahimi *et al.* 2010, Nimbalkar *et al*. 2012, Wang *et al*. 2015).

Review of literature indicates that there have been several experimental studies made on the effect of contamination on the shear strength of ballast using direct shear and triaxial tests (Tutumluer *et al*. 2008; Dombrow *et al*. 2009, Huang *et al*. 2009, Dissanayake *et al*. 2015, Indraratna *et al*. 2012, 2013, Rahman 2013, Tennakoon *et al*. 2014). Fine particles of crushed ballast, coal dust and clay were considered as contaminant materials in these studies. However, vertical load-deformation properties of ballast layer contaminated with sands has not been investigated in the available literature. Considering the growing demands for higher axle loads and faster trains in recent years which increase the risk of derailments, there is an important question on the adequacy of stiffness and bearing capacity of the ballast layer when contaminated with sands. According to the railway reports (Crawford *et*

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al. 2001, Indraratna *et al*. 2011a), track resiliency is changed with ballast contamination and therefore, heavy and costly maintenance operations such as ballast cleaning or replacing should be made to keep the track stiffness to an appropriate level (Shi 2009, Tennakoon 2012). The cost effectiveness of any maintenance planning is very much dependent on the accuracy of the prediction of the time at which the repair action is made. It means that there is a need to study the effect of sand contamination on the stiffness and bearing capacity of the ballast in order to find the situation at which the ballast is unable to fulfill its functions and the track safety is in danger. In response to this need, extensive laboratory tests (several static repetitive plate load tests) were performed to investigate the effects of different dosages of sand-contaminations on the ballast strain modulus.

Review of literature indicates that the strain modulus (E_V) is an indicator of the strength of the soil foundation of infrastructures (such as railways, airports, and highways) and the stiffness of ballast layers (Indraratna *et al*. 2012, 2013, Tennakoon *et al*. 2014, Li *et al*. 2016, Zhou *et al*. 2016). According to the literature, E_{V2} is as an index to investigate the ballast mechanical behavior and performance (Fortunato *et al*. 2010, Paderno 2011). It is the main parameter in the design and quality control of soil foundation and track substructure (Martins and Correia 2008, Correia *et al*. 2009, Dincer 2011, Kavaka *et al*. 2011, Ma *et al*. 2014, Paixao *et al*. 2015, Sun *et al*. 2016). E_{V2} is also an indicator for the investigation of deformation and load-bearing capacity characteristics of track substructure (Gobel *et al*. 1994, Kim and Park 2011, Nie *et al*. 2016). Therefore, E_V in the first and the second cycles of loading (E_{V1} and E_{V2}) was considered for the investigation of the effects of sand contamination on the ballast performance in this research. The critical percent of sand contamination, after which the E_V of ballast drops drastically, was determined. The application and effectiveness of the results in the ballast maintenance planning in the deserts and sandy areas were illustrated.

Fig. 1 The tracks contaminated significantly with sand (Iranian eastern railway network)

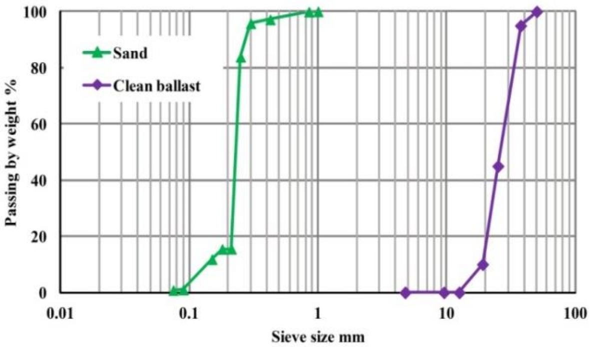


Fig. 2 Particle size distributions of clean ballast and sand materials

Table 1 Properties of clean ballast and sand materials

Material	Specific gravity	d_{50} mm	Cu*	Cc**	Porosity (%)
Clean ballast	2.77	26	1.48	0.92	27
Sand	2.6	0.23	-	-	38

*Cu=coefficient of uniform, **Cc= coefficient of curvature

2. Experimental works

To derive E_{V2} of the ballast with various sand contaminations, two series of static repetitive plate load tests were conducted. In the first series, tests were made on clean ballast samples (i.e., without any contamination); in the second series, the characteristics of the ballast with various dosages of sand contamination were investigated.

