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Graduate School of Engineering
(Civil Engineering)



MASTERS THESIS

**SHEAR STRENGTH BEHAVIOUR OF BASIC OXYGEN SLAG FROM LARGE-
SCALE DIRECT SHEAR TESTING**

by

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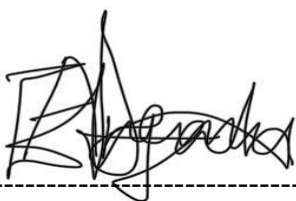
Co-supervised by: Professor Jong Kim

March 2026

Declaration form

I declare that the work presented in this thesis, with the title “Shear strength behavior of basic oxygen furnace (BOF) slag from large-scale direct shear testing” is the result of my own work. Any ideas, data, or words taken from other sources have been properly acknowledged through appropriate citations.

I further confirm that, as far as I am aware, this manuscript has not been submitted previously, either in full or partially, for the award of any qualification at Nazarbayev University or at any other university in Kazakhstan or any other higher institution worldwide.

A handwritten signature in black ink, appearing to be 'Z. B. B.', written over a horizontal dashed line.

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Abstract

The use of natural aggregates as ballast in the railway industry raises sustainability concerns, requiring the application of industrial by-products. This study examines the potential of adopting Basic Oxygen Furnace (BOF) slag as a sustainable alternative to the conventional crushed stone ballast through a combination of experimental and numerical analysis. Laboratory-scale large direct shear tests were carried out to obtain validation results, while the Discrete Element Method (DEM) was employed to model the macro and micro-scale shear response of different mixtures of BOF slag and bauxite sedimentary rock (0%, 20%, 40%, 60%, 80%, and 100%). The findings indicate that although BOF slag has lower shear strength and friction angle values than bauxite, mixtures containing 20-40% BOF slag have relatively similar mechanical properties. Microscopic observations show that the addition of BOF slag causes a randomization of particle contacts and a reduction in fabric anisotropy. Nevertheless, a small amount of BOF slag (20-40%) can be beneficial in reducing localized stress concentrations and particle breakage. The study further establishes a constitutive model linking fabric development and shear strength. Overall, a 20-40% BOF content emerges as an optimal window that deliver meaningful sustainability benefits without materially compromising shear resistance, supporting resource-efficient ballast design and maintenance.

Keywords: Railway ballast materials; BOF slag; Discrete Element Method; Direct shear strength properties; Fabric anisotropy; Sustainable and durable geomaterials

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Chapter 1 – Introduction

1.1. Overview

This study investigates the potential of using BOF slag a sustainable alternative material to the traditional crushed rock used in railway ballast applications. Given the reduced availability of high-quality aggregates, this material presents a viable solution due to its promising physical, mechanical and chemical properties. This study used the large-scale direct shear equipment to examine the shear strength properties of the slag and the mixture with traditional stone under varying normal stresses. In addition, the DEM was used to validate the experimental data and investigate the microstructural properties of the samples. The outcomes of this research could offer a greener railway track design by reducing reliance on natural aggregates and promoting waste management from industries.

1.2. Background

Ballasted rail systems are essential to contemporary transportation systems, which is both economical and sustainable, and safe mode of transporting cargo and people. With respect to other types of transport, they have some unique characteristics such as increased weight carrying capacity, less energy consumption (Janic, 2003), and extensive network reach (Neumann, 2021), and thus play a very vital role in improving economic growth and development. Of the elements of a standard ballasted rail installation, the ballast bed is the heaviest and most important structural element. Since it is constituted of coarse granular material, usually made of high-grade fragmented stones, the layer has a number of main functions: it supplies sufficient reinforcement and even load distribution of the moving trains, assists in retaining the rails in place under diverse weather conditions, and promotes good water runoff (Sadeghi et al., 2016; Z. Yan et al., 2025). The overall efficiency and longevity of the track structure are a function of the physical and mechanical properties of the ballast aggregate. The industry has been dependent on quarrying sites and excavation sites for years to provide high-quality natural granules for use as rail ballast (Ezsias et al., 2023). In addition, the increasing demand for high-loading and quick-transit freight railways, which require robust track stability and strength, requires constant usage of crushed rock owing to its excellent characteristics (Y. Guo et al., 2022a). Yet, they cannot be considered sustainable because of their finite and ascertainable depletion (SNAP-SEE Project, 2019; Sverdrup et al., 2017). According to Ezsias et al. (2024), the period of depletion of such reserves is largely determined by mining timetables, directed by economic requirements, company objectives, regulatory mandates, and operational necessities. Besides, the processing and mining of these materials

have severe environmental effects involving terrain alteration, acoustic pollution, particulate emission, seismic effects, and aquifer degradation (Langer, 2016). It requires an ecological footprint of 11.5 milli eco-prints (mPt), or per-capita temporal effect, to mine a single metric ton of natural granule. This operation also requires 496-518 MJ of energy and dissipates 32-33 kg of CO₂ equivalents as emissions (Hossain et al., 2016). Therefore, authors and managers of railway networks are seeking green substitutes to conventional ballast, addressing reuse of the material, industrial waste as raw material, innovative refining processes, and use of strengthening techniques to improve efficiency, reduce environmental harm, and lower energy usage (Braga et al., 2017; Indraratna et al., 2018; Linares et al., 2024).

Recycling aggregates involves collection and reutilization of worn-out materials, typically through crushing, screening, and sorting operations to generate recyclable products. Previously, deteriorated and fouled (with tiny particles, trash, and coal ash) ballast was unnecessarily removed and replaced with new material in routine maintenance operations. It has resulted in widespread refuse buildup and virgin resource depletion (Gomes Correia et al., 2016). Research indicates that recycled ballast can maintain a significant percentage of its structural qualities provided it is treated properly. For example, Anderson et al. (2003) realized that intensive pressure washing, improved screening, decontamination, and the restoration of drainage capability are capable of making recycled ballast a successful and possible option. Also, the incorporation of reused ballast mixed with fresh aggregate in regulated ratios (10-30%) has been found to yield slightly less shear resistance compared to clean ballast, thereby attaining a balance between sustainability requirements and long-term track performance (Jia et al., 2019; Leus et al., 2021).

Moreover, minimization of virgin natural material dependency for railway ballast is also achievable by embracing secondary materials from industrial processes as substitutes. These are materials that have been regarded as waste but have properties that are comparable to conventional natural stone. Examples are steel slags, coal wash and rubber crumbs (Indraratna et al., 2018). Slags are wastes obtained as a result of steel manufacturing. The primary waste products from this process are Electric Arc Furnace (EAF) Slag, Granulated Blast Furnace Slag (GBFS), and BOF Slag. Previous research indicate that EAF slag has considerable potential for application in sub-ballast and ballast layers (Esmaeili et al., 2025; Godson et al., 2025; Indraratna et al., 2018; Jing et al., 2020). BOF slag is different from EAF slag by the elevated level of carbon, iron, and silicon compounds (Yildirim & Prezzi, 2011). As stated in a study by Netinger Grubeša et al. (2016), one metric ton of BOF slag is generated with each ton of steel

produced. Unsustainable disposal of the residue can cause serious environmental problems like, environmental disturbance and waste landfill space reduction. The use of BOF slag for rail ballast has been considered in many studies. For example, Koh et al. (2018) concluded that it is better than traditional aggregates in unit weight, resistance to wear and unconfined compression. In addition, Olarewaju Olagunju et al. (2023) concluded good mechanical, physical, and environmental properties of BOF slag as a rail ballast material.

