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ORIGINAL PAPER

Study of Ballast Fouling in Railway Track Formations

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Abstract This article presents an overview (requirements) of rail track aggregates, the ballast gradation adopted in railways in different countries and their comparison with Indian ballast gradation, drainage of rail track and ballast fouling in India. Further in situ ballast sampling, testing and ballast fouling quantification are also presented for typical track ballast. Ten ballast samples were collected from in and around Bangalore, India and fouling values were estimated as per international procedures followed for determining the fouling indices. Results show that fouling values of station tracks increase with time. Non coal/ore transport tracks and track on firm sub grade experience moderate fouling due to the break down of ballast and naturally occurring materials like dust, dirt, soil, etc. Fouling indices are specific to fouling materials and gradations. In this study it was found that the existing fouling indices are unable to reflect the representative fouling values for Indian railway ballast studied, hence alternate fouling indices are suggested for Indian railway ballast gradation. The article also presents an overview of the recent advancements in the identification of subsurface rail track problems using geophysical methods and conventional track monitoring and cleaning. The Indian railway follows coarser ballast gradation and conventional procedure to identify the rail track subsurface problems. Many advanced methods need to be experimented in Indian rail tracks to modernize the railway track foundations for the fast transportation of goods and passengers.

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Introduction

Railways are massive transport systems, which carry large quantity of goods as well as passengers when compared to any other modes of transport system. The Indian railways is one of the largest of its kind in the world. Derailing of trains is routine and a major disaster in railways and this happens due to the change in alignment of rails and many other reasons. The geotechnical component of rail track i.e. ballast bed plays an important role in maintaining the gauge between sleepers and there by alignment of the rails. Defects in ballast bed may lead to settlements and deformation of ballast section, which in turn lead to misalignment of rails. The rail track is a layered foundation consisting of ballast followed by compacted sub ballast or a capping layer placed above the formation soil. Ballast is a coarse granular medium (usually hard rock ballast) placed above the sub ballast and below the rails. The loads from the sleepers are distributed to the sub ballast and compacted earth through the main ballast section. A rail ballast bed acts as the main foundation above the capping layers and performs many roles for the proper functioning of the railway network. Rail ballast is a uniformly-graded coarse aggregate produced from crushing locally available rocks such as granite, basalt, limestone, slag or gravel.

The efficiency of track foundation material gradually decreases due to insufficient lateral confinement, ballast fouling, and loss of shear strength of soil due to local liquefaction and clay pumping. A high lateral movement of ballast may occur due to the over limit of wheel load. Ballast contamination or the filling of voids due to ballast breakdown and infiltration of other materials from the ballast surface or infiltration from the base of the ballast layer is called ballast fouling. The fouling materials can be dust from surroundings, slurried (pumped) formation soil (soft clays and silts liquefied under saturated conditions) and coal from freight trains as well as ballast degradation (fine particles then migrating downwards). High maintenance costs in the railways are mainly due to the above geotechnical problems [12]. Finding a means of reducing the maintenance costs and reducing the frequency of regular repair cycles have been a priority for most of the railway organizations. Although the research conducted on geotechnical engineering particularly on sand and clay, road base and rock fills has been extensive, limited research has been conducted on geotechnical issues related to the rail track, particularly in India. Many researchers have indicated that a major portion of the track maintenance budget is spent on tamping, ballast cleaning and renewal operations [12]. If a scientific approach is followed with modern technology, the maintenance cost and frequency of the maintenance can be reduced to the maximum possible extent. Many countries are using modern techniques like ground penetrating radar (GPR) to evaluate the quality of ballast in track [2]. This article presents an overview of ballast gradation in Indian railways, collection of fouled ballast samples from selected tracks, fouling measurement. It also highlights the comparison of Indian railway ballast gradation with international gradation standards, track drainage and the recent advancement in the assessments of fouling and subsurface in the railway tracks.

Railway Ballast

The primary geotechnical component of a rail track foundation is the ballast section. Ballast performance depends on four major geotechnical properties (index and engineering) of ballast materials [12]: characteristics of the constituting particles (size, shape, surface roughness, particle crushing strength and resistance to attrition, etc.), bulk properties of the granular assembly (particular size distribution, void ratio or density and degree of saturation), loading characteristics (current state of stress, previous stress history and applied stress path) and particle degradation (combined effects of grain properties, aggregate characteristics and loading).

Kolbuszewski and Frederick [25] indicated that the angle of shearing resistance increases with large particle size. But Marachi et al. [27] and Indraratna et al. [13] presented experimental data to show that the angle of internal friction decreases with an increase in the maximum particle size and hence the drastic reduction in the friction component of the shear strength which can cause significant reduction in the load carrying ability. The main functions of the ballast layer are to control the stress intensity projected onto the weaker sub grade, to decrease the frequency of track maintenance by minimizing the track settlement and sleeper movement and to promote rapid drainage via the large pore structure [16].

Particle shape plays an important role in shear strength. Angularity of particles increases the frictional interlock between grains and thereby increases the shear strength. The angle of internal friction is remarkably high for angular aggregates when compared to the sub-rounded aggregates when compared to the sub-rounded aggregates [13, 11, 26, 34]. Surface roughness or texture is the key factor that governs the angle of internal friction. Raymond [29] concluded that the particle shape and surface roughness are important and influence the track stability. Most ballast specifications stipulate crushed or fractured particles, which are defined as grains having a minimum of three crushed faces [12]. In a way similar to index properties, engineering properties also play a major role in track stability. It is interesting to note that the ballast behavior given by different researchers is indigenous and contradicting and may not be directly applicable to the ballast of other countries. But the overall major problems of track stability, settlement and drainage problems are the result of ballast breakdown. Breakdown is dependent on ballast properties, gradation, load aspects, etc. When ballast breaks due to over load, repeated cyclic loading of train wheels, interaction with other particles and sleeper movement etc., the stress carrying capacity is reduced and hence the stress intensity projected onto the weaker sub grade is increased which results in the failure of the sub grade [15]. Volume of load carrying ballast is considerably reduced due to breakage and hence movement of sleeper takes place which causes discomforts to the passengers and the voids are filled due to the breakage and hence the drainage reduces which causes further more problems.