2.1 Material properties

The clean ballast used in the current study was dolomite limestone aggregates with an angular shape. This type of ballast has been vastly used in the Iranian railway substructure. The particle size distribution of clean ballast is according to ASTM C136 (2014). The gradation of the ballast used was adapted from Class 5 of the ballast gradation suggested in the Iranian national code 301 (VPSPS 2005). Sands were collected from Talle-Hamid line in the Iranian eastern railway network which passes through sandy terrain. The size distribution curve and the characteristics of the sand grains and the ballast are presented in Fig. 2 and Table 1.

2.2 Sample preparation

Ballast samples were placed in a large steel chamber with dimensions of 120 cm length, 120 cm width and 100 cm depth. The chamber has no top and bottom face. The center of chamber was exactly under the steel rigid frame which was fixed firmly to the laboratory floor. The chamber and the solid frame are presented in Fig. 3.

The ballast depth in the chamber was 30 cm which is the same as that in the railway fields. Clean ballast samples were made in three layers; each layer was compacted with a hand tamper to obtain dry density of 17.5 kN/m^3 which is similar to the density of ballast in the field (Shi 2009). Clean ballast samples in the chamber are presented in Fig. 4.

Fig. 3 The steel chamber and strong steel reaction frame

(a) Clean ballast sample (b) Highly fouled ballast sample

Fig. 4 Clean and highly fouled ballast samples in the chamber (To show inside the chamber front face is temporarily removed in this figures)

Table 2 Percentages of fouling of ballast samples

Contamination condition	Range of percentage of contamination (Anbazhagan *et al.* 2010)	Percentages of contamination of ballast samples in this research
Clean	Smaller than 2%	0
Moderately fouled	9.5-17.5%	14%
Fouled	17.5-34%	19%
		24%
		31%
Highly fouled	Greater than 34%	37%

To quantify the amount of contamination, the percentage of fouling (contamination) was used as a contamination index. Percentage of contamination is the ratio of the dry weight of contaminant materials passing 9.5 mm sieve to the dry weight of the sample (Selig and Waters 1994). The six levels of contamination were considered in the samples. The contamination percentages of the samples are presented in Table 2.

Fig. 5 The assembly of jack, load cell, rigid cylinders and rigid circular plate beneath the strong reaction frame

The amount of ballast voids was obtained based on ASTM C29 (2003). It was found that 32% sand (by weight) of ballast aggregates completely fill up the ballast voids. This amount of the sand in the ballast samples corresponds to 24% percentage of contamination.

Each sand-contaminated sample was prepared in three layers (steps) and the sands were spread uniformly on the top of each layer. At each step, the dry ballast materials were compacted in a 10 cm layer. The reliability of this method has been illustrated in the literature (Huang *et al*. 2009, Indraratna *et al*. 2011b, Rahman, 2013). The amount of the sand for each layer was taken such that the assigned level of contamination was obtained.

2.3 Test procedure

The static repetitive plate load tests were conducted in accordance with DIN 18134 (2012). In order to ensure repeatability of the tests, the experimental procedure and the amount of ballast used for all the tests were kept the same. To perform the test, a steel rigid circular plate with a diameter of 200 mm and thickness of 30 mm was used to apply pressure on the ballast surface. The dimensions of the chamber were 120 cm in length and 120 cm in width which are four times greater than the diameter of the loading plate. This condition allowed free development of the stress in the ballast. Because the ratio of the width of the chamber to the diameter of the loading plate is six, the effect of chamber boundary conditions on the results is negligible (Das and Sobhan 2013, Kar *et al*. 2012). A thin layer of cement mortar was made under the circular rigid plate in order to provide a level surface on the top of the ballast samples and make the circular rigid plate in full contact with the ballast surface. The circular plate was bedded on the cement mortar and leveled using a bubble level. The loading system was a hydraulic jack with capacity of 100 kN by which the normal stress was applied. The jack was capable of applying and releasing the pressure in multi steps. The load was measured by a load cell which is capable of measuring up to 100 kN. The jack was installed under the beam of a rigid frame and the load cell was installed under the jack. Steel rigid cylinders (as a force transfer medium) were placed between the rigid circular plate (which is placed on the top of the sample) and the load cell (connected to the jack). Any sliding, tilting or deviations of the assembly of jack, load cell, rigid cylinders and rigid circular plate were prevented during the test. The assembly of the instruments is presented in Fig. 5.