Prior research have proven the potential use of BOF slag as railway ballast. However, there is a significant gap in assessing the shear behavior of BOF slag and its mixtures with the traditional crushed stone. The macroscopic and microscopic shear properties are significant parameters that control the ballast performance under service loads. The overall understanding of these characteristics is required for the improvement of the application of BOF slag in railway construction. The goal of this research is to fill this gap using an integrated experimental and numerical approach. The experimental work involves a series of large-scale direct shear tests on crushed stone and BOF slag, mostly for the verification of the numerical models. The major focus of this research is the application of the DEM, a highly efficient numerical method that illustrates granular assembly as a group of discrete particles interacting with each other. Based on the DEM, the macroscale and microscale characteristics of BOF slag and its mixtures with conventional crushed stone (0%, 20%, 40%, 60%, 80%, and 100%) were analyzed. In addition, the constitutive equations between the internal particle interactions and the external macroscopic behavior of the granular materials were also developed.

1.3. Objectives

The primary objectives of the study are outlined below:

- Large-scale direct shear testing of BOF slag and slag-stone ballast mixture.
- Modelling and simulating the realistic shape of ballast particle subjected to shearing.
- Validation of the DEM numerical results with experimental data
- Macroscale and Microscopic analysis of slag-stone mixtures (0%, 20%, 40%, 60%, 80%, and 100%)
- Establishing a constitutive relationship between internal contact mechanics and applied stress ratio for stone-slag mixtures

1.4. Thesis outline

Chapter 1 - Introduction: The chapter describes the sustainability issues in the railway ballast sector and the opportunities that sustainable materials can provide in overcoming these issues.

Later, it introduces a new material, BOF slag with some of its unparalleled properties, as shown in the previous studies. The above discussion has indicated the lack of critical knowledge in the area of shear characteristics of slag mixes of BOF and natural aggregates. In this regard, the primary goal of the research is as follows: to compare the macro-level and micro-level shear behavior of BOF slag and its mixes with natural aggregates based on the complex of experimental and numerical research.

Chapter 2 - Literature review: This section integrates the existing knowledge on the requirements of railway ballast, the environmental implications of the extraction of natural aggregates, and the utilization of alternative materials such as steel slags. This chapter also introduces DEM as a powerful numerical tool that can be utilized in understanding the microstructural properties of granular materials under various stress conditions. It also discusses the mechanical behavior of BOF slag and the application of DEM in railway ballast.

Chapter 3 – Methodology: This chapter explains the two-phase approach. First, it explains the laboratory program with a large direct shear apparatus. Second, it explains the numerical modeling phase. This includes the creation of particle clumps in PFC3D, the calibration of the model with experimental results, and the creation of the numerical model. Moreover, the approach to assess the development of fabric anisotropy, a significant microstructural parameter that was later used to describe the variation in macroscopic strength, was also defined.

Chapter 4 – Result and Discussion: This chapter will discuss the results and interpretation of the findings. The chapter will start with the macroscopic stress-strain response and friction angles to determine the best mix of BOF slag. The chapter will then continue with the micromechanical analysis to describe the macroscopic behavior in terms of the development of the coordination number, fabric anisotropy, and the strong and weak contact network. A power-law constitutive model between the fabric deviator and stress ratio will be developed.

Chapter 5 – Conclusion: This chapter gathers the most important results of the research. It confirms the validity of the optimal BOF slag mixtures as a sustainable alternative, summarizing how the particle shape and the packing density are responsible for the macroscopic shear strength. The conclusion focuses on the successful micro-macro correlation, the relationship between fabric and applied stress, and the environmental advantages of the proposed mixture.

Chapter 6 – Limitations and Future Work: This chapter outlines the major boundaries of the research. It also proposes future research directions for subsequent research to build upon and extend the current findings.

Chapter 2 – Literature Review

2.1. Railway Infrastructure

Railway infrastructure consists of two major components: substructure and superstructure as shown in Figure 2-1. The superstructure, typically constructed from cast iron and steel consists of railway sleepers, fasteners, and rails. These components directly interface with train wheels and bear the applied loads and transfer it to the substructure. The substructure of the railway system which supports the loads transmitted from the superstructure, is made up of three layers: ballast, sub-ballast and subgrade. The collective function of all the components within a track system is to ensure a stable and firm foundation for comfortable and safe transportation. To accomplish this, each component must effectively perform its designated role under various loading conditions.

2.1.1. Railway Superstructure

The rails provide for smooth, low-friction movement of the train wheels and aid the wheelsets into the right position. The rail also bears the wheel loads directly and spread them across the supporting structures (Feng, 2011). Braking and traction of the train result in longitudinal and lateral stresses which are also conveyed through the rails. In addition, the rails also serve as electricity conductors for the signaling system (COENRAAD ESVELD, 2001).

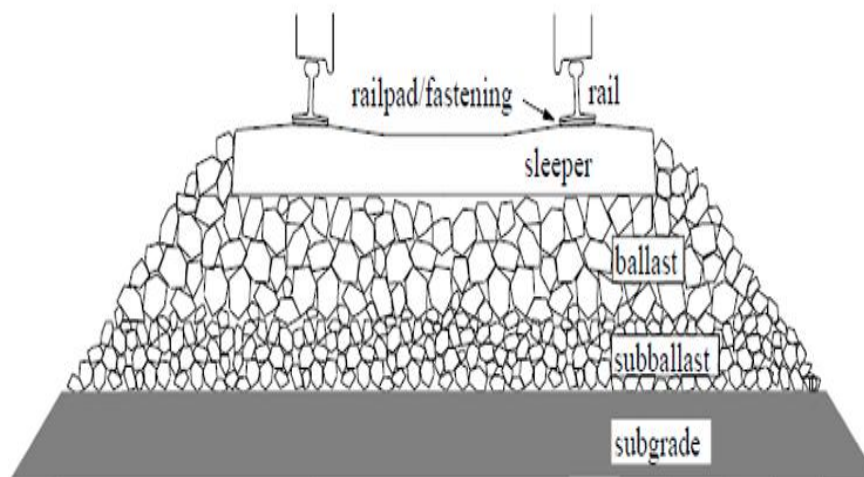


Figure 2-1. Railway Infrastructure System (Dahlberg, 2003)

The rail pads serve as an interface material between the steel rail and the railway sleeper surface. They transmit stresses from the rails to the sleepers while shielding high-frequency components of force. The rail pads also provide electrical insulation, which safeguards the sleepers against wear and tear, as noted by Feng (2011). The rail pads also influence the cyclic response of the track. Fasteners provide the physical link between sleeper and rail, keeping

them in position. They are a major component, resisting any form of lateral, vertical and longitudinal rail movement.

The railway sleeper is an important component of the track system. They serve as beams positioned between the rails and the substructure. Their major functions include maintaining the rail gauge, guarding against abrasion, preventing bearing plate separation and ballast deterioration, and evenly distributing loads to the ballast layer (Zhao et al., 2007). They must possess enough strength, stiffness and durability to maintain the rail gauge distance, prevent lateral movement and distribute forces at the required stress level (Ferro et al., 2020). The most generally accepted materials for sleepers are timber and steel prestressed concrete. From the onset, timber was widely utilized but later replaced with concrete sleepers because of its superior properties.

2.1.2. Railway Substructure

The railway substructure comprises of ballast layer, sub-ballast and subgrade layer. Ballast is a discrete granular material in direct contact with sleepers and providing support. It is made up of individual particles usually larger in size than the ones utilized in common geotechnical engineering materials (C. Shi et al., 2023a). For a material to be a ballast material, there are specifications that must be fulfilled like particle shape and size, gradation, strength, density, surface roughness, hardness and resistance to wear (D. Li et al., 2015).

