Survey of Railway Ballast Selection and Aspects of Modelling Techniques

Master Degree Project

Abateneh Yitayew Alemu

Division of Highway and Railway Engineering
Department of Transport Science
School of Architecture and the Built Environment
Royal Institute of Technology
SE-100 44 Stockholm

TRITA-VBT 11:18
ISSN 1650-867X
ISRN KTH/VBT-11/18-SE
Stockholm 2011
To My Parents Yitayew Alemu & Tebeyin Mebrate
Abstract

Previously great attention has been given for the quality of the track super structure to improve the overall performance of the railway. Frequent research on the track supporting materials shows a good result which improves the existing overall performance. Good ride quality with high speed, minimum initial construction capital, long life service and low maintenance cost are the issue on the railway technology. Ballast is one of the determinant parts of the railway structure which has great influence on the performance of the railway track.

The aim of this project is to assess the different aspects which affect the overall performance on the ballast structure, its material characterization, gradation, failure modes and modelling techniques. Quality based ballast material characteristics investigation and proper selection of ballast gradation with proper modelling methods will lead to an economical, minimum defect, minimum maintenance and replacement cost.

KEY WORDS: Railway; ballast gradation; material characterization; failure; ballast modelling


**Abstrakt**

Tidigare stor uppmärksamhet har ägnats för kvaliteten på ban överbyggnad för att förbättra det totala resultatet av järnvägen. Forskningar på banan material visar ett bra resultat som förbättrar den befintliga generella prestanda. Förbättrad drift kvalitet med hög hastighet, låg konstruktion kapital, lång livslängd service och låga underhållskostnader är frågan om järnvägen tekniken. Ballast är en av de avgörande delarna av järnvägen struktur som har stort inflytande på utförandet av järnvägsspår.

Syftet med projektet är att bedöma de olika aspekter som påverkar den totala prestandan på ballast struktur, dess material karakterisering, gradering, skador och beräkningsmodeller. En ordentlig val av ballast gradering med ordentliga modelleringstekniker kommer att leda till en ekonomisk, minsta defekt, och minimalt underhållskostnader.

**NYCKELORD:** Järnväg, ballast gradering, materialkarakterisering, ballast modellering
Table of Content

Table of Content........................................................................................................... v
List of Figures .................................................................................................................. vii
List of Tables .................................................................................................................. viii
Acknowledgment ........................................................................................................... ix
1. Introduction .................................................................................................................. 1
2. Ballast material ........................................................................................................... 2
2.1 Ballast functions ....................................................................................................... 2
2.2 Ballast structure ....................................................................................................... 2
3.0 Ballast characteristics evaluation .......................................................................... 5
3.1 Mechanical Property Evaluation ............................................................................. 5
3.1.1 Los Angeles Abrasion Test (LAA) .................................................................... 6
3.1.2 Mill Abrasion Test (MA) .................................................................................... 6
3.1.3 Deval Attrition Test (DA) .................................................................................. 7
3.1.4 Clay Lumps and Friable Particles ....................................................................... 7
3.1.5 Crushing Test ...................................................................................................... 7
3.1.6 Impact Test ......................................................................................................... 8
3.1.2 Bearing capacity or Strength – Triaxial Test ...................................................... 8
3.2 Physical Property Evaluation .................................................................................. 9
3.2.1 Shape ................................................................................................................ 9
3.2.2 Flatness or Flakiness ......................................................................................... 9
3.2.3 Elongation .......................................................................................................... 10
3.2.4 Surface Texture .................................................................................................. 10
3.2.5 Sphericity ........................................................................................................... 10
3.2.6 Angularity or Roundness .................................................................................. 10
3.2.7 Unit weight ........................................................................................................ 11
3.2.7.1 Determination of Bulk, Apparent specific gravity and Water absorption ...... 12
3.2.7.2 Rodded Unit Weight ...................................................................................... 12
3.3 Weathering test ...................................................................................................... 12
3.3.1 Freeze-thaw breakdown ..................................................................................... 12
3.3.2 Sulfate Soundness ............................................................................................. 12
4.0 Ballast Gradation .................................................................................................... 15
4.1 Ballast Gradation Benchmarking .......................................................................... 17
List of Figures

Figure 1: Longitudinal View of railroad [19] ................................................................. 3
Figure 2: Transversal or cross-sectional view of railroad [19] ......................................... 3
Figure 3: Typical particle shape defining ri and C [42] .................................................... 11
Figure 4: Ballast gradation representing cumulative frequency [19] ............................... 15
Figure 5: Ballast gradation representing frequency distribution plot [19] ....................... 16
Figure 6: Graphical definitions of grain size distribution [19] ........................................ 16
Figure 7: Plot of European gradation standards (A-F) ....................................................... 20
Figure 8: Comparison plot of Australian, AREMA No.4, European D and Indian standards 20
Figure 9: Normalized power gradation curve for Australian and Indian standards .......... 25
Figure 10: Some aspects of ballast selection criteria [44] ................................................ 26
Figure 11: Sources of ballast fouling combined together from all the sites in North America [19] .................................................................................................................. 27
Figure 12: Formation of ballast pocket [4] ....................................................................... 28
Figure 13: Critical Ballast fouling phases: (a) Clean ballast (b) Partially fouled ballast (c) Heavily fouled ballast [24] ................................................................. 32
Figure 14: Typical GPR Signal [53] .................................................................................. 33
Figure 15: Normalized power gradation chart (n=0.45) [49] ......................................... 35
Figure 16: Common ballast gradation plot used for different countries [49] ................. 36
Figure 17: Common gradations in the normalized 0.45 power gradation chart [49] ....... 36
Figure 18: Repeated loading profile on a single tie [23] .................................................. 37
Figure 19: Ballast layer settlement for different gradations [49] .................................... 38
Figure 20: Sources of water enter to the track [48] ........................................................... 39
Figure 21: Hydraulic action [19] ..................................................................................... 41
Figure 22: Contact point force transfer [23] .................................................................. 42
Figure 23: Calculation Cycle in DEM (ITASCA,1999) [23] ............................................. 43
List of Tables

Table 1: Deutsche Bahn AG Requirements for Ballast [16] .................................................. 8

Table 2: Properties of Ballast for the U.K. and Australian Railways [16] .......................... 11

Table 3: Recommended limiting value for ballast materials quality (AREMA 2007)[16] ........ 14

Table 4: European Standard (a) [11], Australian (b) [7], AREMA No.4 (c) [3] and Indian standard (d) [16] .............................................................................................................. 18

Table 5: Ballast freeze-thaw severity categories (BS EN 13450, 2002) [11] ....................... 21

Table 6: Comparison between the different Nordic countries, France and AREMA gradations .......................................................................................................................... 23

Table 7: Geographical location of Australia and India ............................................................. 24

Table 8: Different sources of ballast fouling [19] ................................................................. 30

Table 9: British Railways sources of fouling [19] ................................................................. 31

Table 10: Comparison between PVC, Percentage of fouling and relative ballast fouling ratio [13] .................................................................................................................. 31

Table 11: Categories of fouling based on the fouling index, percentage of fouling, and relative ballast fouling ratio [13] ................................................................................. 32

Table 12: Characteristic gradation with minimum particle size and air void [49] ............ 37
Acknowledgment

This thesis would have not been possible without the help and guidance of some individuals who contributed their valuable assistance from the beginning to the completion of the paper.

My special thanks go to my supervisor Dr. Elias Kassa giving me all the necessary support during my study without exhaustion. His comments, sightings, directions all the way drove me to work hard, look for problems and approach them in easy and systematic way to find solution. His consideration as a friend, simplifies our interaction whenever we meet.

I am indebted to thank Dr. Milan Horemuz, Dr. Micheal Behin and all friends and relatives all over the world involved directly or indirectly to the successful completion of my study.

My deepest respect and gratitude goes to my family for their love, care and unlimited support during my study.

Abateneh Yitayew

Stockholm, December 2011
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AASHTO</td>
<td>America Association of State Highway and Transportation Officials</td>
</tr>
<tr>
<td>AIV</td>
<td>Aggregate Impact Value</td>
</tr>
<tr>
<td>AN</td>
<td>Abrasion number</td>
</tr>
<tr>
<td>AREA</td>
<td>America Railway Engineering Association</td>
</tr>
<tr>
<td>AREMA</td>
<td>American Railway Engineering and Maintenance-of-Way Association</td>
</tr>
<tr>
<td>ARTC</td>
<td>Australian Rail Track Corporation Ltd</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BR</td>
<td>British Rail</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>DEM</td>
<td>Discrete Element Modelling</td>
</tr>
<tr>
<td>ECS</td>
<td>European Committee for Standardization</td>
</tr>
<tr>
<td>EM</td>
<td>Electro Magnetic</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground Penetrating Radar</td>
</tr>
<tr>
<td>IR</td>
<td>Impact Resistance</td>
</tr>
<tr>
<td>LAA</td>
<td>Los Angeles Abrasion</td>
</tr>
<tr>
<td>LSCT</td>
<td>Large Scale Cyclic Triaxial</td>
</tr>
<tr>
<td>MA</td>
<td>Mill Abrasion</td>
</tr>
<tr>
<td>RIC</td>
<td>Rail Infrastructure Corporation</td>
</tr>
<tr>
<td>STFT</td>
<td>Short time Fourier transformation</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>USCS</td>
<td>Unified soil classification Systems</td>
</tr>
</tbody>
</table>
1. Introduction

Railway is a means of transportation guided by rails giving access to trains to move passengers or freights from one place to another place. It has different components bringing the structure functional. These are rails, fastening systems, sleepers or ties, ballast, fill material and the subgrade. The different parts of the railroad structures can be categorized as superstructure (rail, fastening systems, and sleepers or tie) and substructure (top ballast, bottom ballast, sub ballast, fill material and subgrade). Ballast is the main structural part of the railroad which distributes the train loads to the underlying supporting structure without failure. Ballast can be constructed from different material sources like, basalt, granite, slag, and gravel. The mechanical and chemical composition of the construction materials affects the performance of the ballast structure.