To measure the normal displacement of the ballast, a LVDT (linear variable displacement transducer) was attached on the rigid plate which was installed under the load cell. The normal force and displacement were recorded using a data acquisition system connected to the sensors. Before the commencement of the test, a pre-load was applied on the circular rigid plate corresponding to a pressure of 0.01 MPa. The load was applied in six steps with constant increment, until the maximum pressure was reached. The unloading was made in 3 steps corresponding to 50%, 25% and 2% of the maximum load. After releasing the load, the second cycle of the loading was carried out, in which the load was raised only to the penultimate step of the first cycle. To determine the strain modulus, the load was increased until a pressure under the circular plate became 0.5 MPa or, the settlement reached 5 mm. If the displacement of 5 mm is reached first, the pressure measured at this step was taken as the highest pressure.

3. Investigation of validity of test procedure

To validate the test procedure, the results of the tests performed on the clean ballast samples were compared with those available in the literature. For this purpose, the strain modulus and the resilient modulus of the clean ballast were investigated.

A survey of the literature indicates that the ballast strain modulus (obtained from plate load tests) has been rarely investigated. The only available research on this issue belongs to Paderno (2009, 2011). Paderno (2009, 2011) has investigated the amount of E_V for the clean ballast. Paderno's tests (2009, 2011) were conducted on the clean ballast materials with angular shape and dry density of 17 kN/m^3. The test conditions, ballast properties, and the testing procedure (including loading methods) used by Paderno (2009, 2011) were the same as those adapted in this study. His test results indicate that E_{V1} (the modulus in the first cycle of loading) varies from 9 to 66 MPa, and E_{V2} (the modulus in the second cycle of loading) varies from 43 to 99 MPa. He has also showed that the ratio of E_{V2} to E_{V1} is in the ranges of 2.5-3.1. Comparisons between the results obtained in this research (Table 3) and those obtained by Paderno (2009, 2011) indicate that the results obtained in this study are in a good agreement with the findings of Paderno (2009, 2011).

Table 3 Strain modulus of clean ballast samples in the 1st and 2nd cycle of loading

Percentage of contamination (%)	E_{V1} MPa	E_{V2} MPa	E_{V2}/E_{V1}
0	27.55	72.87	2.65

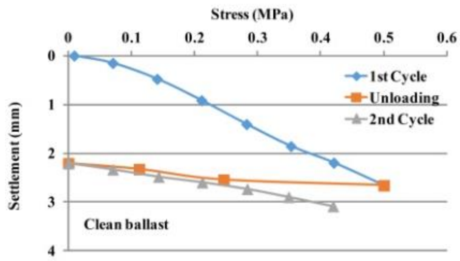
Table 4 Properties and resilient modulus of clean ballast obtained form cyclic triaxial test

Researcher	Resilient modulus MPa	d_{50} mm	Cc	Cu
Ionescu (2004)	74	34	1.6	1.0
Aursudkij (2007)	69	31	1.5	1.0
Shi (2009)	60	35	1.5	0.9
Tennakoon (2012)	75	30	1.55	1.0

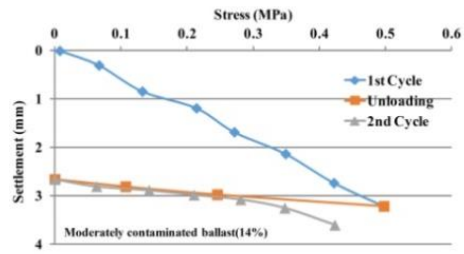
Ionescu (2004), Aursudkij (2007), Shi (2009) and Tennakoon (2012) have obtained the resilient modulus of the clean ballast. The results of resilient modulus obtained from cyclic triaxial test conducted on clean ballast are presented in Table 4. The properties of the ballast used in triaxial tests (presented in Table 4) are almost the same as those of the ballast used in this study (indicated in Table 1). Resilient modulus is comparable to strain modulus (Davich *et al*. 2004, Shi 2009, Tennakoon 2012). As illustrated in Table 4, the resilient modulus obtained in the literature are in a good agreement with the strain modulus of the clean ballast (E_{V2}) obtained in this research.