The sub-ballast is an interface layer that spans between the subgrade and ballast course, whose function is to diminish the stress intensity transmitted from the ballast course to the foundation and provide drainage (Burrow et al., 2007). As far as particle size is concerned, sub-ballast layer has finer particles (0.05mm – 19mm) compared to ballast material (20mm – 60mm). Sub-ballast layer also acts as a barrier in the sense that it prevents fine material from the subgrade from entering the ballast layer and also prevents ballast from penetrating the subgrade. For a material to be classified as a sub-ballast material, it has to be coarse, well-graded, free draining and locally available (Shahu et al., 2008).

The subgrade is the bottommost element of the substructure that forms a hard and solid base for the whole track structure. The status of subgrade may be significantly diverse according to geological structures and site conditions ranging from soft rock or clay to hard rock (Xin, 2019). The subgrade must be sufficient to bear the ballast and sub-ballast layers and must be stiff to withstand the stresses generated because of train passage. Therefore, if the subgrade is not sufficiently strong, it must be provided with strengthening measures so that it does not undergo instability and or failure by any mode.

2.2. Railway Ballast

The term “ballast” stems from its use in marine related concept. It was the gravel and crushed stone used for balancing the weight of coal ships in Britain on their homeward journeys. These gravel and stone materials, after being unloaded from the ships, were placed on the subgrade along railway coal lines. Ballast was subsequently placed over the subgrade, eventually becoming a key component of ballasted track systems (Y. Guo et al., 2022a). Ballast has historically been a measure of well-graded broken stone; however, various other materials have been incorporated to act as ballast material. Ballast is generally placed in a compact layer, usually 250–350 mm thickness, as indicated in Figure 2-2, and serves the following functions (Sadeghi et al., 2016).

- It resists the sleepers from lateral, vertical and longitudinal displacements, thus ensuring a firm support system for train travel.
- It facilitates the transfer of train-induced forces to the subgrade. This ensures that the subgrade (foundation) does not exceed its maximum bearing capacity.
- It preserves the track’s orientation in both lateral and horizontal directions.
- It regulates the stiffness and elasticity of the entire structure of the track.
- It serves as an insulator, preventing interference with the power supply of the track
- It facilitates proper drainage and absorption of noise and vibration.
- It minimizes the potential for vegetation growth within the track structure.

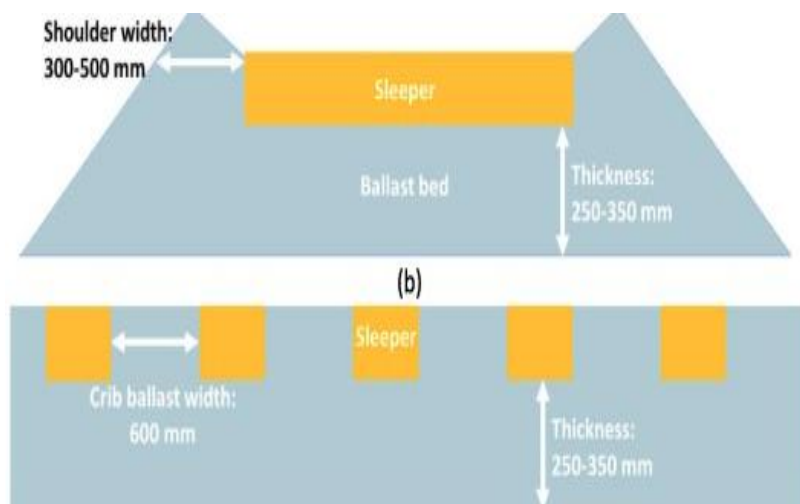


Figure 2-2. The side view of ballast layer profile (Y. Guo et al., 2022a)

2.3. Railway Ballast Properties

The properties of ballast are responsible for long and short-term performance on site, and they fall into two large categories. The first category involves particle properties influencing the mechanical response of ballast and comprises particle size, particle shape, mechanical properties, material composition and density. The second category involves layer properties influencing the behavior in general and comprise particle size distribution, compaction, fouling, permeability, stiffness and geometry.

2.3.1. Particle Size and Distribution

Ballast particle size refers to the individual particle dimension, whereas particle size distribution is the range of sizes in a specific volume of ballast. Railway engineering works use ballast size typically between 10mm and 60mm, depending on the applicable standard. However, over time, the distribution can be altered by reasons like transport, handling, compaction and deposit (Shi et al., 2023). According to Guo et al. (2018), an increase in the number of trains passes causes weakening and reduction in the size of ballast particles. Nevertheless, even after multiple loading cycles, approximately 90% of ballast particles retain their original shape size. This is because most of the ballast particles, with a mean particle size of approximately 30mm, are not prone to cracking compared to larger particles with a size greater than 40mm.

Several studies have investigated the impact of ballast particle dimensions on its mechanical properties. Generally, on the basis of a number of studies, the shear strength of ballast tends to increase with an increase in particle size. This is due to the fact that the bigger the particles, the more they weigh with a lot of inertia, and consequently, contact forces established between large-sized particles are more than those established between small-sized particles, resulting in increased interlocking between particles. This increased interparticle friction, in turn, improves the stability of the ballast granular assembly (Kolbuszewski & Frederick, 1963; Marschi et al., 1972). Indraratna et al. (1998), however, objected that this hypothesis holds true only if the breakage tendency of the ballast materials is assumed to be zero or low. C. Shi et al. (2023) further noted that a definitive conclusion cannot be drawn as smaller particles would result in greater agglomeration, making the ballast course stiffer and stronger.

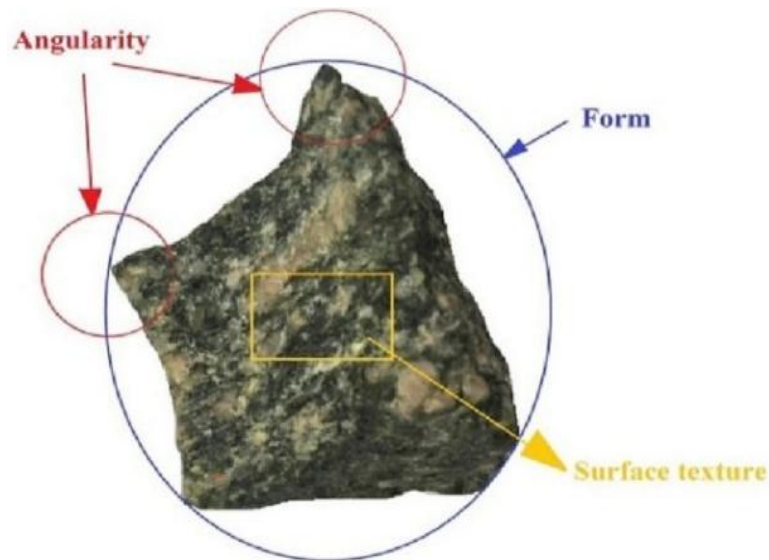


Figure 2-3. Overview of ballast particle shape (C. Shi et al., 2023b)

The particle size variation of ballast varies across various countries. Some nations have developed their own standards, while others adopt the standards of a particular country. As shown in Figure 2-4, the United States uses the American Railway Engineering and Maintenance of Way Association (AREMA) standard. Ballast particles typically exhibit larger sizes and higher angularity compared to traditional geotechnical materials. There exist no viscous forces (internal cohesion) between ballast particles, hence particle size distribution plays a vital function in estimating the mechanical characteristics of ballast (Indraratna & Salim, 2005).