The train running over the track exerts a pressure from different directions (vertical, lateral and longitudinal) to the ballast through the wheel-rail-sleeper combining the static and dynamic forces. There are different empirical methods developed to determine the different loads that can be exerted. The total vertical load is computed as a function of static, centrifugal, wind and dynamic loads. The lateral wheel force and the buckling reaction forces are mainly considered when predicting the lateral loads. It is a complex track load than the vertical load to predict and compute the different effects. The different forces created by a moving vehicle with the rail and the force by wheel or rail abnormalities are also the longitudinal and the impact forces computed for analysis. It is also important to consider the ratio of lateral and vertical forces to avoid the loss of alignment and even track buckling which is the cause of track failure.

The nature of the distribution of the contact pressure between the sleeper and the ballast is inconsistent, and hence uniform distribution is adopted for design purpose. The base width for the uniform distribution pressure is different from standard to standard. The point load coming from the wheel to rail-sleeper and finally to the ballast is also different in different standards. The sleeper just under the point load takes less than half of the incoming load and the neighbouring sleeper shares the rest of the load. Previously, observation and experience based empirical solutions has been used to determine the track bed thickness without considering the loading, hydrology and the geology of the area. Recently, ballast layer can be modelled either by continuum and discrete element methods. Considering the two methods, discrete element method is more realistic since it considers the morphological characteristics of the aggregate.

In this paper the ballast material and its characteristics are discussed under chapter two and its corresponding evaluation seen in detail under chapter three. The ballast gradation, ballast failure mechanism and aspects ballast modelling are elaborated in detail in chapter four, five and six respectively.
2. Ballast material

Ballast is the main structural part of railroad where the sleepers (or ties in US) are laid. Its main function is to transfer the loads coming from the super structure to the subgrade without failure and providing good drainage. Different types of materials used for ballast construction like limestone, basalt, granite, slag and gravel. So, an aggregate with the following property traditionally considered to be best ballast material [19]. i.e.

- Angular, crushed,
- Hard stones and rock
- Uniformly graded
- Free of dust, dirt and resistant to cementing action

2.1 Ballast functions

Even though there are many more functions of the ballast structure, the following are the most important functions of ballast structure [19]:

1. Withstand the actions coming from the sleepers to the substructure. Those actions can be grouped as uplift, lateral and longitudinal forces.

2. Act as resiliency and energy absorbent for the track structure.

3. The voids between the aggregates provide space for movement and accumulation of crushed aggregates due to fouling.

4. Provide quick drainage system down to the structure.

5. Pressure reducing ballast structure to the allowable stress for the underlying structure just below the slipper.

6. Tamping will rearrange ballast particles while adjusting track geometry. This eases and speed up the maintenance operations.

2.2 Ballast structure

Ballast structure may be divided in to four zones:

- Crib – zones between the slippers
- Shoulder – it is the sloppy zone between the end of the sleeper and down to the top of subballast.
- Top ballast – it is the top portion of the ballast structure which is usually exposed to tamping.

- Bottom ballast – it is the bottom and lower part of the structure which support the overall structure. Depend on the quality of the subballast material, loading condition, presence of water and drainage property of the structure; it is the more fouled part of the structure than the rest of the structure [19].

A good mechanical property of ballast can be obtained from the combination of physical properties of the individual ballast material (i.e. particle size, shape, angularity, hardness, surface texture and durability) and its in-situ (i.e. in-place which results from compaction process) [19]. The degradation resulted due to train traffic and maintenance operation will round the aggregate particles and the traffic loading will break the aggregates consequently reduces the interlocking between inter-particles [12].

Figure 1: Longitudinal View of railroad [19]

Figure 2: Transversal or cross-sectional view of railroad [19]
Ballasted track generally have the following shortcomings which arise due to “high frequency vibrations and uneven settlements”,

- It has irregular or uneven settlements with defects in different track positions.
- There is irregular ballast damage in rail defects, insulating rails, bridge approaches, and welded joints.
- After 30-60 million tons of service, when the settlement of the track exceeds 20 mm, general track maintenance is required and after 30 years of service the entire ballast structure needs to be changing [5].
3. Ballast characteristics evaluation

The ballast material should be resistant to or free of the effects coming from the following individual or combined effect of all, i.e. chemical (failure coming due to reactions of (for example coal dust fines), mechanical (failure from moving train and dynamic loading on areas where there is bolted joint of the rail), and environmental (repeated cycle of weather change, i.e. intensive wetting and drying and freezing and thawing). To get these parameters in a reasonable range, the ballast material should be naturally crushed aggregate. For better interlocking the crushed aggregate should be angular, having sharp and cuboids shape. Since it has sharp edges, the contact area with the neighbouring particle will be very small causing large contact stress, which result fracture and abrasion while loading. Consequently the fines formed will go down the layer and deposited in between the voids. When the collected fines get moisture, it will act as a lubricant, causing ballast material abrasion and pumping under the cross ties (finally produce pumping track). Generally, ballast material should be sufficiently tough to resist breakage under impact, hard to resist abrasion due to inter particle contact, dense enough to resist lateral forces and finally holding the ties in place. It must be also freeze-thaw resistant which results further degradation due to weathering and chemical effect. The ballast materials should be non-void particles, when the voids filled with water, during winter it will get freeze, which will form inter particle volume change finally causes bulging of layers [32].

The typical material size used in ballast construction is having a nominal size of 20 to 50 mm. Most of the time, particles size between 6 to 64 mm diameters are used. The performance of a ballast structure can be optimized by controlling particle characteristics and its physical state of the general assembly. This leads to say, the ballast structure can be affected not by single element behaviour but by the cumulative effect of the mixed aggregate characteristics. The cumulative effect of the ballast material characteristics can be evaluated by its mechanical, physical and weathering test [19].

3.1 Mechanical Property Evaluation

It is the aggregates internal friction which helps to transmit the upcoming load to the underlying layer and then to sub grade and the particle needs to be characteristics hard enough to resist crushing, degradation and wear. The characteristics of the ballast particles can be measured by the following testing methods.

- Los Angeles Abrasion
- Mill Abrasion
- Deval Abrasion
- Clay lumps and friable particles
- Crushing value
- Impact

The American Railway Engineering Association (AREA) manual states, LAA is right now the first and the best way of measuring the potential to breakdown of ballast materials under loading. But this test can only measure the degree of abrasion. In spite of the predominance of LAA test on North America railroads, it come up with lot of uncertainty or doubt on dependability of the test. The association is now found a supplementary test for LAA. The primary test recently used by British rail way is the Deval test [19].

3.1.1 Los Angeles Abrasion Test (LAA)

It has been previously used in North America as an abrasion test for ballast, which is a means to measure toughness or tendency for coarse aggregate breakage. The test is performed based on ASTM C535 [19]. It can be also tested by following procedure in BS EN 1097 – 2 (1998) which is later modified by Annex C of BS EN 13450 (2002) [9] to make suitable for the sample in 10 – 14 mm which is much smaller than the actual ballast size. According to BS, LAA value should be less or equal to 20 % [9]. But according to ARTC, the LAA value should be a maximum of 25% [7]. There may cause construction and overall performance problem of the structure if the particle does not have enough toughness and abrasion resistance [40]. It can be quantified after 500 revolutions as:

$$LAA_{500} = \left( \frac{M_o - M_{500}}{M_o} \right) \times 100$$

Where, LAA$_{500}$, M$_o$, M$_{500}$ are loss after abrasion test, original sample and sample after abrasion test respectively [40].

The investigation on the different sources of aggregates, i.e. Sedimentary, Metamorphic and igneous rocks shows, the first two rock types are weaker in abrasion than the later [40]. So, a ballast material is preferred to be from source of igneous than the other sources.

3.1.2 Mill Abrasion Test (MA)

It is a wet abrasion test of ballast material with specified gradation mixed with water. It will get wear without crushing while it is rotating. It has similar testing procedure with the Deval attrition test, except using different angle of rotation and jar size. Still now it has no standard ASTM test procedure, but AREA committee already developed a working procedure. So it is the primary test method used in North America to evaluate the ballast performance by measuring its durability. Most of the particles around 90 % after test will pass 0.075 mm sieve, which is in contrary with LAA since most of the particles after test retained on 0.075
mm sieve. This shows that, these two tests have different applications identifying the characteristics of the aggregate. MA tests the resistance of the particles against crushing, degradation (hardness) and LAA measures the strength of the particle or toughness. Hence the two tests are thought to be supplementary, and then the Canadian pacific Railroad characterizes a combined index for the ballast called abrasion number (AN) [19],

\[ AN = LAA + 5MA \]

From this relation, the smaller the AN value shows that a better ballast quality and the higher corresponds with poor ballast quality [32]. Dry abrasion test is not preferable to use since it produces less breakage than the wet abrasion. Two reasons can be stated,

1. The slurry formed will increased the amount of abrasion and,

2. The apparatus (jar) will be coated with fines or dusts, these particles will affect the direct contact of particle to particle or particle with the jar, hence results less abrasion.