The settlement of ballast can be both elastic (such as the initial settlement due to the compaction of ballast) and plastic (due to breakage of ballast particles). As identified by Selig and Waters [31], settlement of ballast may not be a problem if it occurs uniformly along the length of the track. In fact, differential track settlement is more important than the total track settlement. The settlement behavior of ballast with different particle size distribution was investigated under cyclic loading by Indraratna et al. [14]. Indraratna et al. [14] highlighted that the moderately graded samples display least settlement, followed by the gap-graded specimens. Researchers are working around the world to optimize the railway ballast gradation in order to meet future requirements of heavy traffic and freight movements.

Universal Ballast Gradation

Ballast gradation is a primary factor affecting the stability, safety and drainage of tracks. A specified ballast gradation must provide the following two key objectives [12]: Ballast must have high shear strength to provide increased stability and minimum track deformation. This can be achieved by specifying broadly-graded (well graded) ballast and ballast must have high permeability to provide adequate drainage; this readily dissipates excess pore water pressures and increases the effective stress. This can be ensured by specifying uniformly graded ballast. These two objectives are different and require optimized particle distribution in addition to quality. The optimum ballast gradation needs a balance between uniform and broad gradations. Many countries have optimized ballast gradation through wide range of research studies. Indian railway ballast gradation is not much different from the East Indian rail company period ballast gradation. The presently followed Indian railway ballast gradations are specified in IRS-GE-1 [20]. The ballast gradation followed in American Railway Engineering and Maintenance of way Association [4] and Indian Railways is shown in Fig. 1 (U and L indicated in figures represent the upper and lower limit). It clearly shows that the least particle size used in American railways is 9.5 mm whereas it is 20 mm in the case of Indian railways. American railway gradations are relatively well graded when compared to Indian railway gradations. Figure 1 shows the ballast gradation followed by French railways and British railways [28] in comparison with Indian railways. French and Indian railways gradation curve is similar for more than 50 %. The gradations followed by British railways almost matches with the Indian Railways. Indian railway ballast gradation is perhaps comparable because Indian railway ballast gradations are older and are adapted from the East Indian Rail Company, without much modifications and research. French railway ballast gradation is coarser than Indian railway gradation and the minimum particle size of ballast used is 25 mm. Figure 1 also shows the upper and lower limit gradation followed in Australian (AU) railways [5] and Indian railways. About 70 % Indian railway lower limit gradation curves match with the upper limit of the AU railway gradation curve. About 70–40 % Indian railway gradation lower limit curves are in between the upper and lower limit gradation curves of the AU railway. Less than 40 % lower gradation and 20 % upper limit gradation curves of Indian railways match with the lower limit gradation curve of the AU railways. The upper limit of the Indian railway gradation curve closely matches with the lower limit of AU railway gradation curve. The upper and lower limits of Indian railway gradations are very narrow and poorly graded. From Fig. 1, it is very clear that in Indian railways the upper and lower gradation curves are in a narrow band and have a larger particle size, which are poorly graded when compared to American and Australian railways. This means that Indian railway gradations fulfill the drainage criteria, but may not be more favorable for stability and settlement criteria. Poor gradation leads to the misalignment of sleepers and rails, reduces the bearing capacity of the track and increases the settlement. This can create track instability and other consequences. They are the major cause of the derailing of trains, and discomfort to passengers. Indraratna and Salim [12] suggested modified gradations to Australian railways considering settlement and breakage of ballast without a compromise on the drainage requirement based on research carried out in the large scale cyclic triaxial equipment. Figure 1 shows the modified

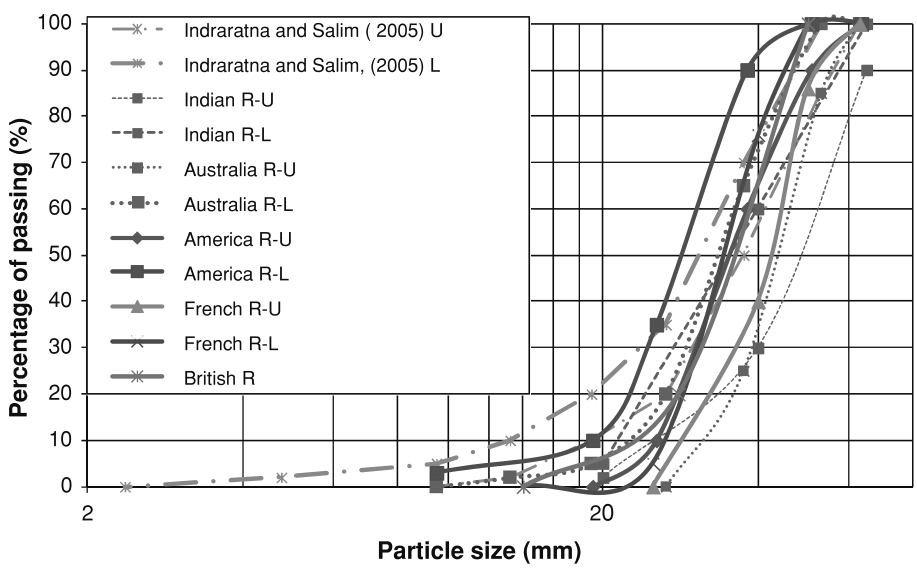

Fig. 1 Ballast gradation followed in India, American, French, British and Australia railways with [12] modified gradation for Australia. *Note* R–U and R–L is railway upper and lower ballast gradation

gradation curve by Indraratna and Salim [12] and upper and lower limit gradations followed in India and Australian railways. Lower limit gradation curve of the Indian railway closely matches with 80 % of the upper limit of the modified gradation of AU railways. Comparing Indian railway ballast gradation with international ballast gradation clearly shows that Indian Railway ballast is poorly graded. Poor gradation of ballast leads to excess of certain particles and deficiency of other. This leads to the movement of the ballast particles under loading and results a poorly packed section. Literature shows that more voids and movement of particles can cause breakage of particles. Hence Indian railway ballast is more likely to undergo breakage as compared to other ballast gradations.