4. Results and discussion

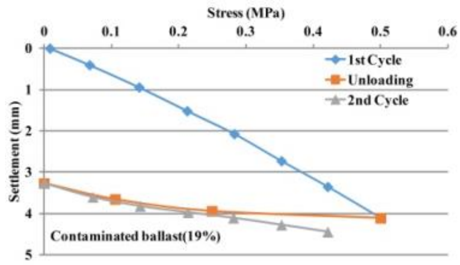
The ballast settlement versus the normal stress for the clean and sand-contaminated ballast samples are illustrated in Figs. 6 and 7. To minimize errors in the tests, two samples were prepared and tested for each contamination condition and the results obtained were averaged. The results obtained for each contamination condition were almost the same, indicating the repeatability of the test procedures. As presented in Figs. 6 and 7, when the contamination increases, the maximum settlement and permanent deformation increase.



(a) Clean ballast

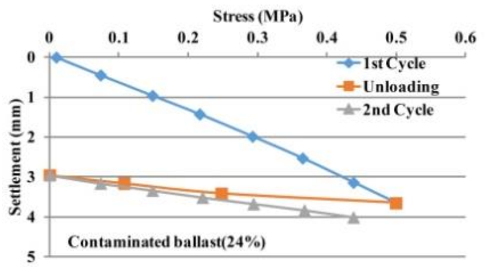


(b) Moderately contaminated ballast (14%)

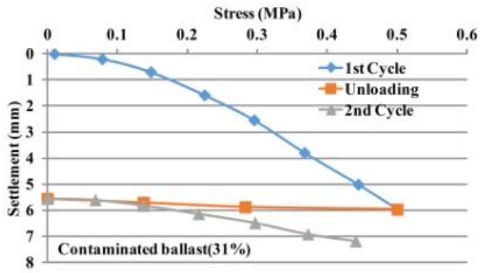


(c) Contaminated ballast (19%)

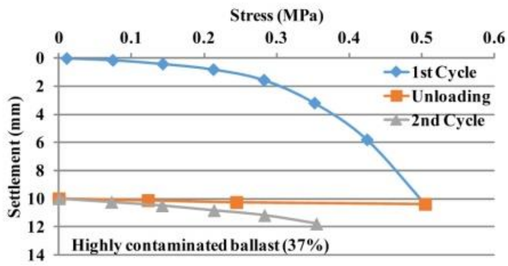
Fig. 6 Normal stress versus settlement for (a) clean ballast, (b) moderately contaminated ballast (14%) and (c) contaminated ballast (19%)



(a) Contaminated ballast (24%)



(b) Contaminated ballast (31%)



(c) Highly contaminated ballast (37%)

Fig. 7 Normal stress versus settlement for (a) contaminated ballast (24%), (b) contaminated ballast (31%) and (c) contaminated ballast (37%)

As indicated in Figs. 6 and 7, the settlement in the first cycle of the loading is much greater than those in the second cycle of the loading, regardless of the level of contamination. Figs. 6(a)-6(c) present normal stress versus settlement for 0, 14% and 19% percentage of contamination respectively. The results of 24%, 31% and 37% percentage of contaminations are presented in Figs. 7(a)-7(c) respectively. According to Fig. 6, when the percentage of contamination is less than 24%, the maximum stress (0.5 MPa), is obtained before the settlement reaches 5 mm.

As illustrated in Fig. 7(c), when the ballast is highly contaminated, the load-deformation characteristics of the ballast changes significantly; that is, the ballast settlement increases considerably. There are substantial changes in the ballast behavior when the ballast percentage of contamination is greater than 24%.