### 3.1.3 Deval Attrition Test (DA)

This test was initially used for highway materials quality measurement (attrition) in England. By then the British Rail (BR) use it for ballast performance testing method since it gives some clue about minimum durability of the ballast life corresponding to their climate and sleeper type [19]. The test can be conducted either in dry state or by adding equal amount of clean water. These states of testing ballast material have its own effect on the quality of the test. The value of wet attrition test has been shown decreased as the test done repeatedly. This is because, the particle will be removed from the surface through testing and the degree of resistance of the particle attrition will be increased [19]. It can be evaluated by:

\[ DA = \left( \frac{W_i - W_f}{W_i} \right) \times 100 \% \]

Where; \( W_i \) and \( W_f \) are the initial weight of the sample retained on 1.6 mm or 2.36 mm sieve size after test respectively, according to French railways and British railways [42].

### 3.1.4 Clay Lumps and Friable Particles

It is a degree of measuring the amount of particle breakage by finger after the sample has been soaked in water for 24 ± 4 hours. It is a routine examination of ballast materials given by ASTM C142 [19].

### 3.1.5 Crushing Test

It is a measure of the ballast material due to gradually applied load given by British Standard Institution, British crushing value test, British standard 812 [19].
3.1.6 Impact Test

It is a measure to toughness, resistance to dynamic or impact loading, “sudden shock loading” [19]. It can be tested in either dry or soaked condition in accordance with BS 812. If the aggregate impact value is found to be greater than 30%, it should be reported with caution [47].

Table 1: Deutsche Bahn AG Requirements for Ballast [16]

<table>
<thead>
<tr>
<th>Ballast Material</th>
<th>Los Angeles Test</th>
<th>Aggregate Impact Value</th>
<th>Impact Resistance</th>
<th>Deval Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>8.7-9.5</td>
<td>10</td>
<td>10.2-11.7</td>
<td>10.3-13.8</td>
</tr>
<tr>
<td>Porphyr</td>
<td>10.3</td>
<td>10</td>
<td>11.9</td>
<td>11.1</td>
</tr>
<tr>
<td>Sandstone</td>
<td>12.5</td>
<td>11</td>
<td>14</td>
<td>9.8</td>
</tr>
<tr>
<td>Limestone</td>
<td>13.7-23</td>
<td>15-23</td>
<td>16.3-21.3</td>
<td>5.9</td>
</tr>
</tbody>
</table>

3.1.2 Bearing capacity or Strength – Triaxial Test

The individual particle strength in the structure influences the overall performance. The cumulative bearing capacity or strength of each ballast particle can be seen and estimated in the laboratory by triaxial test.

There will be high stress on the ballast structure when a moving wheel load is applied on the rail. This stress condition should be simulated in the laboratory. Triaxial test method is best suit to predict the stress condition in the actual structure considering the typical loading condition coming to the ballast [27]. It can be either of monotonic or cyclic triaxial test method based on the controlling mechanism of the confining pressure. Advantages of the test method:

- Load can be applied as required. Number of application, its frequency and amplitude can be varied based on the expected output.

- The confining pressure of the testing machine can be controlled. Based on the methods used to apply the load, the confining pressure can be cyclic or constant.

- The testing machine is so accurate to measure the radial and axial strains. So the permanent deformation and the resilient modulus can be predicted accurately [27].

Some of the disadvantages of the test method:

- Not suitable for undisturbed sample
- Not suitable for larger sized samples
- A problem to simulate the principal stress rotational direction in a continuous mode.
- Time consuming to conduct a sample and hence very expensive [27].

The presence of more water in the sample will reduce the inter-particle friction and cohesion which leads to conclude that, unsaturated samples need much effort to compress than the saturated samples [36].

In addition, ballast distribution should be uniform throughout top of the ballast, i.e. aggregates should not exist in excess on the top since it may interrupt the train movement. The quality of the ballast and the profile of the ballast structure should conform to the required specification. Indirectly, it is just to say that, the quality of the ballast material should fulfil the criterion, where, there will not be crushing on the structure which finally affects the performance of the structure and hence finally it results ballast failure by contamination. Not only the crushed particles on the structure results contamination but also presence of weeds, dirt materials, and accumulation of water in the structure due to poor drainage system are the other cases [25].

3.2 Physical Property Evaluation

The physical behaviour of ballast material can be estimated by evaluating the shape, surface texture, sphericity and its angularity.

3.2.1 Shape

The particle shape of an aggregate is the percentage of the mass determined as flaky or elongated. These behaviours affect the workability and stability of the composition. Mix of aggregates should not contain too-many flaky and elongated particles. The method of two-dimensional image analysis can be used for both size and shape analyses [13].

3.2.2 Flatness or Flakiness

These two names are indicated and used for the same shape characteristics in different standards and countries. Flaky materials, according to BR, are particles where the ratio of thickness to width is less than 0.6. So an index can be computed from the percent weight of flaky aggregate particles. In the other side, according to U.S. Army corps of Engineers, a material is said to be flat, when a particle has a thickness to width ratio of less than1/3. Based on the corps, ASTM [19] recently provides different ratios for flat particles. i.e.1/2, 1/3 and 1/5. The Australian railway ballast specification also recommends the amount of flaky particle on 6.7 mm sieve shall not exceed 30 % [7].
3.2.3 Elongation

It is an aggregate shape test which can be defined as the percentage by weight of the elongated particles in a sample. The different values of the elongation index are listed below according to different standards used in different countries [19].

- British Standard – particle as one with a length to width ratio of more than 1.8.
- U.S. Army corps of Engineers – particle as one with a length to width ratio of greater than 3.
- Recent ASTM – based on corps of Engineers method, it provides a choice of three ratios: 2, 3 and 5.

Section 3.2.2 and 3.2.3 can be related with another factor called shape factor. It is the ratio of the summation of all longest dimensions to smallest dimension of the particle. Its approximate evaluation of the flatness and elongation characteristics of the particles indicates how the shape of the particles looks like. Shape factor is designated by $S_f$ [19];

$$S_f = \frac{\sum L_i}{\sum T_i}$$

Where, $L_i$ and $T_i$ are Longest and Smallest dimension of the particles respectively.

3.2.4 Surface Texture

The characteristics of the fractured surface of a particle can be explained by surface texture of the material. Even though it has an influence on the performance of the ballast, it has no direct way to evaluate the particles, but it can be quantified from different tests, such as, particle index and rodded unit weigh test [19].

3.2.5 Sphericity

It is an indirect measure to the sphericity of an aggregate particle in a sample, i.e. “measure of how much the shape of a particle deviates from a sphere.” When a particle is said to be perfect sphere, the value of sphericity is unity or one. The sphericity value of a granular material is the average of the sphericity value of each particle in a ballast sample [19].

3.2.6 Angularity or Roundness

Materials used in ballast construction should be naturally crushed having angular and sharp edges for better inter-particle interlocking. Its angularity (inverse of roundness) means; how
the edge of the particles has sharp corners in each particle [19]. The average roundness will be the weighted average of the group roundness.

Roundness, $\rho$, is computed by the following relation:

$$\rho = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{r_i}{R} \right)$$

![Figure 3: Typical particle shape defining $r_i$ and $C$ [42]](image)

Where, $r_i$ is individual corner radius, $R$ is the radius of the circle subscribed by the particle and $N$ is number of corners on particle.

Table 2: Properties of Ballast for the U.K. and Australian Railways [16]

<table>
<thead>
<tr>
<th></th>
<th>Maximum %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Network Rail</td>
</tr>
<tr>
<td>Shape</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flakiness index</td>
</tr>
<tr>
<td></td>
<td>Elingation index</td>
</tr>
<tr>
<td>Strength</td>
<td>Aggregate crushing value</td>
</tr>
<tr>
<td>Durability</td>
<td>Wet attrition value</td>
</tr>
</tbody>
</table>

3.2.7 Unit weight

Particle specific gravity (bulk and apparent specific gravity), absorption and rodded unit weight are some of the factors which affect the ballast unit weight. The nature of the particle to be porous is an indication of the quality of the aggregate, by porous means, it will contain more water on the space and it will have greater chance to be broken down while freezing.
3.2.7.1 Determination of Bulk, Apparent specific gravity and Water absorption

The following three formulas can be used to estimate the bulk, apparent specific gravity and water absorption [19].

\[ G_b = \left( \frac{D}{C-(A-B)} \right), \quad G_a = \left( \frac{D}{D-(A-B)} \right), \quad A_b = \frac{100 \times (C-D)}{D} \]

Where:
- \( G_b \) - Bulk specific gravity
- \( A \) - Weight of container + sample + water
- \( G_a \) - Apparent specific gravity
- \( B \) - Weight of container + water
- \( A_b \) - Water Absorption (%) = Water Absorption (%)
- \( C \) – Weight of sample in surface dry and saturated condition
- \( D \) – Weight of oven dried sample.