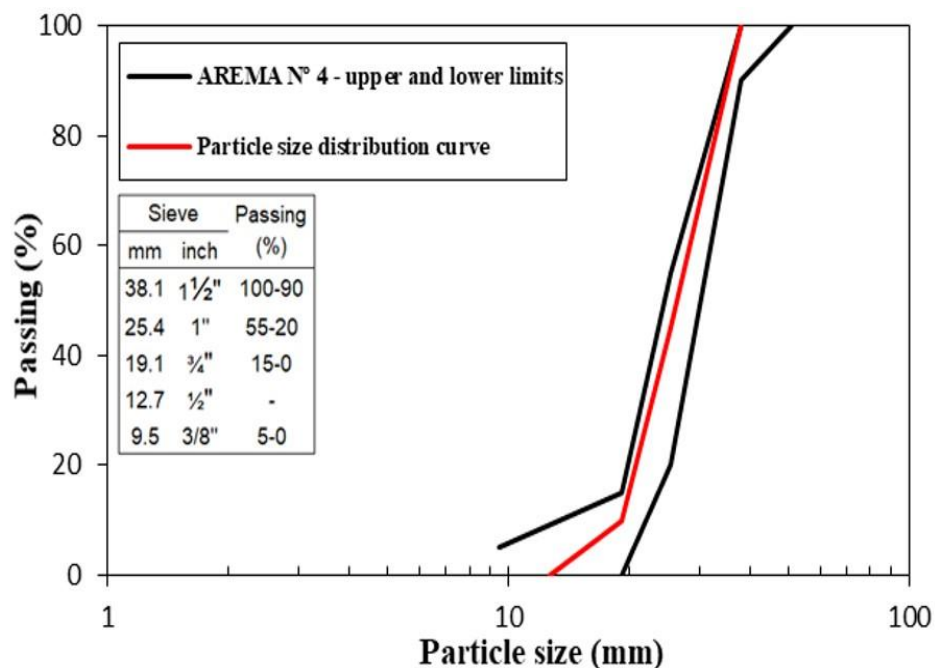


Figure 2-4. AREMA 4 standard particle size distribution (Andrade et al., 2024)

2.3.2. Particle Shape

The various shape characteristics of ballast particles that have been proposed are flakiness, elongation, sphericity, angularity and surface structure (Y. Guo et al., 2020). However, because of the complexity and irregularity of ballast particles, there has been no universally accepted shape characteristics suitable for ballast material. Among these, elongation and flakiness variables have gained prominence in international standards. There were comprehensive experimental and numerical studies that analyzed the effect particle shape has on ballast performance. It was concluded from the research that shape, form, and texture of the ballast are amongst the most important parameters affecting performance. These properties affect ballast particle deformation and interlocking and thereby have a profound impact on strength. Some numerical analyses using DEM have been performed and they proved to show the impact that particle shape has on the mechanical response of ballast layers. For instance, Kodicherla et al. (2019) found that particles with rough surface and jagged edges significantly increase particle friction.

2.3.3. Particle Form

The form of a ballast particle is described in terms of its longest (L), shortest (S), and intermediate (I) orthogonal states. These dimensions characterize ballast as cubic, elongated, or flaky (Guo et al., 2019). Elongation is described as the intermediate dimension divided by the longest dimension (I/L), and flakiness is taken as the intermediate dimension divided by the shortest dimension (I/S). The definitions of elongated and flaky ballast differ between countries. The British standard have defined ballast to be flaky when the ratio is more than 1:1.67 (B.s.p.B.E, 2013). The American standard ranges the ratio between 1:2 to 1:3 and 1:5. The Brazilian standard applies a ratio of 1:2. The British, Brazilian and American standard apply 1:1.8 for elongated particles. A particle is said to be cubic if it doesn't belong to the above categories.

According to numerous research, flaky and elongated particles have the highest tendency to break due to abrupt alteration of contact forces. For instance, in a uniaxial static load test conducted by Juhász & Fischer (2019): the finding showed that most of the broken ballast are flaky while cubic ones exhibited the least breakage. the finding revealed that most of the broken ballast are flaky while cubic ones experienced the lowest breakage. Another instance is Los Angeles Abrasion tests, and image analysis carried out on ballast: the findings revealed that greater LAA losses was seen for flaky and elongated particles (Y. Guo et al., 2018a). Overall, the cubic shape of ballast gives the best strength and resistance to breakage performance.

2.3.4. Particle Angularity

Angularity of ballast particles has a substantial effect on their compaction, stability, and response in railway tracks. Angular particles enhance shakedown action and frictional interlocking, hence enhancing shear strength while reducing deformation. During the service of ballast layers, especially tamping, angular ballast particles wear easily due to the tendency of moving towards sphericity, which results in loss of stability.

A study by Fardin Rosa et al. (2021) showed that increased angularity is associated with increased porosity when compressed while rounded particles, without interlocks, settle more through particle moving more easily relative to each other. Particle shape is also important as cubic particles resist loss of angularity more than flaky or rod-shaped ones which degrade faster through more pointed edges. DEM simulation by Huang (2010) shows that high Angularity Index (AI) and low flat-and-elongated ratios increase the lateral resistance against ballast layer to sleeper, even though these models do not include breakage and abrasion. Similarly, Bian et al. (2019a) observes that high-AI particles can strengthen the ballast skeleton in shear tests, resisting deformation and failure, even though it is non-crushable in simulation. Typically, angularity enhances track stability but deteriorates with age, affecting long-term performance.

2.3.5. Particle Degradation

Ballast particle degradation occurs when the particles are subjected to stresses that exceed the acceptable range. Intense maintenance activities and heavy haul loadings are some of the operations that trigger such degradation (J. Chen et al., 2023). As a result, the initially sharp edges and angular corners of the particles begin to wear out, gradually forming rounded and blunter ends. When dynamic loading is applied to ballast, the stresses induced cause two kinds of breakages. The first type, corner breakage, involves the wearing of sharp corners into round ones. The second involves breaking the ballast into halves or thirds. The former is likely to occur with low confining pressures while the latter occurs with very high confining pressure (Lackenby, 2006). Figure 2-5 shows how the various loading conditions influence the ballast particle degradation. Based on the figure, abrasion or polishing tends to be often brought about by relative motions of ballast such as rotation and rubbing.

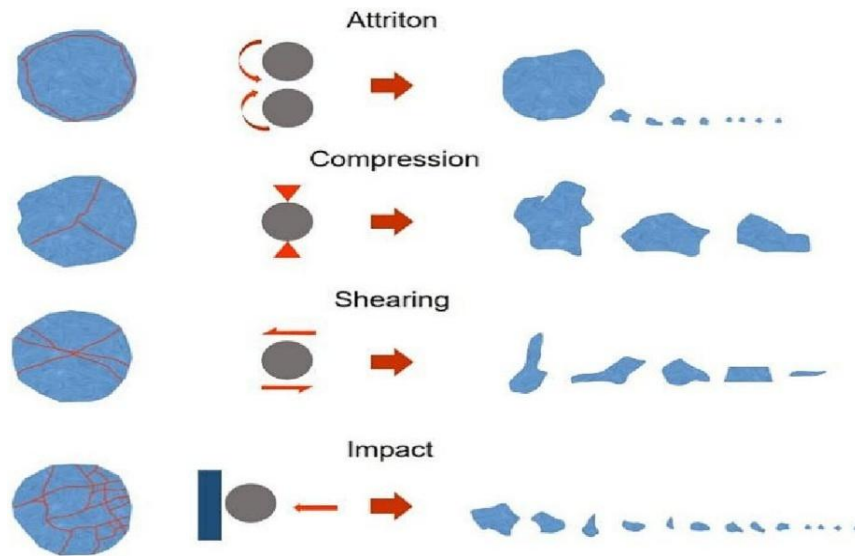


Figure 2-5. How different loading conditions affects particle degradation (C. Shi et al., 2023b)