In accordance with DIN 18134 (2012), E_V was computed based on the parameters obtained from the curve fitted to the load-settlement curves. The curve fitted to the results is a second-degree polynomial (as suggested by DIN 18134 (2012)). It is presented hereunder.

$$S = a_0 + a_1\sigma_0 + a_2\sigma_0^2 \tag{1}$$

in which, S, σ_0 are the settlement of the loading plate and the average pressure below the plate, respectively. a_0, a_1 and a_2 are the constants of the second-degree polynomial. E_V was computed based on the following equation

$$E_V = \frac{1.5r}{a_1 + a_2\sigma_{\max}} \tag{2}$$

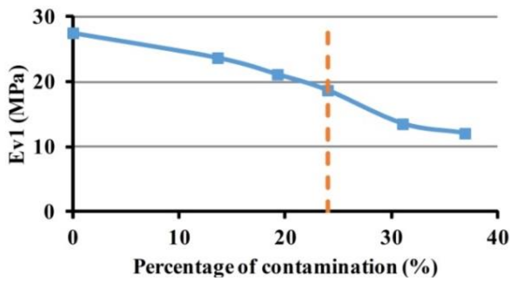
in which, E_V, r and σ_{max} are the strain modulus, the radius of the loading plate and the maximum average normal stress under the loading plate in the first cycle of loading, respectively. The results are presented in Table 5 and Fig. 8.

The results obtained indicate that, a_1 increases with increases in the sand dosages in the first cycle of loading; but when the percentage of contamination gets greater than 24%, a_1 decreases. According to the results, a_2 increases with increases in the sand dosages in the first cycle of loading. As the contamination percentages get greater than 24%, a considerably higher rate of increase in a_2 is observed.

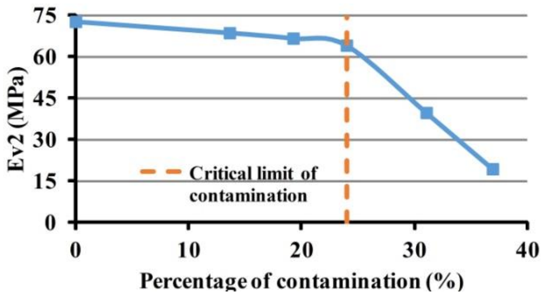
The trend of changes in a_1 in the second cycle of loading is approximately similar to those obtained for a_1 in the first cycle. In the second cycle of loading, a_2 reduces when the sand contamination increases in the range of 14%-24%. On

Table 5 The strain modulus of ballast samples in the 1st and 2nd cycle of loading

Percentage of contamination (%)	a_1 mm^3/N 1st cycle	a_2 mm^5/N^2 1st cycle	a_1 mm^3/N 2nd cycle	a_2 mm^5/N^2 2nd cycle	E_{V1} MPa	E_{V2} MPa	E_{V2}/E_{V1}
0	4.69	1.97	1.56	1.18	27.55	72.87	2.65
14	5.82	1.53	0.46	3.61	23.72	68.82	2.90
19	6.36	2.06	2.60	-0.52	21.16	66.83	3.16
24	6.67	3.37	3.74	-2.62	18.71	64.26	3.44
31	4.17	16.60	1.87	4.64	13.54	39.90	2.95
37	-23.80	108.02	3.64	12.79	12.71	29.31	2.31



(a) E_{V1}



(b) E_{V2}

Fig. 8 The strain modulus versus percentage of contamination in the (a) 1st cycle of loading and (b) 2nd cycle of loading the other hand, a_2 increases with increases in the percentage of the sand contamination, if it is more than 24% or less than 14%.