3.2.7.2 Rodded Unit Weight

It is an important parameter to evaluate the unit weight of a ballast material in dry condition by filling the material and compacting, in a container having almost equal height and diameter. This all involves placing the ballast in three layers having equal depth in the container. Each layer should be tamped twenty five times with a steel rod [19].

3.3 Weathering test

Freeze - thaw and soundness tests are the most pronounced methods to check the resistance of the aggregates disintegration due to environmental effect.

3.3.1 Freeze-thaw breakdown

It is used to evaluate the resistance to disintegration after immersion in water, alcohol or another solution several times by cycling, freeze and thaw. Fractured surfaces are very sensitive to freeze-thaw degradation, since the solution can penetrate and go deep in to the particles, results disintegration of the particles during the process [19].

3.3.2 Sulfate Soundness

It is a typical aggregate test to evaluate the loss of particles after several immersions of the aggregates in to sodium or magnesium sulfate. It is a kind of cyclic aggregate test which involves immersing and drying the aggregates and performing sieve analysis and calculating
the percent loss from each sieve size. Immersion and drying is considered to be one complete cycle [29].

Care must be taken while performing soundness test since the result is affected by different cases, i.e. nature of the surface (degree of fracture), number of cycle used during the test, the porosity of the particle, amount and type of solution used and the chemical composition of the aggregates [19].
Table 3: Recommended limiting value for ballast materials quality (AREMA 2007)[16]

<table>
<thead>
<tr>
<th>Ballast Material</th>
<th>Granite</th>
<th>Traprock</th>
<th>Quartzite</th>
<th>Limestone</th>
<th>Dolomitic Limestone</th>
<th>Blast Furnace Slag</th>
<th>Steel Furnace slag</th>
<th>ASTM Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>% material passing No. 200 sieve %</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>C 117</td>
</tr>
<tr>
<td>Bulk specific gravity(^a)</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>2.65</td>
<td>2.30</td>
<td>2.90</td>
<td>C 127</td>
</tr>
<tr>
<td>Absorption Percent</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>C 127</td>
</tr>
<tr>
<td>Clay lumps and friable particles %</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>C 142</td>
</tr>
<tr>
<td>Degradation %</td>
<td>35</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>b</td>
</tr>
<tr>
<td>Soundness (Soundness sulfate) 5 cycles %</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>C 88</td>
</tr>
<tr>
<td>Flat and / or elongation particles %</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>D 4791</td>
</tr>
</tbody>
</table>

\(^a\) Limits for the whole test shows the maximum value except for the bulk specific gravity value

b Gradations containing particles retained on 25 mm sieve shall be tested by ASTM C 535. Gradation with 100% passing on 25 mm sieve shall be tested by ASTM C 131. Use grading most representative of ballast material.
4.0 Ballast Gradation

A method set to categorize the different sized aggregates in to its size by use of series of graduated sieve and applying mechanical sieving by agitator on it according to ASTM C117, C136 and D422 procedure [19]:

The test will be performed by washing, drying the particles and agitating the sieve series by mechanical shaker. The gradation of aggregate mix can be classified as, well graded (dense or broad graded), uniformly graded (open) and gap graded based on the particle size included on the composition. It can be plotted in two ways:

1. Cumulative frequency curve - which is the curve made by using percent pass as vertical axis versus log of particle size as horizontal axis shown in figure 4.

2. Frequency distribution curve - developed by using percent retained as vertical axis versus function of log of particle size shown in figure 5.

From the above two methods of showing the different classes of gradation, the frequency distribution curve is the most useful one, since it shows the predominant size of the aggregate [19].

![Figure 4: Ballast gradation representing cumulative frequency](image)

New ballast material, which supposed to fall under uniformly graded class, is considered to fit the above frequency distribution plot. In contrast, after sieve analysis, the fouled ballast material will meet the requirement of the gap graded [19].
Even though there is major problem in degradation and permanent deformation, uniformly graded aggregates are used in ballast structure construction for the sake of drainage requirement. But when broadly graded aggregates used, more fines will be produced, it is because of train loads, which is the main reason for ballast contamination [37].

Naturally obtained and crushed, angular, rock material is good for ballast construction. To achieve on better particle interlocking and to get the required resistance to dynamic loading in the transverse and longitudinal direction, angular stones are the best than rounded shape. When particles used bigger than the maximum size of the particle, there will be only some particles beneath the tie or slipper which will distribute the load insufficiently to the subgrade. In the other hand, when too much smaller size particles used than the minimum, the void between the bigger sizes will be filled with these particles exposing the structure for further drainage problem [12].
Further investigation shows that, ballast particles degradation will be caused by either by traffic or operation during maintenance. During these process, particle may be suffer from loss of edge, become rounded which minimizes the inter particle interlocking and crushed due to repeated loading. Rail joints, which most of the time gets an impact loading will cause ‘wet spots’, furthermore it will give bad riding comfort and will be reason for rapid failure of the structure [12].

Basically there are two gradation curve shape factors used in unified soil classification systems (USCS), these are $C_u$ (coefficient of uniformity which sometimes called coefficient of “non-uniformity”) and $C_c$ (coefficient of curvature). These shape factors are defined as,

$$
C_u \equiv \frac{D_{60}}{D_{10}} \quad \quad \quad \quad \quad \quad C_c \equiv \frac{(D_{30})^2}{D_{10}D_{60}}
$$

$D_{10}$, $D_{30}$, and $D_{60}$ are particle diameters, where; 10%, 30% and 60% are percent weight finer than each sieve size respectively.

According to USCS, the value of $C_u$ for uniformly graded material i.e. material used for ballast should have a value $C_u < 4$ and when it is not gap graded. In the other hand, when $C_u > 4$ and $1 < C_c < 3$, the gradation classification can be considered as well graded or broadly graded material [19].

Under the repeated loading test, it is found that, compacted well graded aggregates have better or good tendency to resist loads than uniformly graded aggregates [20].

### 4.1 Ballast Gradation Benchmarking

Recently, more attention is given for both the superstructure and substructure part of the track to get good performance for heavier wheel loads, higher operating speeds and unit trains. Based on the performance evaluation after each research, physical and chemical properties of the ballast material has been obtained good which insures better overall performance of the track structure which requires minimum cost of maintenance. Specifications for ballast materials which yield good performance are obtained by conducting series laboratory, field tests and also evaluating the performance of the different ballast materials under existing condition on the track [3]. Ballast is an important structure on the railway track. Its first function is to provide drainage and distributes the loads coming from the super structure to the structure supporting the ballast without failure. For this reason, ballast material in general should be kept uniformly graded, fresh, angular and crushed faces [23]. Different researches are undergoing on gradation and shape of the particle to reason out their effects on the performance of the ballast structure. But still different countries uses different gradation and shape of aggregates without definitely knowing the effects on the performance of the ballast structure [23]. Article [38], says “the effect of grain size
distribution on the behaviour of crushed rock aggregates in the track structure is a complex issue and in many ways decisive”.

The following list of tables shows different standards used in different countries.

Table 4: European Standard (a) [11], Australian (b) [7], AREMA No.4 (c) [3] and Indian standard (d) [16]

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>European standard (13450, 2002) [11]</th>
<th>Railway Ballast Size 31.5 to 50 mm</th>
<th>Railway Ballast Size 31.5 to 63 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage passing by mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grading category</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>80</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>63</td>
<td>100</td>
<td>97 to 100</td>
<td>95 to 100</td>
</tr>
<tr>
<td>50</td>
<td>70 to 99</td>
<td>70 to 99</td>
<td>70 to 99</td>
</tr>
<tr>
<td>40</td>
<td>30 to 65</td>
<td>30 to 70</td>
<td>25 to 75</td>
</tr>
<tr>
<td>31.5</td>
<td>1 to 25</td>
<td>1 to 25</td>
<td>1 to 25</td>
</tr>
<tr>
<td>22.4</td>
<td>0 to 3</td>
<td>0 to 3</td>
<td>0 to 3</td>
</tr>
<tr>
<td>31.5 to 50</td>
<td>≥ 50</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
<tr>
<td>31.5 to 63</td>
<td>-</td>
<td>-</td>
<td>≥ 50</td>
</tr>
</tbody>
</table>

**Note 1** The requirement for passing the 22.4 mm sieve applies to railway ballast sampled at the place of production.

**Note 2** In certain circumstances a 25 mm sieve may be used as an alternative to the 22.4 mm sieve when a tolerance of 0 to 5 would apply (0 to 7 for category F)
Comparing the above tables, AREMA gradation is finer than the rest of the other gradations. In the European standard, gradation D, E, F contains coarser material than the other three (A, B and C). Even though, there is no exact figure to estimate the amount of coarser material on the range between 37.5 and 63 mm, the Australian standard contains smaller sized materials than the European gradation. In Europe, different countries use different gradation which satisfies their requirement on the bases of the European standard. The above European standard gradation category is depend on the location and climatic condition of the area since climate is a decisive factor for freeze-thaw character of the materials shown in table 5. The following table shows the range of the different climate, environmental conditions and type of gradation used in specific situation. The European gradation D is selected for comparison since it is used in most of the European countries referring table 5.