Indian railway ballast standards do not address the requirements of bulk density and particle density for the rail ballast. The Australian standard [5] specifies that the bulk density of ballast material shall not be less than 1,200 kg/m^3 and that the particle density on a dry basis of ballast material shall not be less than 2,500 kg/m^3. In order to ensure the stability of the track and the quality of the ballast, bulk density and particle densities are very important and therefore similar parameters can be included in the Indian railway ballast standard of IRS-GE-1 [20]. The durability of ballast is usually assessed by the aggregate crushing value (ACV), wet attrition values, wet/dry strength variations and Los Angeles values in America, Australia and British railways. Indian railway ballast standard of IRS-GE-1 [20] specifies the requirements of aggregate abrasion value, water absorption and impact values. The impact value of ballast for Indian railways has to be determined in accordance with IS 2386 part IV, 1963 [22]. This test is similar to the ACV test followed by other countries. This test should be carried out for the maximum and minimum particle size of 12.5 mm and 10 mm respectively. IS 2386, part IV (1963) is basically for the testing of small aggregates used for concrete. Indian railways are using this test as a standard for railway ballast requirements. The samples are prepared to the required size as per IS 2386 by crushing the ballast and are used without any modifications in the test procedures and instruments. The literature shows that the size of the particles and the testing method influence the impact value and crushing values of the testing materials. Hence, using the standards IS 2386 part IV, 1963 [22] developed for concrete aggregates without any modification may not be appropriate for railway ballast. After selecting the appropriate ballast considering aggregate properties and suitable gradation, performance of the track ballast can reduce due to another major problem called ballast fouling. Summary of ballast fouling quantification, in situ ballast sampling and fouling estimations are presented in the following sections.

Drainage of Ballast Sections

One of the main factors that determine the safety and stability of a track structure is drainage. Drainage is typically defined as the interception, collection and subsequent disposal of water away from the rail track [10]. It plays a major role in track maintenance and stability which is evident by the saturated track condition that is created in the event of an inefficient drainage. Subsequently it results in plastic strain accumulation, decrease in stiffness, decrease in strength and increase in settlement due to the excess pore water pressure under train loading [31, 17]. This needs for a quick and efficient drainage system, most importantly the quick disposal of water from the formation top/slopes of the track.

One of the major requirements for efficient track maintenance is the presence of ballast that is fairly permeable to drain water and maintain dry condition. Various guidelines issued by Research Development and Standard Organization (RDSO) suggest the same [10]. Clean ballast can have free drainage. However, the free drainage path gets blocked in fouled ballast section starts holding the water because of the fines that have accumulated with the clean ballast. The amount of moisture and blocking also increases considerably if the degree of fouling is more in the rail track section. The ideal ballast is a poorly graded or uniformly graded aggregate with a particle size in the region of 20–50 mm giving high void ratio [24]. Due to fouling there is considerable change in the gradation of the track section leading to the reduction of the permeability of the track. The permeability of fouled ballast less than 10^{-4} m/s is considered unacceptable based on Selig and Waters [31] and Anbazhagan et al. [1].

Anbazhagan et al. [3, 1] used ballast fouled with clayey sand and coal to demonstrate the variation in shear strength and permeability with the percentage of fouling. As the fouling of the track bed increased, the shear wave velocity also increased and the overall ballast permeability decreased rapidly before approaching optimum fouling point (OFP). Following OFP the permeability decreased marginally. The shear wave velocity of fouled ballast decreased less than the clean ballast when permeability was approaching 10^{-4} m/s for ballast fouled with clayey sand and coal. This point is defined as Critical Fouling Point, beyond which track maintenance becomes necessary [3, 1]. Change in gradation due to the breakage and reduction of permeability are the functions of fouling materials, subsurface condition and other factors. Hence it can be concluded that a good drainage condition should be maintained within the ballast to ensure acceptable track performance.

Ballast Fouling

Ballast contamination or the filling of voids due to ballast breakdown and infiltration of other materials from the ballast surface or infiltration from the base of the ballast layer is called ballast fouling. Possible factors for ballast fouling are breakdown of ballast due to mechanical forces, ballast degradation (fine particles that migrate downwards), coal/iron ore from the railcars, dust from surroundings-naturally occurring: dust, dirt, plant life decay etc., traction sand-slurried (pumped) formation soil (soft clays and silts liquefied under saturated conditions), brake shoe dust, diesel soot and rail road maintenance practices. Figure 2 shows typical fouling process and fouled ballast sections of the rail track. Fine ballast due to breakdown of ballast and fines from railcars migrates from top to bottom as shown in Fig. 2a. In this case subgrade will be hard and all fines will be accumulated in the base of ballast layer as shown by the arrow where less fines in the top are indicated in light color and more fines at the bottom indicated in dark color. If rail track has soft soil subgrade then the fouling takes place from top as well as from bottom as shown in Fig. 2b. In this case the rate of fouling and amount of fouling will be much more than the previous case and also this is the worst fouling condition. Figure 2b is also a typical section of highly fouled track due to mud pumping from the soft soil subgrade. Ballast fouling can cause reduction in resistance to the vertical (including uplift), lateral and longitudinal forces applied to the sleepers to retain the track in its required position, decrease in resiliency modulus/strength and energy absorption capacity, reduction in the voids there by leading to a considerable decrease in the movement of particles through the ballast, poor drainage of water falling onto the track, vegetation growth in the rail track, increase in noise level, inadequate electrical resistance between rails [3, 12]. Therefore it is mandatory to identify the degree of fouling and to remove the fine materials before resulting in a decrease in the performance of the rail track and other severe problems. Quantification of ballast fouling is a unique problem in geotechnical engineering because of two similar and/or dissimilar materials are evaluated and represented in single value. Detailed classification scheme is available for most of the geotechnical materials. But limited classification scheme is available for two dissimilar materials combination, which is a case for most of the ballast fouling. Ballast fouling results due to mixing of two distinct materials having large variation in particle size, particle shape and specific gravity. In order to evaluate ballast fouling there are several fouling scales presented by different researchers worldwide in compatible with their country's track conditions. Summary of these scales are presented below:

Fouling conditions are measured using five methods which are fouling index, percentage of fouling, D-bar method, effective degree of fouling, percentage void contamination and relative ballast fouling ratio. The first four measures are commonly used, the fifth one is used by Queensland Railways and sixth one is recently developed [1, 18]. These methods are laboratory based and require field sampling and testing, which are normally carried out by digging trenches with even spacing.

Fouling Index

Selig and Waters [31] considered clay pumping and the infiltration of the foreign materials as the other major sources of fouling. Foreign material penetrating into the ballast from the surface can include objects delivered with the ballast, dropped from trains, or wind and water blown matter. They have proposed quantification of fouling in terms of fouling index (FI)

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

where $P_{0.075}$ and $P_{4.75}$ are percent by weight of ballast sample passing 0.075 mm sieve and 4.75 mm.