For the assessment of ballast particle degradation through multiple cyclic loadings, various standards and testing procedures are employed, of which the most widely used ones are Los Angeles Abrasion (LAA) and Micro-Deval (MD) tests. The recent advancements have incorporated machine vision technology and image segmentation that offer rapid, effective, and automatic means of analyzing aggregate particle size and shape compared to conventional techniques (Tutumluer et al., 2005). These technologies enable precise measurement of changes in aggregate shape property during deformation and breakage under simulated train loading. Multiple imaging systems utilize specific mathematical algorithms to compute validated indices for describing form, angularity, and texture properties of aggregates. Flat and Elongated Ratio (FER), Angularity Index (AI), and Surface Texture Index (STI) have been universally accepted as the key parameters of aggregate shape characterization in national studies (Moaveni et al., 2014). The impact of ballast degradation on particle size distribution and particle shape of the ballast aggregates is shown in Figures 2-6 and 2-7. Ballast degradation decreases particle size by fracturing larger particles initially and gradually smoothing others, transitioning gradation from uniform to well-graded. It also modifies particle shape by rounding edges, lowering angularity (AI), smoothing surface texture (STI), and reducing flat and elongated ratios, resulting in more uniform, cubical particles.

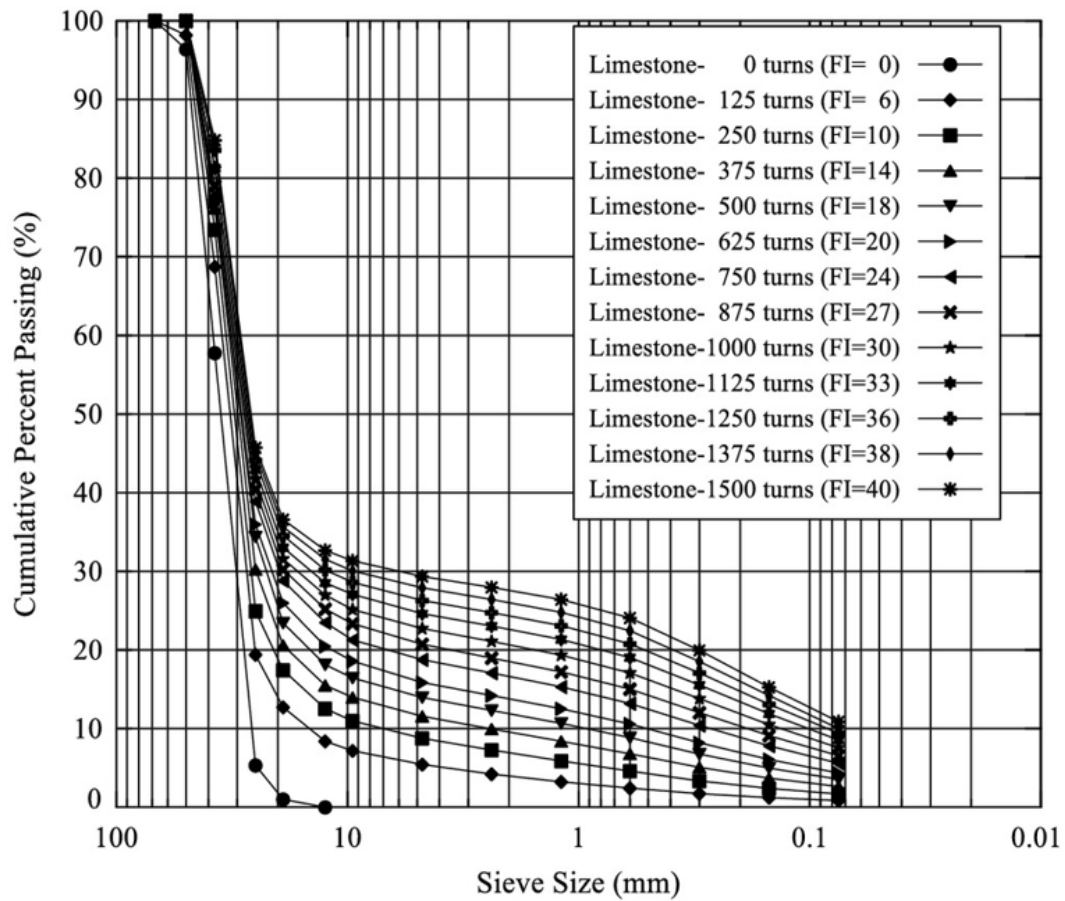


Figure 2-6. Impact of ballast degradation on particle size distribution (Diyaljee, 2018)

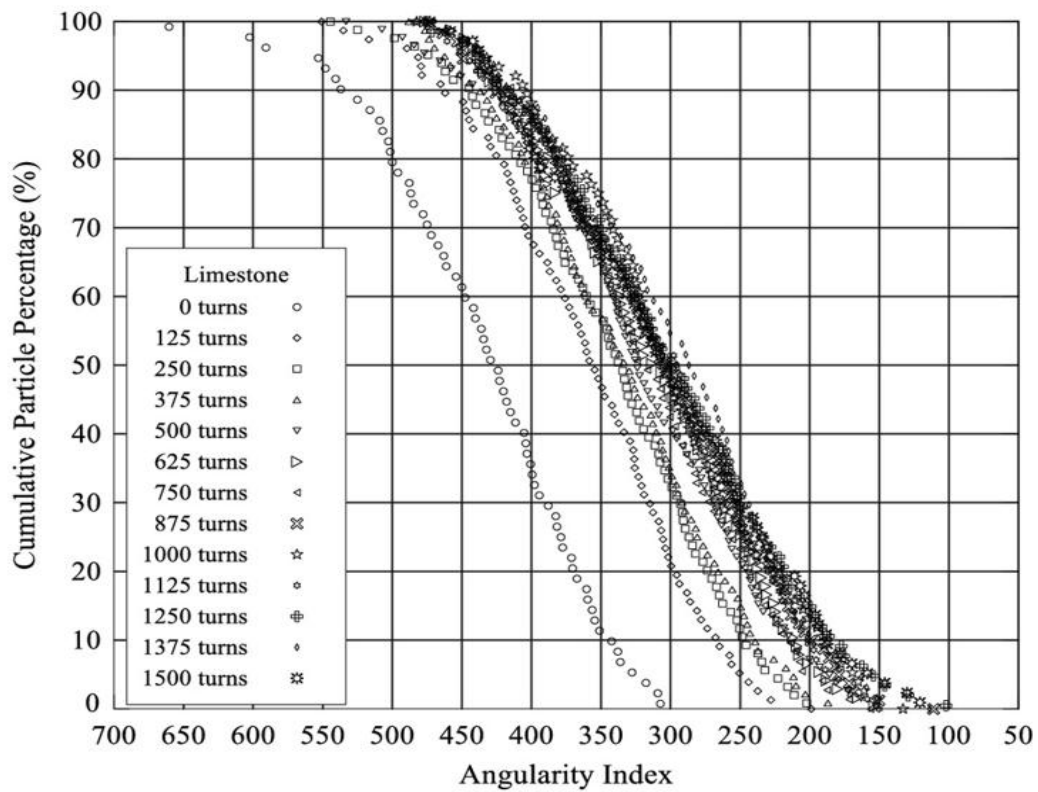


Figure 2-7. Impact of ballast degradation on particle shape (Diyaljee, 2018)

2.3.6. Particle Layer Fouling

A major cause of ballasted track disintegration, inadequate drainage and misalignment is ballast fouling (Y. Gong et al., 2023). Fouling occurs when the voids between ballast particles become contaminated, predominantly by fine particles. It is widely agreed that ballast is considered greatly contaminated when the percentage of fine particles smaller than 14 mm surpasses 30% by mass (China, 2013). When voids are contaminated, it reduces permeability and elevates the moisture content within the ballast layer, as illustrated in Figure 2-8.