<table>
<thead>
<tr>
<th>Australian standard</th>
<th>AREMA No.4</th>
<th>Indian Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve size (mm)</td>
<td>Sieve size (mm)</td>
<td>Size (mm)</td>
</tr>
<tr>
<td>% Passing</td>
<td>% passing</td>
<td>% passing</td>
</tr>
<tr>
<td>63.0</td>
<td>100</td>
<td>51</td>
</tr>
<tr>
<td>53.0</td>
<td>85-100</td>
<td>38</td>
</tr>
<tr>
<td>37.5</td>
<td>20-65</td>
<td>25</td>
</tr>
<tr>
<td>26.5</td>
<td>0-20</td>
<td>19</td>
</tr>
<tr>
<td>19.0</td>
<td>0-5</td>
<td>9.5</td>
</tr>
<tr>
<td>13.2</td>
<td>0-2</td>
<td></td>
</tr>
<tr>
<td>9.50</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4.75</td>
<td>0-1</td>
<td></td>
</tr>
<tr>
<td>1.18</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>0.075</td>
<td>0-1</td>
<td></td>
</tr>
</tbody>
</table>

(d)
Figure 7: Plot of European gradation standards (A-F)

European standards A-C contains more than 50% of the grain size between 31.5 – 50 mm, D and E contains more than 50% grain sizes between 31.5-63 mm and gradation F contains more than 85% of the grain size between 31.5-63 mm.

Figure 8: Comparison plot of Australian, AREMA No.4, European D and Indian standards
Iceland, parts of Scandinavia and some mountainous regions experiencing severe winter weather conditions can be categorized under “continental” (sea water) and frost free dry weather conditions grouped under “Mediterranean” [11]. Different countries in the world experiences different types of track failure.

Generally there are two types of track deformations, recoverable and permanent deformations. Within a selected gradation, increasing the particle size increases the stiffness of material hence solution for recoverable deformation. The same conditions also observed when selecting and using uniformly graded aggregate of the same size. Research shows that using broadly graded aggregates will resist permanent deformation better than uniformly graded in cyclic loading. It is because; smaller particles will fill the gap between the larger which will improve the package [38]. The total load coming from the super structure is finally resisted by the underlying subgrade structure. So, the gradation of the ballast structure is depending on the subgrade stiffness [38] when recoverable deformation is considered.

Basically there are some factors considered to decide and select the type of gradation used for each of the different countries. The boundaries for upper and lower limit of the ballast materials which gives good performance are obtained by conducting series laboratory test, field tests and also evaluating the different ballast materials under existing condition on the track [3].

The European Committee for Standardization (ECS), proposed five different gradations containing particle nominal size varies from 32 -63 mm [46]. Further studies shows, the European standard have six categories where its size ranges from 31.5 to 63 mm [11]. Some of the Nordic countries have their own gradation with specific ballast requirements. According to article [46] Sweden, Finland and Norway from Nordic countries and AREMA, in addition France gradation and its criterion are compared and presented. For simplicity, the comparison is condensed and listed on the table below. As it is shown on the table, the ballast

<table>
<thead>
<tr>
<th>Environmental conditions</th>
<th>Climate</th>
<th>Gradation category for the different climates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mediterranean</td>
<td>Atlantic</td>
</tr>
<tr>
<td>Frost free or dry situation</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Partial saturation, no salt</td>
<td>D</td>
<td>C</td>
</tr>
<tr>
<td>Saturated, no salt</td>
<td>D</td>
<td>B</td>
</tr>
<tr>
<td>Salt (sea water)</td>
<td>C</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 5: Ballast freeze-thaw severity categories (BS EN 13450, 2002) [11]
division condition is differing from country to country. For example Finish and Norwegians consider only the annual tonnage and the number of passenger but Swedish railway simply classifies the ballast structure in to two, i.e. main ballast and the yard. Where class one will be used for main ballast structure and class two for yard [46]. Frances standard accounts only the speed and the mechanical properties of the material for two different rail lines i.e. classical and high speed lines.
<table>
<thead>
<tr>
<th>Countries</th>
<th>CEN</th>
<th>Sweden</th>
<th>Norway</th>
<th>Finland</th>
<th>France</th>
<th>AREMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast division</td>
<td>$5^a$</td>
<td>$2^a$</td>
<td>$5^a$</td>
<td>$4^a$</td>
<td>1</td>
<td>$7^a$</td>
</tr>
<tr>
<td>Nominal aggregate size (mm)</td>
<td>32-63</td>
<td>32-63</td>
<td>25-63</td>
<td>32-64</td>
<td>Based on the European standard only class A</td>
<td>37.5-45 $^f$</td>
</tr>
</tbody>
</table>
| Quality test | - Shape test (flakiness, elongation and particle length) 
- Modified LAA or macro-deval test | - LAA and Impact value tests | - LAA for abrasion and impact | - LAA with impact test | LAA and Mde (Macro deval) based on the speed of the trains | - list of tests with required values shown on table 13 |
| Note | - Maximum 3% passes 22.4 mm and more than 50% shall be between 32-50 mm | - 4% passes on 31.5 mm 
- maximum of 10% between 63-80 mm | - 73 mm is the maximum size 
- 10% by weight retained on 25 mm 
- 10% between 63 and 77 mm | - 70 mm is the maximum, where 0 to 15% may be smaller than 64 mm and 7% may be finer than 32 mm. | - Material range is on the basis of European standard class A 
- classical lines 
LA=16, Speed ≤ 220 km/h 
Mde=7, Speed ≤ 220 km/h 
- High Speed Lines 
LA=14, Speed > 220 km/h 
Mde=5, Speed > 220 km/h | - 51 mm is the maximum size, 10% retained on 38 mm and at most 15% should pass on 19 mm and materials up to 5% may be retained on 9.5 mm |

$^a$ Two of them have a nominal size 32 – 63 mm and the rest three have a nominal size of 32 – 50 mm (Skoglund, 2002)

$^b$ Class 1 and Class 2 gradations. Class 1 for ballast structure and class 2 for yards with nominal size 11-32 mm (Skoglund, 2002).

$^c$ At yard areas, smaller sized grading are used.

$^d$ Mechanical properties are linked to the classification of the specific line but not the gradation.

$^e$ Two finer gradation basically used for yard areas and the rest five are accepted as bit coarser. From this accepted coarser material, No. 4 gradation is most commonly used for railway line ballast construction.

$^f$ No.4 gradation is taken since it is commonly used

Note - On the quality test category, the limit is depend on the type of ballast gradation selected and line category.
Article [41] also classifies the Swedish railway ballast material as two by the following grain size distribution.

<table>
<thead>
<tr>
<th>Grain size Class</th>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>32 – 63 mm; &lt; 32 mm max 4%, &gt;63 mm max 10%</td>
<td></td>
</tr>
<tr>
<td>Class II</td>
<td>11 – 32 mm; &lt; 11 mm max 4%, &gt;32 mm max 10%</td>
<td></td>
</tr>
</tbody>
</table>

Class I ballast is used in the upper ballast layer of railway bench and Class II for sub ballast or as upper and sub ballast at the private low traffic railways [41].

As it is shown on table 4, even though the cumulative percent pass of the different sizes are small, the Australian Rail Track Corporation standard seems to be broadly graded than the European and Indian standards. Since the climate of Australia is classified as arid or semi-arid, the average annual rain fall of the country is about 420 mm [8]; its drainage requirement is very less. In contrary, the Indian Railways standard has only three coarser different sized materials, makes the composition coarse graded. As the geographical locations of these two countries shown in table 7, the tropic of cancer passes through at the middle of India which divides the southern part of India under the Torrid Zone or tropical circles (between tropic of cancer and tropic of Capricorn). Where each of the tropic of cancer and the tropic of Capricorn lies at 23.5° north and south of the equator respectively [21].

Table 7: Geographical location of Australia and India

<table>
<thead>
<tr>
<th>Country</th>
<th>Australia</th>
<th>India</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>10°00 00’ &lt; Lat &lt; 40°00 00’ south</td>
<td>08°04 00’ &lt; Lat &lt; 37°06 00’ North</td>
</tr>
<tr>
<td>Longitude</td>
<td>110°00 00’ &lt; Lon &lt; 160°00 00’ east</td>
<td>68°07 00’ &lt; Lon &lt; 97°25 00’ east</td>
</tr>
<tr>
<td>Average annual rainfall (mm)</td>
<td>420</td>
<td>1250</td>
</tr>
</tbody>
</table>

Lat=Latitude and Lon=Longitude

India, which lies within the tropical circles, is having an average rainfall of about 1250 mm where its 80% annual rainfall recorded between June and September [21]. The rainfall distribution throughout the period is about 8.33 mm/day (80% annual rainfall for four months) and 1.15 mm/day for India and Australia respectively. Based on the corresponding rainfall intensity, the ballast gradation should be coarser for Indian standard to properly drain the increased over precipitation. The differences in annual rain fall between Australia and India shows that, the gradation in the sense of drainage shall be efficient and contain coarser material insuring bearing capacity.
For high speed and heavy duty train services, good quality materials classified as high grade should be used. Recommendations based on research and experience, the crushed slag and crushed stones are grouped under high-grade materials. For heavy axle loads and high density rail lines the trap rock and granites including basalt are found to be good. Limestone, sandstone and quartz varies in quality since their degree of degradation is depend on the type of mineral in it (calcium and magnesium) and amount of edges present in each particle in limestone, sandstone and quartz respectively [22].