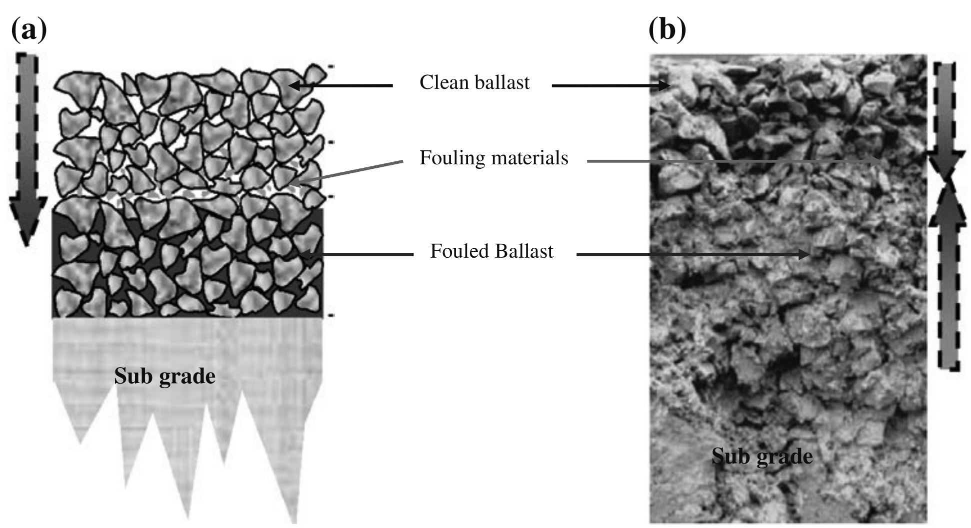

Fig. 2 Typical fouled ballast sections. **a** Fouling due to migration from top and **b** fouling due to infiltration from the base and migration from top

North American railway systems use typical ballast sizes ranging from 4.75 to 51 mm. However, Australian railways [5, 33] uses ballast sizes varying from 13.2 to 63 mm. Thus fouling index defined in equation above needs to be modified to suit the Australian railways track condition. Hence, Ionescu [19] had proposed a new ballast fouling index as follows

$$FI_p = P_{0.075} + P_{13.2} \tag{2}$$

where $P_{13.2}$ is percent by weight of ballast sample passing 13.2 mm sieve.

Ionescu [19] has also suggested use of more practical ballast fouling index given as below:

$$FI_D = \frac{D_{90}}{D_{10}} \tag{3}$$

where D_{90} and D_{10} grain diameter corresponding to 90 % passing by weight and 10 % passing by weight respectively.

Percentage of Fouling (% fouling)

Selig and Waters [31] also stated the percentage fouling to be obtained as the ratio of dry weight of material passing 9.5 mm sieve to the dry weight of total sample. Both the methods calculate the ballast fouling based on mass calculation in the sieve analysis.

The percentage of fouling and fouling index are based on mass calculations in the sieve analysis and thus do not consider the relative densities of fouling material and ballast. When fouling material and ballast have different unit weights, then the above indices does not represent the correct volume or quantity of fouling materials with respect to ballast. Hence Feldman and Nissen [9] proposed new test method i.e. percentage void contamination (PVC).

Percentage Void Contamination (PVC)

Feldman and Nissen [9] defined PVC as the ratio of volume of voids in ballast to the volume of contaminates present in the ballast (fouling materials). It is measured in percentage.

$$\text{PVC} = \frac{V_2}{V_1} \times 100 \tag{4}$$

here V_2 = volume of voids in the ballast and V_1 = volume of contaminants in the ballast.

Although the PVC method is a direct measure of percentage of voids occupied by fouling particles, the measurement of volume is time consuming. Furthermore, as the bulk volume of fouling particles is used, the gradation of fouling particles cannot be taken into account. For example, if the contaminates are all composed of coarse particles (4.75–9.5 mm) there should still be sufficient voids between the fouling particles, hence the Ballast drainage capacity would not be significantly reduced. In this regard PVC may overestimate the extent of fouling. Anbazhagan et al. [1] and Indraratna et al. [18] have suggested the use of the solid volume of fouling particles rather than the bulk volume in calculating the PVC. By using the solid volume, smaller value of PVC will be obtained if there is an insufficient quantity of fine particles within contaminates, and vice versa.

Relative Ballast Fouling Ratio ($R_{b\text{-}f}$)

Relative ballast fouling developed by Anbazhagan et al. [1] and Indraratna et al. [18] is defined as the ratio of the dry weight of fouling particles (passing 9.5 mm sieve) to the dry weight of ballast (particle retaining on 9.5 mm sieve). It is calculated by using the formula given in Eq. 5.

$$R_{b-f} = \frac{M_f \times \frac{G_{S-b}}{G_{S-f}}}{M_b} \times 100\% \tag{5}$$

where M_f and $G_{S\text{-}f}$ are the mass and the specific gravity of ballast fouling (fines), M_b and $G_{S\text{-}b}$ are the mass and specific gravity of ballast. In this, only the mass and specific gravity of the ballast as well as fouled material need to be measured. Authors' claim that $R_{b\text{-}f}$ will greatly speed up the measurements compared to the PVC method and hence will be more attractive to the practicing track engineer. However limited experimental evidence has been given to strengthen their findings.

In Situ Sampling

Clean Ballast placed in the rail track is fouled because of several reasons as discussed above, but its quantification is not universal. Several consequences are frequently reported in Indian railway due to ballast fouling, but very limited attempt has been made to scientifically understand the same. The old track ballast is periodically cleaned in Indian rail tracks. But cleaning interval is constant for particular type of track and is not based on quantified fouling values. Indian Railway field engineers report reveals that old track are widely cleaned once in 10 years irrespective of the track condition and also there are few tracks not cleaned for more than 15 years. Limited attempt is made to decide the cleaning interval by considering the scientific research. Many advanced technologies are followed in other countries to identify the ballast fouling and prioritize the maintenance cycles. In order to understand ballast fouling in Indian tracks, in this study an attempt has been made to collect the field fouled ballast samples and the fouling content have been estimated by carrying out laboratory experiments. Necessary permission was obtained from railway authority to collect the samples. The in situ samples were collected at the locations where technical feasibility and safety existed. Fouled ballast samples were collected from Whitefield railway station (WHFR) and Yeshwanthpur railway station (YPR) in Bangalore, Karnataka, India. Total 5 samples were collected from each station with approximate quantity of about 15 kg. Among these 10 samples, one sample was collected from the relatively new track i.e. fresh ballast.