Figure 2-8. Particle layer fouling (C. Shi et al., 2023b)

Common contaminants include fines from the ballast itself, sand, clay from the subgrade and coal from passing trains. The reaction mechanism of clean ballast differs significantly from that of fouled ballast in several aspects, including particle interlock and friction, sleeper-ballast interaction, changes in pore structures, particle fragmentation rate and corrosion. Some common problems associated with fouled ballast include difficulty in maintaining the geometry of the track and poor drainage which gives rise to moisture accumulation at the ballast-subgrade interface (Y. Guo et al., 2021).

2.4. Ballast materials

Over time, various materials have been employed as railway ballast, each offering its own advantages and drawbacks as highlighted in Table 2-1. The selection of ballast material is significantly affected by factors such as drainage capacity, durability, economic cost, and compatibility with specific railway application. Though, materials such as sand, moorum rock, and coal ash have been used under some circumstances, they typically possess certain limitations that compromise long-term performance. Crushed rocks, however, have emerged

as the widely proven choice due to its superior durability and stability, rendering it most suitably adaptable for modern railway application.

Table 2-1. Overview of Railway Ballast Materials (Y. Guo et al., 2022b)

Materials	Merits	Demerits	Application
Sand	Moderate drainage capacity, low cost, effective vibration and noise mitigation, and compatibility with sleepers made from steel	Increased wear of rails, insufficient wind resistance, poor retention of compaction, unsuitability for high-demand railways.	Effective for tracks having steel sleepers but not appropriate for high-speed railways.
Moorum rock	Cost-effective, poor water absorption capacity, and visually appealing.	Soft texture, prone to breaking down into fines, difficult to repair and maintain, and fast deterioration when wet.	Used as sub-ballast and fill for virgin railway tracks
Coal ash, cinder	Readily available, cost-effective, and offers great drainage efficiency.	Causes corrosion of sleepers and rails, texture surface not hard, tends to break down into fines and degrades rapidly when moist.	Used for emergency repairs when slope failure occurs, not efficient for high-speed railways
Crushed stone rocks	Durable, firm, provides great drainage, highly stable, elastic, tough and has long-term economic benefits.	Expensive initial cost, limited availability in mountainous regions of some nations, and increased wear on wooden sleepers.	Suitable for medium- and high-speed railways as well as heavy movement applications.

2.5. Railway Ballast Testing Methods

The mechanical performance of railway ballast is essential for ensuring track stability, durability, and long-term performance. A series of laboratory tests are carried out to access the strength, deformation and durability under diverse loading conditions. These tests provide valuable insight into the material properties such as compressive strength, shear resistance and degradation potential. Table 2-2 outlines some ballast test methods, concise procedures and objectives.

Table 2-2. Overview of Ballast Testing Methods

Type	Procedure	Purpose	References
Single Particle Crush Test	A single ballast particle is positioned between two steel panels and gradually compressed until it crushes.	The aim of the SPT test is to estimate the material's strength prior to breakage, it includes the force-displacement curve and size-dependent failure stresses.	(Ji & Liu, 2020)
Angle of repose test	A cylindrical box is filled with ballast material, which are then poured out. The angle formed by the resulting pile of ballast particles serves as an indicator of the internal angle of friction.	The goal of the test is to obtain the internal angle of friction generated. Density, roughness, angularity and form are some properties that affects the outcome of the test.	(Y. Guo et al., 2019b)
Compression test	The compression test is divided into two types. The first, the confined compression test, involves completely filling a cylinder with the sample using a jack to pull down a plate positioned on top of the ballast assembly within the container. The second, the unconfined compression test, is applied to treated ballast assemblies, such as those stabilized with materials like polyurethane or asphalt.	The cylinder serves as a container with boundaries that are fixed. The purpose of the test is to plot the force-displacement curve, enabling the evaluation of the compressive strength properties.	(Jing, Qie, et al., 2019)
Direct shear test	Samples are placed in two distinct shear boxes, and one is made to move horizontally relative to the other while maintaining a constant vertical stress. Dilation effect is also estimated.	The purpose of this test is to determine the shear strength properties of samples under varying normal stresses, represented by a stress-strain curve. Additionally, the volumetric strain changes are assessed by measuring the dilation that occurs.	(Indraratna et al., 2014a)

Los Angeles Abrasion Test	Twelve steel balls and ballast particles of about 5kg are placed into the cylinder of the equipment. The cylinder is then rotated for a set number of turns (500 or 1,000) at a speed of 31–33 revolutions per minute (r/min).	This test is employed to evaluate how strong and durable a ballast is. The loss, expressed as a mass percentage of particles smaller than 1.6 mm, serves as an indicator of the material's properties.	(Y. Guo et al., 2018b)
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2.5.1. Direct Shear Test of Railway Ballast

The direct shear test provides valuable information about different behaviors of granular materials, including friction angle, dilatancy angle, strength envelope parameters, and flow function (Schwedes, 2003). For fine soils, a small-scale apparatus is sufficient, whereas for ballast material between 10 mm and 60 mm, a large-scale apparatus must be used. This gives a representative simulation of ballast response to normal, and shear stresses and minimizes the boundary condition effects. Indraratna et al. (1993) have noted that boundary effects may be overlooked if the ratio of the dimension of the shear box to particle size is higher than 7–8 for most particles. Various authors have conducted direct shear tests under diverse conditions, as summarized in Table 2-3. These studies differ in sample sizes, particle gradation, shearing rates, and applied normal stresses.

Table 2-3. Overview of Large-Scale Direct Shear Test Setup for Ballast Materials

Research Content	Sample Dimension (mm)	Particle Size (mm)	Vertical Stress (kPa)	Shearing rate (mm/s)	Reference
The shear properties of clean and fouled ballast	300x300x300.	2-25	27, 51, 75	0.04	(Indraratna et al., 2014a)
Direct shear properties of two distinct ballast material	300x300x200	20-40	111, 222, 333	0.02	(Suhr et al., 2018)
Shear strength behavior of tire derived aggregate on ballast	500x500x350	5-63.5	50, 100, 150	0.04	(H. Gong et al., 2019)
Shear strength properties of clean and fouled ballast with geogrid	300x300x200	2-25	27, 51, 75	0.04	(Ngo et al., 2016)

Direct shear properties of fresh and fouled ballast: Experimental and Numerical analysis	Lower: 365x305x152 Upper: 305x305x51	12.5-76.2	158, 248, 317	0.2	(Bian et al., 2019a)
Experimental and numerical analysis on the shear properties of recycled ballast	Lower: 600x700x250 Upper: 600x600x300	22.4-63	50, 100, 200	0.005	(Jia et al., 2019)

2.6. Discrete Element Method

The DEM is a computational technique for the simulation of behavior of discrete particle systems through explicit consideration of each particle and their interactions. It was initially introduced by Cundall & Strack (1979) and it has since been used as a solution to geo-mechanical problems. Development started with the use of the BALL program to calculate constitutive relations for granular soils. Initially applied in geotechnical engineering, DEM has now been applied in many other industries, including agriculture and food technology, for simulating phenomena such as silo discharge, bulk material transport, and mixing systems (X. Wang et al., 2021).