The conclusion drawn from the above different gradations considered, Europe, Australia, AREMA and Indian standards, the minimum aggregate size that has to be used as ballast material should be 36 mm in spite of the other governing factors. The above analysis shows that, at this size, the ballast will develop minimum settlement and air void which satisfies both the deformation and the drainage property of the structure.

In this paper, it is found to be difficult to compare the performance of each countries gradation. Their geographical location and geological nature affects the source of the ballast material (basalt, limestone, granite, dolomite, rheolite, gneiss and quartzite). The availability of the parent rock on the construction area has a great influence on the economic aspect of the project. Generally, the ballast selection should compromise the following:

Figure 9: Normalized power gradation curve for Australian and Indian standards
Wheel loadings, volume and speed of traffic are highly depending on the size, surface roughness and degree of irregularity. The integral property of these factors determines the efficiency of the bearing capacity or load bearing capacity of the ballast structure for traffic requirement. In this case, for high speed and main line railways, crushed, angular, rough surface are the best. There will be unpredictable expense if there is an unstable location on the track which requires frequent addition of ballast material and renewal. In addition to fulfilling the bearing capacity of the induced traffic, the selection should incorporate the drainage requirements. The recommended ballast size should have more resistance against crushing due to loading hence the flatter edges and angles of the larger particles size has weaker efficiency to grip and hold the sleeper in place.

All over performance and required life span of the railway should be become economically safe project. Hence the cheapest ballast means that, a structure having low cost all over its service period. The overall service period is depend on the initial cost, duration of renewal, track and equipment maintenance and cost of train operation.

It is also observed by [51] and concluded that, there is no universal specification of ballast material because of the difference in property of the subsoil condition of the structure and its index characteristics such as size, shape, hardness, friction, texture, abrasion resistance and mineral composition.
5.0 Ballast Failure Mechanism

Ballast failure has a major contribution for uneconomical maintenance cost and shortening of the service life of the railway system. Generally ballast failures can be due to ballast fouling or formation of ballast pocket.

5.1 Ballast Fouling

5.1.1 Causes

The cause of fouling in ballast structure is due to the presence of more fines in the ballast material. The source of fine materials can be categorized as external and internal. The external ("surface spillage") fines are from fright transportation, coal fouling and an upward migration of fine particles from the sub-grade and fines produced from tie wear (wood or concrete) and the internal ("mineral fouling from crushed aggregate") fines are generated due to traffic repetition and heavily loaded traffic frequency [6]. Even though there are conditions where one of the above conditions dominates for the formation of fines, the most and frequent cause of ballast fouling is from ballast particles breakdown [48].

![Diagram of ballast structure with labels for Ballast, Underlying Granular Layer, Surface, Subgrade, and Sleeper, indicating Ballast 76%, Underlying Granular Layer 13%, Surface 7%, Subgrade 3%, Sleeper 1%](image)

*Figure 11: Sources of ballast fouling combined together from all the sites in North America [19]*

If sub-grade is found to be the main cause for the ballast fouling, one of the following two reasons may exist [48]: due to contact abrasion between the sub-grade surface and the ballast aggregate or crack pumping; this happen when hydraulic erosion of water filled cracks on the sub-grade is subjected to repeat loading.

Even though tamping is an important technique to correct geometry problems, it has long run side effect resulting ballast damage. Accompanied with ballast bed loosening, it creates settlement. Further usage of the railway for rail traffic, the degree of settlement increases and finally ballast deterioration will happen.
Generally, when the fines become fully saturated and becomes like a mud, most of the ballast structure becomes softer and deformable. When these muddy and wet fouled material frozen, it lost its resiliency. When dried but still moist fouled material still exist on the structure, it act as a binding agent between inter particles, which finally reduces the resiliency [48].

![Diagram](image1)

Figure 12: Formation of ballast pocket [4]

The formation in figure (14) shows the area where the ballast layer starts to fail due to effect of loading. The depression developed beneath the rail and forms ballast pocket where is it filled with water. Further accumulation of the water in the ballast pocket causes bearing capacity failure Progressive failure observed in the sub-grade due to continuous loading on the track and compression on sub-grade (d), squeeze out of shoulders [4].

5.1.2 Detection

Ballast maintenance period has a detrimental effect on the transportation system and life span of the ballast structure. One of the most factors which determines the period of maintenance is, the degree of fouling. It was traditionally evaluated by normal inspection using necked eye and traditional drilling methods [53]. The percent of fouling for the specific causes are; 16% comes from an upward infiltration (which is the main source of ballast fouling) which further produces 7% from above. Breakdown of the ballast material results 76%, it is due to the interaction between inter-particles [11]. The general description of ballast fouling sources and its category with the estimated percentages are shown in table 3 below. The percentage of fouling can be estimated by the fine particle parameter which indirectly predicts the fouling index [19], percentage void contamination and the relative ballast fouling ratio [13].
5.1.2.1 Percent void contamination

Even though this method takes longer time and disregard gradation condition, it measures the gap or void between the fouling particles. It can be computed by using the following relation,

\[
PVC = \left( \frac{V_2}{V_1} \right) \times 100\%
\]

Where PVC, V₁, V₂ are the percentage of void contamination, volume of the void of the re-compacted ballast layer (since sample covers all the depths of the ballast layer), and volume of fouling material after re-compaction respectively [13].

5.1.2.2 Relative ballast fouling ratio (R_{bf})

It is the fastest method to predict ballast fouling than PVC method described above. The result obtained using this method is found to be better in comparison with the fouling index method. It is the ratio of the volume of dry ballast and dry fouled particles. It can be quantified as:

\[
R_{bf} = \left( \frac{M_f \left( \frac{G_b - f}{G_s - f} \right)}{M_b} \right) \times 100\%
\]

Where: \( G_s, G_b, M_b \) and \( M_f \) are specific gravity and dry mass for ballast and fouling materials respectively [13].
Table 8: Different sources of ballast fouling [19]

<table>
<thead>
<tr>
<th>Category</th>
<th>Sources of Ballast Fouling</th>
<th>Amount (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast breakdown</td>
<td>Mechanical interaction from handling (at quarry, from dumping, compaction, tamping, transportation)</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Mechanical interaction due to traffic(repeated loading, vibration, slurry hydraulic action)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemical weathering, including acid and rain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Freezing of water in particles</td>
<td></td>
</tr>
<tr>
<td>Ballast surface infiltration</td>
<td>Delivered with ballast</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Dropped from trains</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind blown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water borne</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Splashing from adjacent wet spots</td>
<td></td>
</tr>
<tr>
<td>Sleeper wear</td>
<td>Vertical axial loading/movement</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Horizontal/lateral loading movement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical abrasion and between sleeper/ballast</td>
<td></td>
</tr>
<tr>
<td>Underlying granular layer</td>
<td>Old track bed breakdown</td>
<td>13</td>
</tr>
<tr>
<td>layer infiltration</td>
<td>Sub-ballast particle migration from inadequate gradation</td>
<td></td>
</tr>
<tr>
<td>Subgrade infiltration</td>
<td>Infiltration from subgrade into ballast</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 9: British Railways sources of fouling [19]

<table>
<thead>
<tr>
<th>No.</th>
<th>Source</th>
<th>Degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Kg/sleeper</td>
</tr>
<tr>
<td>1</td>
<td>Delivered with ballast (2%)</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>Tamping:</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>7 insertions during renewal and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 tamp/yr for 15 years at 4 kg/tamp</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Attrition from various causes including traffic and concrete sleeper wear</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>(Traffic loading: 0.2 Kg/sleeper/million tons of traffic)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>External input at 15 Kg7yr</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>(Wagon spillage: 4.0 Kg/sq m/yr)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Airborne dirt: 0.8 Kg/ sq m/yr)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>432</td>
</tr>
</tbody>
</table>

Table 10: Comparison between PVC, Percentage of fouling and relative ballast fouling ratio [13]

<table>
<thead>
<tr>
<th>PVC</th>
<th>Percentage of fouling</th>
<th>Relative ballast fouling ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Value</td>
<td>Category</td>
</tr>
<tr>
<td>Fouled</td>
<td>32.78</td>
<td>Moderately clean</td>
</tr>
<tr>
<td>Moderately fouled</td>
<td>27.68</td>
<td>Moderately clean</td>
</tr>
<tr>
<td>Fouled</td>
<td>35.69</td>
<td>Moderately clean</td>
</tr>
<tr>
<td>Clean</td>
<td>11.63</td>
<td>Moderately clean</td>
</tr>
<tr>
<td>fouled</td>
<td>31</td>
<td>Moderately clean</td>
</tr>
</tbody>
</table>
Table 11: Categories of fouling based on the fouling index, percentage of fouling, and relative ballast fouling ratio [13].