The Whitefield samples from the actively running railway track route from Bangalore to Chennai and the sampled location was about 30 km from Bangalore city towards Kollure. These track routes are about 150 year old and are high traffic routes because of frequent passengers and goods railcars. The samples collected from Yeshwanthpur are from the tracks within the station operating limit. The trains are operated with limited speed in these station tracks. In order to capture the actual status of fouling in the field, high resolution photos are captured at each location and selected photos are presented in Fig. 3. Figure 3a, b shows the fouling status of Yashwanthpur tracks. It can be observed from Fig. 3a, b that YPR station tracks are fouled by brake shoe dust, diesel soot and dust from surroundings-naturally occurring: dust, and dirt, etc. The last cleaning or replacement period in years (approximate age of track) of each sample at YPR were gathered from the railway staff during sampling. Aggregate particles at YPR were having smoothed surface and no breakage of particle was found. Figure 3c, d, e show the fouling status of the tracks in the Whitefield station limit. Photos clearly show that these tracks are fouled by break down ballast and surroundings-naturally occurring: dust, dirt, soil, etc. It is observed that the ballast samples close to rail sleepers (Fig. 3c, d) fouled by many angular broken aggregates and samples from centre of the track fouled by soil and surroundings naturally occurring dust (Fig. 3e). Station (Yeshwanthpur) tracks lines were having less fouling materials when compared to the main line tracks (Whitefield). Standard procedures are available for collection of field samples for fouling estimation outside India. No such standardized procedure is available and/or followed in India. In this study field samples are collected manually, stored in empty cement bags and transported to geotechnical laboratory, Indian Institute of Science, Bangalore for further laboratory tests.

Laboratory Testing

All samples were air dried in the laboratory and the necessary tests like sieve analysis and specific gravity tests were carried out to estimate the fouling content. The samples were graded according to the IS 2386 (Part I) [21] and IS2720 (Part I) [23]. The sieves used were 63, 53, 37.5, 26.5, 19, 13.2, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.212, 0.150 and 0.075 mm. Grain size distribution of each samples are estimated and presented in Figs. 4 and 5. Figure 4 shows the grain size distribution of fouled and fresh ballast collected from YPR station and these samples are collected from the centre of the track. Among YPR samples, YPRS1 is the fresh and clean ballast from recently constructed track. Particle size distribution shows that more than 70 % particle distribution matches with the Indian railway ballast standard of IRS-GE-1 [20], but the lower portion of the particle size of the gradation is coarser than the standard upper and lower limit boundary. Approximate ages of collected fouled samples are gathered from the railway staff in the station. Sample YPRS2 is from 2 year old track, YPRS3 and YPRS4 are from the three and 5 year old tracks. Particle size distribution curve of these samples reveal that fines are increasing with increase in age of the track. Similar fouling materials were found in all the samples and fine contents are increasing with respect to time. Age of YPRS5 samples is not known but it can be inferred from the above results that this track is relatively new and age may be less than 1 year. Particle size distribution of Whitefield station samples are shown in Fig. 5. Samples are collected from same track line, this means that the age of sample is same and collection locations are different. Ballast samples of WHFS2–WHFS5 are collected close to the sleepers and WHFS1 is collected from centre of the track. Figure 5 shows that all samples are having fines (size less than 20 mm) of about 15 % of total material collected. Difference in fouling material particle size can also be observed in Fig. 5. Broken aggregates with less soil size particles are noticed in WHFS2-WHFS5 from the photos in Fig. 3c, d and more soil size particle and less broken aggregate are noticed in the photo in Fig. 3e for WHFS1. Among 15 % fine materials, more than 13 % of the materials are having size 4.75 to 20 mm in WHFS2-WHFS5 and these are broken aggregates due to heavy rail traffic load. More soil size particles are noticed in WHFS1 when compared to the other samples from the same track. Coefficient of uniformity (Cu) and coefficient of curvature (Cc) are estimated from the particle size distribution curves for each sample. The Cu values for all the samples were found to be less than 4 and the Cc values for all the samples were found to be in the range of 1–3 and hence all the samples used for the tests were poorly graded gravel (GP). Fouling content of each sample is estimated and are presented in next section.

Indian Railway Ballast Fouling

Several fouling scales are followed by different countries. Particular fouling scale should be used based on type of the fouling materials. Mass based fouling scales are suitable for fouling martial having comparable specific gravity values with ballast. Volume based fouling scales are suitable for fouling material having different specific gravity values