DEM operates under dynamic equilibrium, resolving dynamic issues by simulating particle motion in small discrete time steps. Particles are assumed to have constant acceleration and velocity within every time step, limiting the transmission of disturbances to nearby neighbors (Cundall & Strack, 1979). Particle contact forces are also represented by an approximated force-displacement relationship, which can usually be found in well-accepted theories such as Hertz-Mindlin model (Hertz, 1882; Mindlin & Deresiewicz, 1953). Newton's Second Law is then employed to find the acceleration because of unbalanced stresses acting on individual particle. Numerical simulation is utilized in computing the velocity and consequent displacement of every particle, for which this procedure is iteratively applied throughout the system (O'Sullivan, 2011).

A major unique aspect of DEM is its capability to simulate particle-level processes that govern the complex behavior of materials, extracting information that is impossible to get from traditional experimental tests. To make the simulations more efficient, the arrangements of particles are idealized as discs in 2D simulations or as spheres in 3D simulations, which helps to simulate large numbers of particles while retaining the dominant features of their behavior (Itasca, 2014). The explicit integration method necessitates the use of small time steps to enable

numerical stability, which helps to accurately update the particle properties of position, velocity, and contact forces at each time step. This ability to numerically apply loads and deformations makes DEM an excellent tool for the study of granular materials across numerous disciplines. Numerous software packages exist to model discrete particles, although PFC (Particle Flow Code) will be utilized for this research.

2.6.1. Model Objects

A typical discrete element model comprises bodies and mechanical contacts. Three types of bodies exist: balls, clumps, and walls. A body comprises one or more constituent parts which determine its surface: clumps are formed by pebbles, while walls are formed by facets. Mechanical contact between the surfaces of two bodies is by one or more contacts.

2.6.1.1. Walls

In PFC, walls serve the same purpose as boundary conditions and allow for the prescription of an initial displacement per time unit and fixity. Walls differ from other bodies since they are without weight and do not follow the laws of motion. There is an interaction with other particles with different types through contact mechanisms, though. One of the principal roles of walls is to confine particles inside the model. They may also simulate moving boundaries by prescribing the specified velocity. Moreover, walls can apply loading through a servo-control algorithm and modify their translational speed to maintain the target reaction force (Itasca, 2014).

2.6.2.2 Balls and Clumps

Spheres or balls are the simplest form of particle in PFC and DEM. They are not only simple because they are spherical but also because their volume, mass, contact points, and centroid coordinate are easily computed. The first DEM programs, like BALL, only allowed sphere modelling, and later development included ellipsoids (e.g., ELLIPSE). As insight into particulate operation has advanced, so too has the DEM framework to allow for more complex particle types, such as clumps.

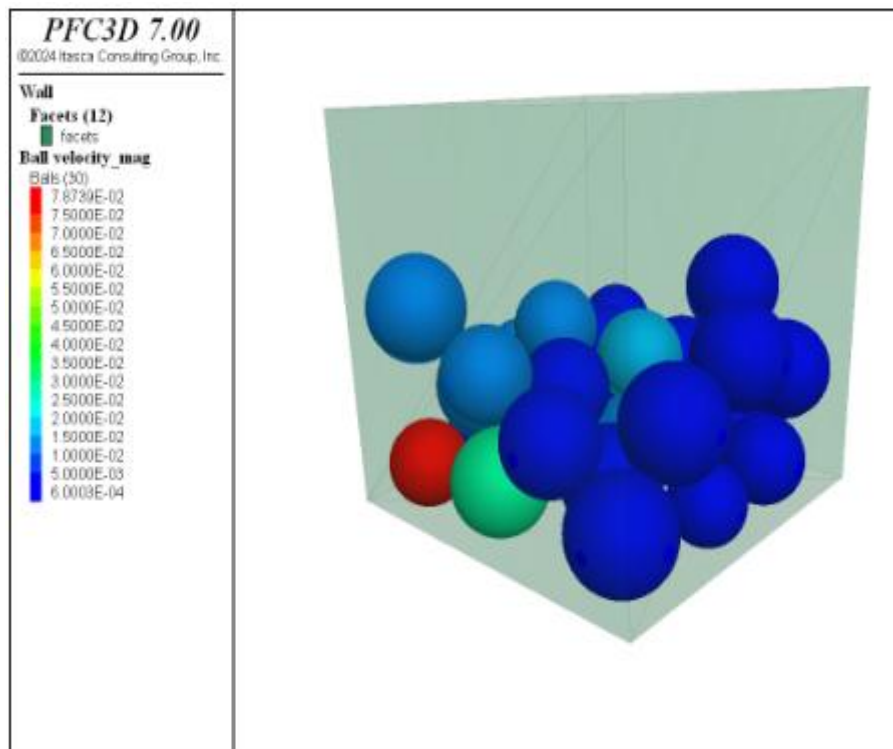


Figure 2-9. Balls in a box (Itasca, 2014)

A clump, as defined by Itasca (2014), refers to a group of overlapping spherical balls, or "balls," in PFC used for DEM. Clumps in PFC are not deformable, i.e., the relative positions of balls within a clump are static, with deformations or overlaps occurring only at surface balls during contact with outer elements like other clumps or boundaries. This rigidity keeps the internal structure of the clump, allowing shape representation to be consistent. Clumps can be as straightforward groupings of a handful of spheres or considerably more complex groupings of dozens of spheres organized to precisely represent the geometry and surface topology of real particles, as illustrated in Figure 2-10. Optimization of ball packing within clumps is an important area of research in DEM, balancing the efficiency of computation with the accuracy of representation of particle shape. Using fewer balls is computationally efficient but at the expense of accuracy of shape and texture. Using more balls improves accuracy of shape but is computationally expensive. There is research on algorithms to optimize ball packing to a maximum, capturing shape, angularity, and texture with the least number of balls. This is useful in areas such as the analysis of ballast degradation, where accurate representation of particle shape is essential for accurate simulation of mechanical properties under cyclic loading.

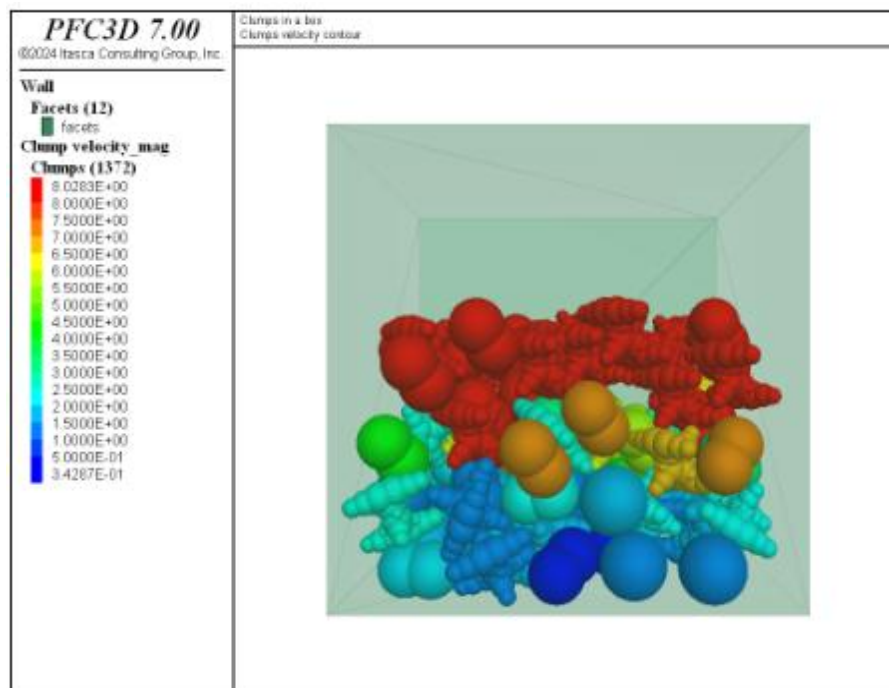


Figure 2-10. Clumps in a box (Itasca, 2014)