<table>
<thead>
<tr>
<th>Category</th>
<th>Fouling index (%)</th>
<th>Percentage of fouling (%)</th>
<th>Relative ballast fouling ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>&lt;1</td>
<td>&lt;2</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Moderately clean</td>
<td>1 to &lt;10</td>
<td>2 to &lt;9.5</td>
<td>2 to &lt;10</td>
</tr>
<tr>
<td>Moderately fouled</td>
<td>10 to &lt;20</td>
<td>9.5 to &lt;17.5</td>
<td>10 to &lt;20</td>
</tr>
<tr>
<td>Fouled</td>
<td>20 to &lt;40</td>
<td>17.5 to &lt;34</td>
<td>20 to &lt;50</td>
</tr>
<tr>
<td>Highly fouled</td>
<td>≥ 40</td>
<td>≥ 34</td>
<td>≥ 50</td>
</tr>
</tbody>
</table>

5.1.2.3 Ground Penetrating radar (GPR)

It is used to evaluate ballast fouling. It is a non-destructive, very fast and effective continuously measuring technique.

![Figure 13: Critical Ballast fouling phases: (a) Clean ballast (b) Partially fouled ballast (c) Heavily fouled ballast [24]](image)

The accuracy of this technique is influenced by the undetermined dielectric constants (which determine the speed of electromagnetic (EM) wave inside the ballast, influence on the ballast thickness estimation, location of fouling location), unclear interface between clean and fouled ballast (since the gradation changes through time) and noise (from the rails and sleepers).

From the different types of GPR systems, Impulse system is the most commonly used GPR fouling measuring techniques in railroad. To mention the different types of GPR measurement techniques;
- Frequency Modulated GPR
- Synthetic GPR
- Stepped Frequency GPR
- Synthetic Aperture GPR and,
- Impulse or Pulsed GPR

The impulse system sends short time electromagnetic pulse and receives the reflected pulse (T/R). The reflected pulse may come from the different surfaces at different depth [53].

![Typical GPR Signal](image)

**Figure 14: Typical GPR Signal [53]**

These are;

$S_1$ - signal from the transmitter to the receiver

$S_2$ - reflection from ballast surface (this pulse amplitude is influenced by the dielectric constant of the top layer, which is the clean ballast)

$S_3$ - local scatters (it is from the air voids from the clean ballast)

$S_4$ - interface between clean ballast and fouled ballast or subballast

Moreover, there are variations of frequency energy at different depth on the structure. To show this variation graphically, time-frequency method called the short time Fourier Transform (STFT) is used. According to the research done on granite and limestone ballast material [53], STFT is found to be good technique to determine the fouled depth on the ballast structure by comparing laboratory test and field tests. Generally, direct relationship has been observed between moisture content, dielectric constant and fouling level. As the moisture
content increase in the material, there will be an increase of dielectric constants and fouling level and the reverse.

Field test has been conducted to check the effectiveness of the STFT method on GPR system. The fouling index of the samples can be determined by the same method and formula described above [19]. The dielectric constant measured during laboratory test is used to determine the thickness of ballast in STFT colour-map. The study on granite and limestone ballast materials [53] under laboratory and field condition shows that:

- Considering the same fouling level, a greater dielectric constant has been found for limestone ballast than granite ballast. Generally, if accurate field and laboratory data used to detect the fouling and water accumulation location, STFT colour map is found to be effective and shows clear image of the ballast [53].

5.1.3 Mitigation

Using hard and durable ballast material, select and use proper gradation, avoid ground water table and surface infiltration to avoid migration of fines from the subgrade and applying regular lubrication on the wheel-rail contact [43].

5.2 Settlement

5.2.1 Minimum aggregate size determination based on settlement and air void

An inverse relation exists between the grain size and contact points of each particles. As the size increases the contact points between particles will be smaller. This will lead to conclude, the force transferred from each particle on the contact surfaces will be greater and hence results particle breakage due to inter-particle surface abrasions [38]. Due to the breakage, there will be more fines produced. The presence of large amount of fines results permanent deformation. When fines exist between the coarser particles, it will reduce the void between the coarser materials. Since it has the capacity to retain water, it will reduce the permeability of the structure. This will develop excess pore water pressure which aggravates degradation of coarser particles and permanent deformation by reducing material skeleton contact [38].

“Effect of aggregate gradation on ballast performance” [23] states that, the void space and the load carrying capacity of the structure i.e. the performance of the structure can be evaluated by using “Ballast DEM model”. The study focuses on in AREMA common gradation, to check the structural performance (stability) and the drainage property under the induced traffic volume.

These are compared by considering the settlement and air void developed after the load application. By working on and re-engineering the percentage of gradation, the settlement can be reduced and hence the performance of the structure improved. A maximum density can be obtained if Fuller and Thompson (1907) formula is used which results good contact between
particles and better structural stability [23]. The formula is sometimes called as Talbot Equation and shown below [23].

\[ p = \left( \frac{d}{D} \right)^{n} \]

Where;  
- \( p \) - the percentage finer than the size;
- \( n \) - 0.45 for maximum density according to FHWA, and 0.5 according to Fuller and Thompson;
- \( d \) - the aggregate size being considered;
- \( D \) - the maximum aggregate size

Impact of functional performance of the different AREMA gradation is still not clearly investigated. Good ballast gradation should have proper drainage property. But for the specific gradation, it might not fulfil the load carrying criteria for structural support. By adjusting the percentage of the different sized aggregates on corresponding sieve sizes, it is possible to produce denser material which satisfies both the drainage and the carrying capacity [49]. Void space and structural stability are the main concern in designing good ballast.

Based on the above fuller and Thompson equation, the following chart developed taking the x-axis as the \( n \)th power of the sieve size (Normalized power sieve size). The diagonal solid line generated from zero to the maximum aggregate size is a line which results aggregate mix of maximum density and stability. Depend on the required maximum density; it is possible to calculate the percentage by weight of any size from the chart.

![Figure 15: Normalized power gradation chart (n=0.45) [49]](image)

This computation is further used to prepare a series of aggregate sizes having maximum density and better stability against the applied loading. But the slope of the different gradations varies with the selected minimum size shown above; increasing the minimum size
of the particle increases the slope of the gradation (i.e., from gradation a to f, range of particle size is getting smaller). The steeper the slope means that (gradation f is steeper), the particle size distribution is going to be uniformly graded. These gradation curves are called “Characteristic gradation curve” [23]; [49]. In this article, two Australian (RIC and Queensland), French and US (AREMA (No. 24, No. 3, and No.4)) standards are studied [49]. The gradations or size distributions for the above listed countries are shown below. The plot of AREMA No. 24 and AREMA No. 4 is different from the other plots.

![Figure 16: Common ballast gradation plot used for different countries [49]](image)

It is clear to see the plot similarity between AREMA No. 4 and the other gradations except AREMA No. 4 has smaller maximum size. AREMA No. 24 has totally different size distribution with different maximum aggregate size [49]. The different countries gradations are re-plotted again together with the normalized power gradation curve shown below.

![Figure 17: Common gradations in the normalized 0.45 power gradation chart [49]](image)

Comparing with the different characteristic gradation curves, AREMA No.24 is much closer to gradation “e” than the others, since (Queensland, AREMA No.3 and AREMA No.4) seems to have similar power distribution curve close to “f”. It is clear to say that, AREMA No.24 is denser than the other three distributions. In the normalized power chart, the entire different
countries gradation plot has an extension just like a tail than the characteristic gradation curves. It means that all the different countries gradations commonly used small fine particles [49].

The output obtained from the discreet element modelling (DEM), after analysing the air void content are shown on the table below.

Table 12: Characteristic gradation with minimum particle size and air void [49]

<table>
<thead>
<tr>
<th>Characteristic gradation curve</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum particle size (mm)</td>
<td>22</td>
<td>30</td>
<td>36</td>
<td>41</td>
<td>46</td>
<td>56</td>
</tr>
<tr>
<td>Mean air void content (%)</td>
<td>35.14</td>
<td>35.08</td>
<td>34.63</td>
<td>35.39</td>
<td>35.73</td>
<td>36.69</td>
</tr>
</tbody>
</table>

As it is clearly seen in the above table, curve f is more or less uniformly graded with maximum mean air void value of 36.69%.

Since the ballast structure is symmetrical, only half width considered during DEM ballast layer settlement simulation. The loading with repetition of 300 cycles on a single tie is shown below.

Figure 18: Repeated loading profile on a single tie [23]

The above characteristic gradations are subjected to repeated loading and their corresponding settlements are shown below. From the settlement plot, small amount of settlement seen at gradation “d” and bigger settlement observed at gradation “f”. In other words, when the particles are getting coarser and coarser, the layer settlement generated becoming bigger and bigger [49].
Figure 19: Ballast layer settlement for different gradations [49]

Higher settlement also observed on gradation “a” and “b” under same loading condition [49]. It is also seen from table 11; these two gradations have small mean air void content than gradations “d”. A more or less similarity exists between the settlement plot of gradation “c” and “d” [23]. The higher the settlement is the lower performance in structural stability. So, the lower boundary of minimum size set to be gradation “c”, since it has lower mean air void content and ballast layer settlement beyond which it is not considered to be good for ballast layer [23].

When repeated train loads are applied on uniformly graded aggregates where there is larger air void, there is tendency to be broken down which results permanent deformation. Articles [23]; [49] come up with a conclusion that, to fully avoid any drainage problem, larger particle sizes are preferred even though 36 mm particle size gives good drainage and structural performance. Among the different types of gradations seen in the research, plot of AREMA No.24 seems to be the same as characteristic gradation “e”. Evaluating the ballast layer settlement for “e”, it results lower settlement compared to the other gradations and hence AREMA No.24.