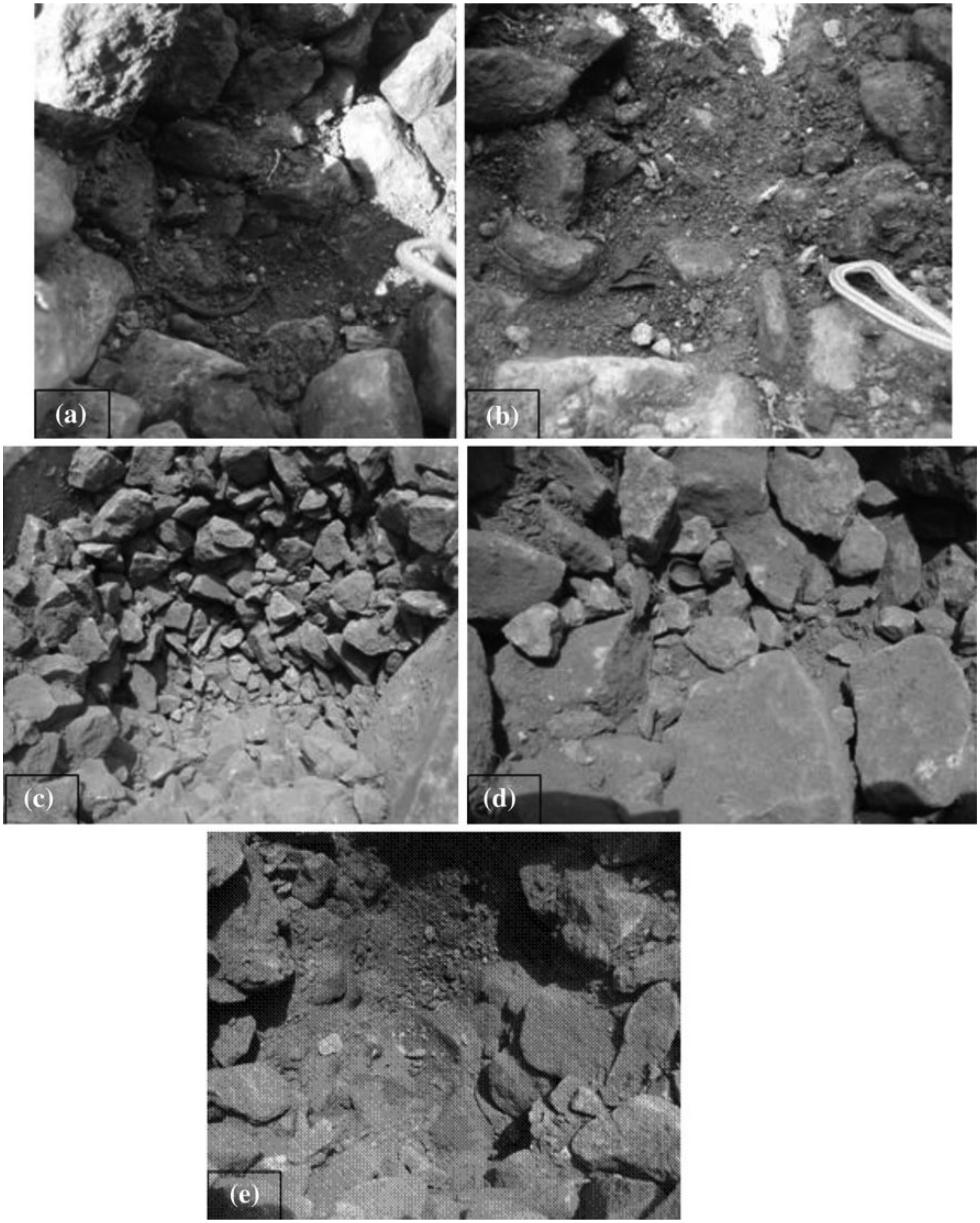

Fig. 3 Typical fouled sections of rail track where filed samples were collected. **a**, **b** Photo from Yashwanthpur railway station (YPR) and **c–e** photo from Whitefield railway station

with ballast. Even though Anbazhagan et al. [1] and Indraratna et al. [18] discussed these differences, but more experimental investigations are needed to compare different fouling scales with various fouling materials. This study is limited to fouling content estimation considering mass based methods. Because percentage void contamination and relative ballast fouling ratio require standard apparatus and these apparatus are not readily available right now. Fouling indices and percentage of fouling has been estimated for all samples and are given in Table 1. The range of fouling values used to classify fouled ballast track are given in Table 2. Fouling index of all the ten samples are given in

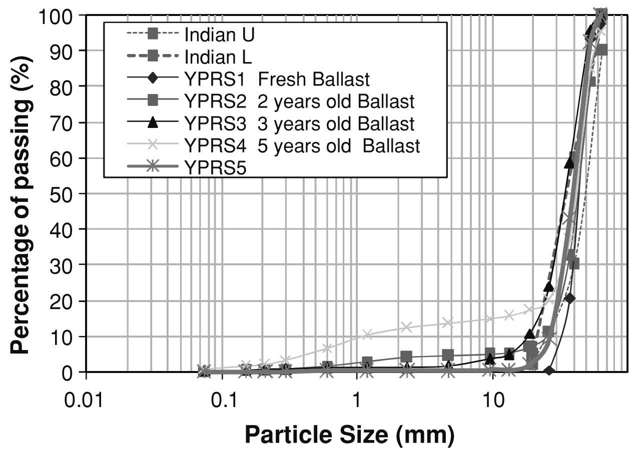

Fig. 4 Grain size distribution curves of the samples collected from Yashwanthpur railway station (YPR) with upper and lower limit specified by the Indian railways

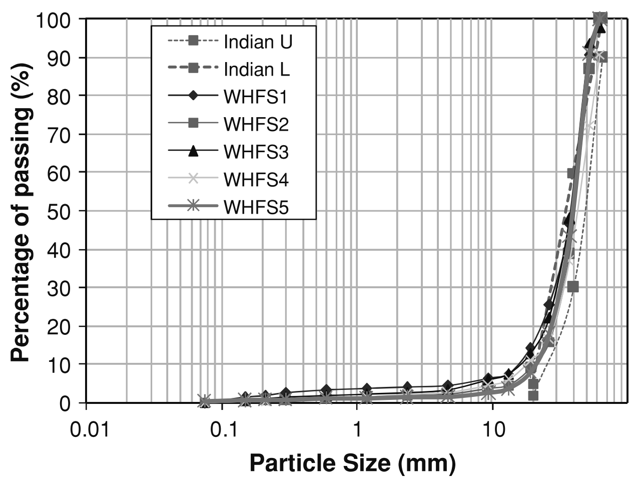

Fig. 5 Grain size distribution curves of the samples collected from Whitefield railway station (WHF) with upper and lower limit specified by the Indian railways

column 2 of Table 1 as per Eq. 1 given by Selig and Waters [31]. YPRS1 and 5 are classified as clean ballast and other samples are classified as moderately clean ballast except YPRS4 as per row 1 in Table 2. The YPRS4 sample having a fouling index value of 14.41, can be classified as moderately fouled ballast. These fouling indices are considered for the particle size of 4.75 mm and 0.075 mm as by Selig and Waters [31]. These fouling index values are changed considerably (column 3 in Table 1) when larger particle size of 4.75 mm changed to 13.2 mm as per Eq. 2 given by Ionescu [19]. Ballast fouling classification remains same as per row 2 in Table 2. Practical ballast fouling index values (FI_D) estimated considering diameter of 90 % and 10 % passing as per Eq. 3 by Ionescu [19] is given in column 5 of Table 1. It can be noted here that when 10 % passing particle size are relatively larger then FI_D gives classification (row 3 in Table 2) similar to FI discussed earlier. FI_D value for YPRS4 is more than 58 and this sample cannot be classified as highly fouled because of mismatching of other criteria. This sample may not be classifiable as per row 3 in Table 2. Percentage fouling is estimated for all samples by taking the ratio of dry weight of material passing 9.5 mm sieve to the dry weight of total sample as per Selig and Waters [31]. Percentages fouling for Indian samples are given in column 6 of Table 1. These samples can be classified as per row 4 in Table 2 and all sample classifications are similar to other classification except YPRS2 and 4. YPRS2 sample is classified as moderately clean ballast as per fouling index but the same sample can be classified as a moderately fouled ballast as per percentage of fouling. Similarly YPRS4 sample can be classified as moderately clean as per percentage of fouling and moderately fouled as per Fouling index. This highlights need for comprehensive study of ballast fouling scales and classification scheme. This study clearly shows that Indian track ballast samples are fouled because of several reasons. Samples collected for this study are from the station and non coal/ore transport lines with firm sub grade. Fouling values may be more if samples are collected from coal/ore transport lines and/or soft soil sub grade lines. More studies may be carried out on these tracks to understand complete fouling status.