Based on Figs. 8(a) and 8(b), as the percentage of contamination increases, E_{V1} and E_{V2} are reduced considerably. This results obtained here confirm the findings of Tannakoon (2012) as he has shown that the ballast resilient modulus and stiffness decrease when the ballast gets contaminated. The considerable reductions in the strain modulus of the contaminated ballast are due to the sand filling the voids and covering the ballast aggregate surfaces. Ballast is cohesion-less material and its strength originated from the friction between aggregates; therefore, as the sand surrounds the aggregates the contact and interlocking between the ballast particles decreases. This causes increases in the ballast settlement and reductions in the bearing capacity. In this study, the bearing capacity is considered as the maximum load which ballast can sustain without significant settlements, assuming a flexible behavior for the ballast. The slope of the reductions (due to contamination) in E_{V2} is much more than those of E_{V1}. This difference is because of the nature of these two indicators. E_{V1} concerns with the density and the short term behavior of the ballast, whereas E_{V2} is related to the mid-long term behavior of the ballast (Paderno 2011). Because the density of the samples are the same, E_{V1} is influenced less by sand contamination when compared to E_{V2}. In the second cycle of loading, when the ballast is clean or the percentage of the contamination is low (less than 24%) frictional forces between the ballast aggregates increases because of the pre-compaction in the primary loading. As the percentage of contamination rises, frictional forces between the ballast aggregates is not increased because the sand percentages are large enough to prevent contact between the aggregates. Based on Fig. 8(b), mathematical expressions derived for E_{V2} as a function of the ballast percentages of contaminations (BPC). They are indicated in Eqs. (3a) and (3b).

$$E_{V2} = -0.35BPC + 73.1 \qquad BPC \geq 24\% \tag{3a}$$

$$E_{V2} = -2.7BPC + 128.1 \qquad BPC < 24\% \tag{3b}$$

Significant difference in the slope of E_{V2} expressions indicates considerable change in the behavior of the ballast when percentage of contamination becomes more than 24%. The ratio of E_{V2} to E_{V1} for various percentages of the contamination is presented in Fig. 9. This ratio is an indicator of the instability of the bearing capacity. When the ballast bearing capacity is not changed in time, this ratio approaches 1 (Paderno 2011). Based on the results presented in Fig. 9, as long as the increase in the percentage of the contamination is limited to 24%, by increasing the sand dosages, the instability of bearing capacity becomes more and the short term behavior of ballast differs significantly from that of the mid-long term. As the contamination percentage gets greater than 24%, the instability of the ballast decreases. It is worthwhile to mention that the descending trend in Fig. 9 is due to the sharp reduction of E_{V2} when the contamination is greater than 24% in one hand, and the change made in the maximum stress (σ_{max}) when the sand dosages exceed 24% on the other hand.

Since E_{V2} is more influenced with sand contamination

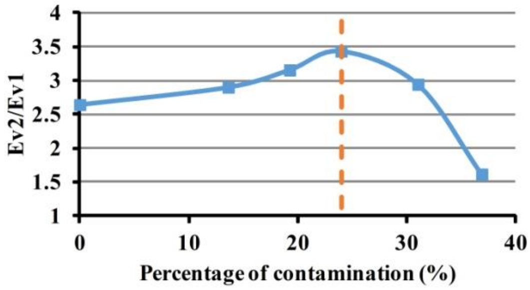


Fig. 9 E_{V2} to E_{V1} ratio versus percentage of contamination

(compared to E_{V1}), a descending trend is observed in Fig. 9 for contamination of greater than 24%. If the settlement become greater than 5 mm before the normal stress reaches 0.5 MPa, the stress obtained at the settlement of 5 mm must be taken as σ_{max} (DIN 18134 2012). For instance, when the percentage of contamination is less than 24%, the settlement is less than 5 mm and therefore, σ_{max} is 0.5 MPa. As the percentage of contamination exceeds 24%, the settlement is more than 5 mm and σ_{max} is less than 0.5 MPa. As σ_{max} decreases, the denominator of Eq. (2) reduces, and in turn, the rate of reduction in E_{V1} decreases. It causes reduction in the ratio of E_{V2} to E_{V1}.

As indicated in Fig. 8, the effects of sand contamination on the results (especially on E_{V2}) are not considerable when the percentage of the contamination is less than 24%. However, there is a significant drop in E_{V2} when the contamination becomes more than 24%. It indicates that 24% of contamination is a critical limit after which substantial decreases in the mechanical properties of ballast take place. For the contamination higher than 24%, the strength of sand governs the bearing capacity of the mixture of ballast and sand.