5.2.2 Causes

The main cause of ballast settlement is ballast fouling. As it is mentioned in section 5.1 fouling can be developed by different reasons. Vibration of ballast material normally causes inter particle interaction which causes degradation and sort of particle rearrangement, hence settlement will occur [52]. The amount of plastic deformation has direct connection with fouling and moisture or water content which is seen in large-scale cyclic triaxial test [6]. Another cause for settlement is repeated train loading [23]. Due to this reason, ballast structure will start to accumulate both recoverable and non-recoverable vertical deformation. Ballast maintenance should be progressively done when the repeated train loading cause considerable settlement. The severity of the settlement normally depend on the quality
(mechanical, physical, shape and strength) of the ballast structure and the underlying structure.

5.2.3 Mitigation

Ballast cleaning, it is a technique to remove the fouled ballast material and replace it with new material. Measure should be taken when the fouling percent reaches more than 30% and is necessarily ballast cleaning should be done when fouling reaches 40% finer than 22.4 mm. [10].

5.3 Drainage Failure

5.3.1 Causes

The three main water sources in the substructure of railway are listed below:

- Precipitation on the surface of the track
- Collected surface flow from the surrounding area
- Upward groundwater flow.

![Figure 20: Sources of water enter to the track [48]](image)

The precipitated water will drain down to the sub-ballast or laterally flow out of the ballast structure. For free lateral drainage from the ballast and sub-ballast, the draining stream should not be blocked. To achieve this situation, the sub-ballast edge and ballast shoulder should drain freely which fully remove the water from the track [48]. Water drains freely out in clean ballast with no problem. The presence of fouling on the structure affects the drainage property of the whole structure. When fouling progressively increasing on the ballast structure, the permeability is reducing, reducing the velocity of flow where the sub-ballast finally will exposed to infiltration problem. Accumulation of water in one side of the track and between two different tracks is also another drainage problem in the system which damages the ballast structure [1].
Specific descriptions are made by [14] on the effect of fine particles on the ballast structure. Hence its presence within the coarser material will change the permeability property of the coarser material. During this time, if the temperature drops below freezing, ice lenses will be formed and hence heaving occurred [14]. The term Frost action is basically refers to a circumstance coming due to freezing and thawing which is called thaw softening and frost heave [38]. The risk of ice formation in road structure is very dangerous if the temperature stays between $0^\circ$C and $-5^\circ$C, but, if the temperature stays for longer time very far from $0^\circ$C, the accumulation of water in road base will be minimal. The physical and chemical properties of a road section is influenced by time variation in water content or moisture content in the soil, depth of ground water table from the formation level, period where the temperature stays below $0^\circ$C and composition of soil material (heterogeneity) [31]. It is basically happened in the sub-grade where its particle composition is from soil material.

The biggest support from the sub-grade may be lost during fall season which is just after the winter where the heave part of the sub-grade start to melt and lost its strength and on very fast spring thaw [14]. Due to the flow of water from the unfrozen soil to the freezing zone, the ice lens will be formed which the cause for the formation of frost [38]. The resilient property of the granular material is influenced by the presence of water on the pore space. Its base layer modulus [18] during spring thawing observed to have weak response and it reaches in its maximum value during summer by double increment [18].

An inverse relation still exists between the amount of moisture in granular material and its resilience. It is observed that, when an applying a pore pressure of 70% of the confining pressure, the resilience found to be reduced by about 50-80%. Due to low permeability in small voids, the formation of ice lens is limited but there will be very high heaving pressure [39]. Generally speaking, laboratory research shows that, an increase in water content causes a reduction in resilient modulus but field experience is still found to be uncertain [18]. The effect of frost action can be avoided by considering the following conditions during designing [39].

- Avoiding the intrusion of water in the structure and controlling the height of capillary rise by using non frost susceptible soils.

- Introducing an insulation which protects frost penetration and replacing the frost susceptible soils of the depth of the frost penetration with clean granular material.

- Provision of surface drainage and intercepting ditches, which can lower the level of the water and avoid any accumulation of the water from the structure.
Figure 21: Hydraulic action [19]

Figure 21, shows the accumulation of water in the ballast caused by drainage problem, this water forced out due to dynamic loading on the sleeper consequently creates opening between the ballast and the sleeper. Loaded trains traffic is a very severe action for sleeper wearing than speed of the traffic as it is observed in the openings beneath the sleeper which is due to the presence of water in the void around the sleeper.

5.3.2 Mitigations

As a remedy – since thawing during spring occur from top to down, the structure will still be affected by the trapped water since the shoulder and bottom area stayed freeze for longer time. This excess saturation will damage the structure. So, proper drainage system reduces the risk of failure due to thaw [14].

5.3.3 Presence of mica in granular material

Another problem regarding heaving is the presence of mica in the aggregate. In excess presence of water in mica rich aggregate is another reason for heaving, rutting and reducing the bearing capacity of the structure when there is seasonal climate change, this is a critical problem in base-course [33]. During the investigation on the water absorption of different rocks having different percentage of mica, a source with high amount of mica (greater than 30%) absorb water and retain it for longer time compared with source of smaller amount of mica (less than 20%) [33]. A conclusions which is drawn by [33], that the degree of water retaining is a function of the grain size of the granular material and the amount of mica present and hence a positive correlation if observed between the water absorption, mica content and the water retaining capacity of the aggregates [33]. Generally, [18] concluded that, an excess presence of free mica in unbound granular material is believed to highly affect the bearing capacity with decreasing density.
6. Aspects of Modelling

Before railway technology becomes modernized, observation and experience based empirical solution has been used to determine the track bed thickness without considering the loading, hydrology and the geology of the area [34].

There are different kinds of railway track models, among those models most of the most of them are continuum and the rest are discrete. The one dimensional (1D) Winkler’s foundation beam (a mass-spring system) is one of the continuum models, very simple method and it is used most frequently. The 3D linear elastic model and the 3D nonlinear models are another continuum models which can be solved by semi-analytical and Finite Element Methods (FEM) respectively. Due to the discrete nature of the ballast structure, the continuum models have some difficulties [35].

Comparing the two modelling techniques, the discrete element method is more realistic; simulating the real condition than the continuum approach (it does not account the morphological characteristics of aggregates, such as shape and particle size distribution) as it is shown in figure 22 below. The discrete nature of the ballast material such as individual movement of the particles and physical interaction at contact points makes the continuum modelling very complex. It is also observed by [35] that, due to the discrete nature of the ballast structure, the continuum models have some difficulties.

![Figure 22: Contact point force transfer [23]](image)

There are three major operations in DEM techniques:

1. Computation of element contact forces
2. Computation of particle motion and
3. Detection of contacts

The detection of contacts can be calculated by cyclic DEM, shown below where the force-displacement relates the displacement developed between two elements which acts force on each other.

![Diagram of calculation cycle in DEM](image)

*Figure 23: Calculation Cycle in DEM (ITASCA, 1999) [23]*

In the start of each cycle, new contact force is obtained. The normal and shear components are obtained by resolving this computed new contact forces [23].

Railway structure has different components; usually the following components are used during construction based on the interest and stated below from top to bottom of the structure. i.e. Rail, sleeper, railpads, fastenings, ballast, subballast and subgrade. The design of each component can be done by simple conventional beam theory (Euler-Bernoulli beam) or my sophisticated method (Rayleligh-Timoshenko beam).

Most of the time when the track is designed, it is treated as a beam rests on continuous elastic foundation. This elastic foundation can be modelled by evenly distributed linear spring stiffness. Hence the deflection of the beam is proportional to the distributed load supporting the rail beam, as it is introduced by Winkler. In this model, the beam bending stiffness and the foundation stiffness supporting the beam are the only track parameters required [15]. Hence two responses are expected from the performance measurement of the track, i.e. the vertical track stability and the lateral track stability [48]. Subgrade is part of the component which has major influence on the stiffness of the rail. It is also part of the structure which creates uncertainty on the stiffness of the rail since its behaviour changes with time [48].
Conclusions

Naturally obtained and crushed, angular, rock material satisfying all the physical and mechanical property is good for ballast construction. To achieve on better particle interlocking and to get the required resistance to dynamic loading in the transverse and longitudinal direction, angular stones are the best than rounded shape when proper gradation is used. There is no universal specification of ballast material and gradation because of the difference in property of the subsoil condition of the structure and its index characteristics such as size, shape, hardness, friction, texture, abrasion resistance and mineral composition.

The presence of more water in the structure is very disastrous during winter season and also more mica in the structure which also causes ballast structure failure. In the survey, to avoid any structural failure it is found that, the minimum aggregate size that has to be used as ballast material should be 36 mm in spite of the other governing factors which results minimum settlement with adequate drainage.

From the two different ballast structure modelling techniques, it is seen that, discrete element method is more realistic; simulating the real condition than the continuum approach (it does not account the morphological characteristics of aggregates, such as shape and particle size distribution). The discrete nature of the ballast material such as individual movement of the particles and physical interaction at contact points makes the continuum modelling very complex.
References

[39]. Ochola, C. (n.d.). Investigating Failure of a Road Section Due to Frost Heave.
[40]. Ozcelik, Y. (2011). Predicting Los Angeles abrasion of rock from some physical and mechanical properties.