Fouling Indices for Indian Railway Ballast

Fouling indices and percentage of fouling were developed in North America and Australia based on the ballast gradation and fouling material used in their region. For the same Indian railway fouled ballast sample different fouling values are noticed in Table 1. Selig and Waters [31] and Ionescu [19] have developed fouling index and percentage of fouling considering the least particle size in the recommended ballast gradation. This might be the reason for getting different fouling values for the same sample. Moreover Indian railway ballast has the least particle size of 20 mm and which is much larger than North America's and Australia's least particle size. But, fouling index and the percentage of fouling are estimated and classified as per Selig and Waters [31] and Ionescu [19] for initial understanding and are not directly applicable to the Indian railway ballast because these scales giving different fouling values for the same sample. To propose fouling scale and classification for Indian railway ballast, a detailed study need to be carried out considering the bearing capacity and permeability on fouled ballast. This needs sophisticated laboratory setup and huge amount of materials and man power. As an initial attempt, alternate fouling index and percentage of fouling are defined for Indian railway ballast based on this study and considering the particle size similar to Selig and Waters [31] and Ionescu [19] approach. Indian

Table 1 Fouling values for Indian fouled ballast samples

Samples	Fouling index (FI)			FI_D	Percentage fouling	
	[31]	Lonescu (2004)	Indian track	[19]	[31]	Indian track
YPRS1	0	0	0	1.65	0	0
YPRS2	4.55	5.60	7.18	2.15	15.07	17.25
YPRS3	1.87	5.09	11.20	2.78	3.52	10.92
YPRS4	14.41	16.59	18.16	58	4.98	7.082
YPRS5	0.29	0.59	2.1	1.82	0.59	2.10
WHFS1	4.46	7.60	14.15	3.19	6.68	14.57
WHFS2	2.25	4.66	8.92	2.52	3.92	9.21
WHFS3	3.32	7.45	12.83	3.16	6.31	13.19
WHFS4	2.65	5.80	10.77	3.94	4.78	11.05
WHFS5	1.83	3.87	8.17	2.43	2.54	7.91

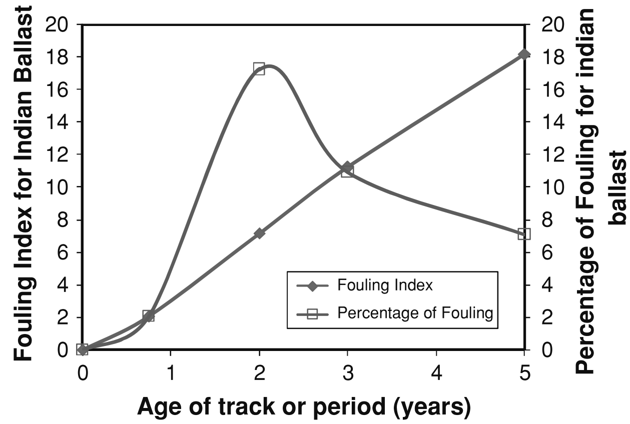

Fig. 6 Fouling index and percentage of fouling versus age of track for samples collected in this study

railway ballast fouling index may be calculated using the relation (6).

$$FI_{IN} = P_{0.075} + P_{20} \quad (6)$$

where $P_{0.075}$ and P_{20} are percent by weight of ballast sample passing 0.075 mm sieve and 20 mm sieve respectively.

Percentage of Fouling of Indian railway ballast may be estimated by taking the ratio of dry weight of material passing 20 mm sieve to the dry weight of total sample. As per Indian railway ballast gradation any ballast having size less than 20 mm may be treated as fines. Fouling index and percentage of fouling as per Indian railway ballast gradation has been estimated and given in column 4 and 7 of Table 1. These values represent full gradation curve and values that concur with the qualitative field observation and age of the track. Indian railway ballast fouling index (FI_{IN}) increases with the increase in the age of track. Based on FI_{IN} values it is assumed that YPRS5 sample is about less than a year (about 9 months) old track. Figure 6 shows Indian railway ballast fouling index versus ages of track based on five samples collected from Yeshwanthpur station tracks. Percentage of fouling versus age of track is also shown in Fig. 6. It can be observed that no trend has been observed between percentage of fouling and age. With limited samples and fouling materials it is difficult to propose fouling classification suitable to Indian track. Even though proposed definition for fouling index and percentage fouling formula for Indian track is relatively comparable with Selig and Waters [31] and Ionescu [19] definition. But it is not enough to accurately define the fouling status of Indian track because the aggregates in the range of 4.75 to 20 mm will have good permeability and bearing capacity. More research is needed to precisely define the fouling scale and classification system for Indian rail ballast by accounting the bearing capacity, settlement and permeability.