When the ballast is contaminated with higher degrees of sand (i.e., more than 24%), the ballast bearing capacity and stiffness are reduced considerably. This can cause substantial permanent ballast deformation and differential settlement of the track (i.e., large track geometry deviations which can cause derailments). Although sand contamination is combined with ballast breakage, sand infiltration has considerably more important role on the ballast contamination when compared to the aggregate breakage in the desert and sandy areas. Based on the available reports (Zakeri *et al.* 2011), the ballast gets sand-contaminated in the initial years (even months) of its operation in the sandy areas before a noticeable ballast breakage occurs. Therefore, particular attention should be paid to the ballast cleaning in the dessert areas particularly when there are frequent sand storms. It means that ballast maintenance should be planned based on the level of sand contaminations as a main maintenance criterion in these areas. For this purpose, 24% of ballast contamination should be considered as the critical limit before or at which maintenance/repair actions (such as ballast renewal or ballast cleaning) should be taken.

5. Conclusions

Significant parts of railway lines in most of the Middle

East and some of Asian countries pass through sandy deserts where railway tracks get considerably contaminated because of numerous sand storms. Despite a large number of railway derailments reported in the sandy areas, there is a lack of sufficient investigations on the effect of sand contamination on the strength and stiffness of the ballast. A review of the literature indicates that although the characteristics of the ballast contaminated with coal dust, clay or ballast breakage have been studied, the impacts of sand contamination on the ballast behavior have been rarely examined. Addressing this limitation, an extensive experimental study was made in this research, investigating the effects of sand contamination on the load-deformation characteristics of the ballast.

For this purpose, several static repetitive plate load tests were carried out on the clean and contaminated ballast with various percentage of sand-contamination (i.e., 14%, 19%, 24%, 31% and 37%). To minimize possible errors in the tests, two ballast samples were prepared and tested for each percentage of contamination. The results obtained for each sand dosage were averaged. The differences between the results obtained for each contamination condition were negligible, ensuring the repeatability of the tests. The testing procedure for clean ballast was validated by comparing the results obtained in this research with those available in the literature. Through analyses of the results, mathematical expressions were derived for the strain modulus in the second cycle of loading (E_{V2}) as a function of ballast levels of contamination. Considerable difference in the slope of E_{V2} expressions indicates an important change in the properties of the ballast when the percentage of contamination gets higher than 24%.

The results reveal that ballast contamination with sands leads to significant reductions in the bearing capacity of ballast materials. When the percentage of contamination reaches to 37%, the settlement and permanent deformation of the ballast increase and consequently the E_{V1} and the E_{V2} are reduced by 56% and 60% respectively. That is, the settlements of highly fouled samples in the first and second cycles of loading are 3.9 and 2.6 times greater than those of the clean sample.

It is found that the effects of the sand contamination on the ballast mechanical behavior (i.e, strain modulus) are not noticeable if the percentage of the contamination is less than 24%. However, there are substantial changes in the ballast behavior (such as a significant drop in the E_{V2}) as the contamination becomes greater than 24%. That is, it causes sharp decreases in the ballast bearing capacity and stiffness.

It was found that 24% of sand contamination is a critical limit after which the behavior and geotechnical characteristics of the ballast substantially influenced by the amount of sand. It is shown that contamination of 24% corresponds to the conditions in which sand completely fills up the ballast voids, and as a result, contact and friction between ballast aggregates reduces drastically. This can cause rapid deterioration of track stability conditions as large track geometry deviations (such as non-uniform vertical settlements of the rail along the track) occur. Sudden changes in track geometry (i.e., profile, alignment, and twist) cause unexpected derailments. The results obtained indicate that appropriate ballast maintenance actions (such as ballast renewal or ballast cleaning) should be taken if the percentage of ballast sand-contamination becomes more than 24%, in order to ensure the required level of track safety.

The sand contamination critical limits derived in this research should be considered as the main criterion in the maintenance of sand-contaminated railways. This helps railway industries to make optimum decisions on the railway maintenance required actions and timing.

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