Track Maintenance and Recent Advancement

The foundation of rail tracks deforms vertically and laterally under cyclic wheel loads causing a deviation from the design geometry. Even though the deviations are apparently small, but they are irregular and are based on the geotechnical properties of the track foundation, which in turn further effects track alignment and stability. Worldwide rail track maintenance is a costly and routine exercise. A major portion of the maintenance budget is being spent on geotechnical problems [30, 32, 13]. Maintenance is mandatory because of ballast fouling and the weakening of track

Table 2 Fouling status of track ballast based on fouling values

Fouling quantity with reference	Clean	Moderately clean	Moderately fouled	Fouled	Highly fouled
FI [31]	<1	1 to <10	10 to <20	20 to <40	≥40
FI [19]	<2	2 to <10	10 to <20	20 to <40	≥45
FI_D [19]	<2.1 and $P_{13.2}$ ≤1.5 %	2.1 to <4	4 to <9.5	9.5 to <40	≥40, $P_{13.2}$ ≥40 %, $P_{0.075}$ >5 %
Percentage of fouling [1]	<2	2 to <9.5	9.5 to <17.5	17.5 to <34	≥34

subsurface layers (sub ballast and sub grade). Ballast cleaning and renewal is an expensive and time-consuming process which is also highly disruptive to train traffic. Thus, the need for this process must be considered carefully. Basically ballast cleaning and renewal is required when the ballast becomes extremely fouled that it cannot fulfill its functions. Many modern non-destructive tests such as ground penetration radar (GPR), infra-red imaging, seismic surveys and electrical resistivity are widely used for identifying fouling in the field [1, 2]. Most of the GPR testing was carried out on actual railway lines [6, 7, 8]. There are a lot of uncertainties within the actual rail track and it is difficult to calibrate the GPR data with actual ground condition because of limited number of trenches and time constraint. Anbazhagan et al. [2] carried out GPR survey on model track and field track using 500 MHz, 800 MHz, 1.6 GHz and 2.3 GHz ground coupled antenna and concluded that 800 MHz antenna gives relatively comparable results. Most of these GPR results are dependent on a visual interpretation and are qualitative in nature. However, a railway engineer still needs quantitative numbers to establish an appropriate design and maintenance program. GPR can be used to obtain the information on fouling depth but it cannot clearly define the degree or type of fouling. In order to address this issue. Anbazhagan et al. [1] and [3] carried out seismic survey on model and field track and defined optimum fouling and critical fouling point based on the shear wave velocity measured in different fouled samples. Authors observed that the shear wave velocity of clean ballast is increasing due to the addition fouling particles and reach peak and then decrease below the value of clean ballast. Two degree of fouling points has been defined, degree of fouling corresponding to peak SWV which is defined as the optimum fouling point and degree of fouling at which SWV of the fouled ballast equals the SWV of clean ballast which is defined as the critical fouling point. Variation of SWV with degree of fouling is similar to the typical compaction curve of soil. SWV of fouled ballast after reaching optimum fouling point decreases irrespective of fouling materials.

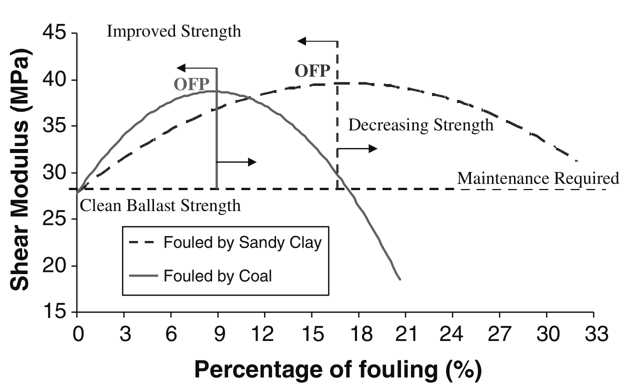

Fig. 7 Typical variation of shear modulus with percentage of fouling

Figure 7 shows typical variation of shear modulus of fouled ballast with different percentages of fouling for coal fouled and clayey sand fouled ballast. This unified plot can be used to define critical and optimum fouling points. More details about the critical and optimum fouling point (OFP) with the permeability of track foundation are given by Anbazhagan et al., [1, 3]. Modern geophysical methods are used in identification of track problems and ballast fouling for effective maintenance in foreign railways. They found that these kinds of testing are more effective and less time consuming. Modern scientific knowledge can be adopted to deduct ballast fouling and monitor subsurface condition for the effective maintenance in developing countries like India.

Discussions

Railway ballast used in Indian track has been studied and compared with international ballast gradations. American railway engineering and maintenance association [4] uses the minimum ballast size of 9.5 mm and Indian railway uses minimum ballast size of 20 mm. American railway ballast is relatively well graded when compared to Indian railway ballast gradation. The ballast gradation followed by French railways and Indian railways are about 50 % similar, the minimum size used by French railways 25 mm. The gradation followed by British railways [28] almost matches with the Indian railways. Indraratna and Salim [12] suggested modified gradation to Australian railways based on a cyclic triaxial test considering settlement and breakage of ballast without a compromise on the drainage requirement. The Indian railways use poorly graded ballast when compared to the American and Australian railways. This means that Indian railways gradation fulfils the drainage criteria, but may not be favorable for stability and settlement criteria. Poor gradation is more favorable for breakage and results in ballast fouling. Hence poor gradation leads to the misalignment of sleepers and rails, reduces the bearing capacity of the track and increases the settlement. This can create track instability and other consequences. Ballast fouling is one of the major causes for derailing of trains, and causes discomfort to passengers. Indian railway gradation can be modified by research, considering the breakage of ballast, settlement, stability and drainage of the track. Indian railway ballast standards do not mention anything about the requirement of bulk density and particle density for rail ballast. The Australian standards [5] specify that the bulk density of ballast material shall not be less than 1,200 kg/m^3 and particle density of ballast material shall not be less than 2,500 kg/m^3. In order to ensure the stability of the track and quality of the ballast, bulk density and particle density are very important ant therefore similar parameters can be included in the Indian railway ballast standards of [20].

Fouling tests are conducted on ten samples collected from Indian rail tracks and classified as per Fouling values given by Selig and Waters [31] and Ionescu [19]. However these values are not directly applicable to Indian railway ballast because of the difference in the least particle sizes. Alternate fouling indices are recommended in this study. These indices need to be validated with many experimental studies by considering bearing capacity and permeability.

Summary

This study reviewed ballast gradation followed in India and other few countries. Study shows that the ballast gradation followed by the Indian railways is poorly graded and more favorable for drainage. Ten ballast samples collected from the field track shows that the fouling of studied track increases with time. Fouling indices are specific to the ballast gradation and type of fouling materials. Fouling values are estimated considering existing fouling scale and further new fouling indices are suggested in this study based Indian railway ballast gradation. More experimental research are needed to define the suitable fouling indices and fouling classification scheme for Indian track by considering different fouling materials. The inspection of track foundations and the maintenance followed in Indian railways are conventional and the cleaning of ballast is once in 10 years irrespective of the amount and type of fouling. Advanced geophysical methods such as seismic survey and ground penetration radar can be utilized to identify the ballast fouling and sub grade evaluation.

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