The rigid blocks in the PFC are an extension of the DEM to simulate manifold convex, closed, and polygon (2D) or polyhedral (3D) bodies with facets that are linear segments or triangles, respectively. Unlike clumps, where more than one pebble constitutes a body, a rigid block has only one contact with other objects like balls, clumps, walls, or other rigid blocks. This increases the efficiency of computations but at the expense of robust contact detection and solution algorithms. Rigid blocks are defined by their vertices, can be imported from geometry objects, and allow modifications like cutting or edge/vertex rounding. Their inertial properties are computed from the complete inertia tensor in order to update rotation motion.

2.6.2. Contact Models

According to Y. Guo et al. (2020), the general constitutive behavior of railway ballast assemblage in DEM is largely determined by the type of contact model applied between pairs of ballast particles. Contacts between particles are relatively non-linear and complex. However, in DEM simulations, these interactions are simplified and represented using constitutive contact models. To capture the complex behavior of interacting particles, different contact models have been proposed for numerous scenarios. These include the linear contact model, Hertz model, rolling resistance contact model, and conical damage contact model.

Table 2-4. Overview of Different Types of Contact Models

Contact Model	Software; Particle Type	k_n ; k_s (kN/m)	μ	ζ_n ; ζ_s	Damping	Reference
LCM	PFC/Clumps (2D)	2.5e8; 2.0e8	0.5	0.01; 0.01	Nil	(X. Zhang et al., 2017)
LCM	PFC/Clumps (2D)	1.5e7; 1e7	0.5	0.15; 0.15	Nil	(X. Zhang et al., 2019)
LCM	PFC/Clumps (3D)	1.5e9; 0.77e8	0.8	Nil	Nil	(Jing, Aela, et al., 2019a)
LCM	PFC/Clumps (3D)	5e8; 5e8	0.5	Nil	0.7	(Z. Wang et al., 2015)
HCM	YADE/3D Clumps	0.15; 0.2	0.5	Nil	Nil	(H. Gong et al., 2019)
RRLM	PFC/Sphere (3D)	5e8; 5e8	0.7	0.7:0.7	0.05	(L. Li et al., 2019)

LCM: Linear Contact Model; k_n : Normal Stiffness; k_s : Shear Stiffness; ζ_n : Normal Damping Ratio; ζ_s : Ratio of Shear Damping; μ : Friction Coefficient.

The linear contact model (LCM), introduced as the simplest contact model in Cundall & Strack (1979), employs linear and dashpot elements made up of an elastic stiffness mechanism and a damper. This is to facilitate energy transmission and dissipation in tangential and normal directions. The linear component provides friction and non-tensile elastic stiffness, while the dashpot component contributes viscosity. These two components operate over a very tiny contact area (the point of contact), transferring forces without generating contact moments. The total contact force (F_c) is the summation of the linear component (F_l) and the dashpot component (F_d), expressed as ($F_c = F_d + F_l$), as illustrated in Figure 2-11. For ballast particles, viscous behavior is absent at contacts. Consequently, the dashpot component of the LCM is typically inactive and is often neither described nor mentioned in most ballast studies utilizing PFC.

Dashpot force ($\mathbf{F}^d$), viscous.

Linear force ($\mathbf{F}^l$), linear elastic

(no tension) and frictional.

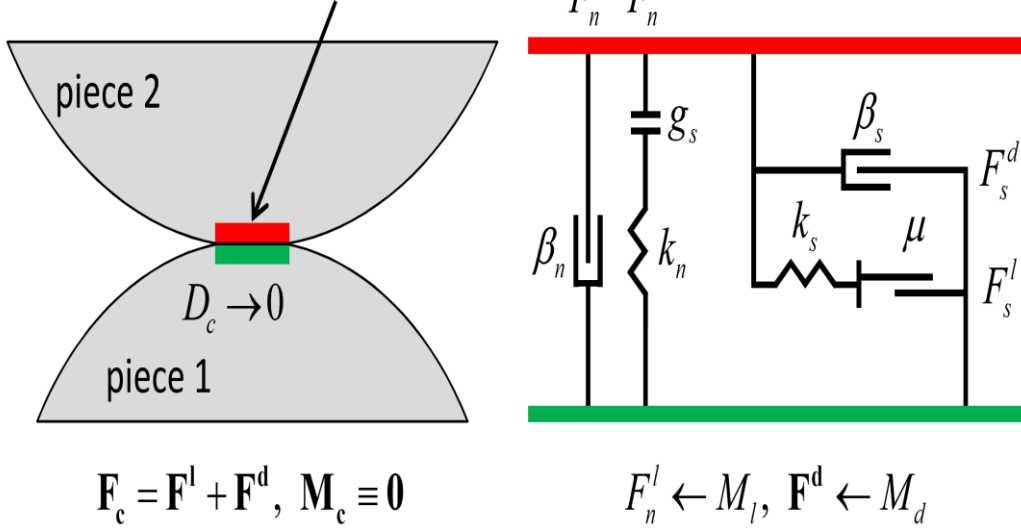


Figure 2-11. Linear Contact Model (Itasca, 2014)

The linear component consists of normal and shear forces, which can be expressed as shown below. In this equation, k_n is the normal stiffness while k_s is the shear stiffness. The terms δ_n denote the overlap of contact in the normal direction while $\Delta\delta_s$ denotes the shear overlap increment, respectively. The term $(F_l^s)_0$ refers to the shear force from the previous timestep, and μ is the interparticle friction coefficient.

$$F_l^n = k_n \delta_n$$

$$F_{l*}^s = (F_l^s)_0 + k_s \Delta\delta_s$$

$$F_l^s = \begin{cases} F_{l*}^s, & F_{l*}^s \leq \mu F_l^n \\ \mu F_l^n, & F_{l*}^s > \mu F_l^n \end{cases} \quad (2.1)$$

In most DEM simulations using PFC with the LCM, the kinetic energy of particles is dissipated via local damping and sliding, with an inbuilt damping magnitude of 0.7. In PFC, local damping is treated as a particle property rather than a contact model variable. For instance, with the default local damping value of 0.7, 70% of the unbalanced force is dissipated at each timestep. This local damping is better suited for static or quasi-static simulations, such as the single sleeper push than for dynamic simulations, like the large-scale simulation test (C. Chen et al.,

2015; Khatibi et al., 2017). For this study, the linear contact model will be utilized to represent the force-displacement relationship of ballast particles.

The linear contact model has a wide gap that does not provide resistance to relative rotation, making the contact moment equal to zero. The contact model also contains three distinct sets of gaps which are the surface gap g_s , the contact gap g_c , and the reference gap g_r . The relationship between these three parameters and the working operation is expressed in Figure 2-12. It can be deduced that when the reference gap is zero, the notional surface collides with the piece surface. Additionally, the contact can be regarded as active only if the surface gap is less than or equal to zero.

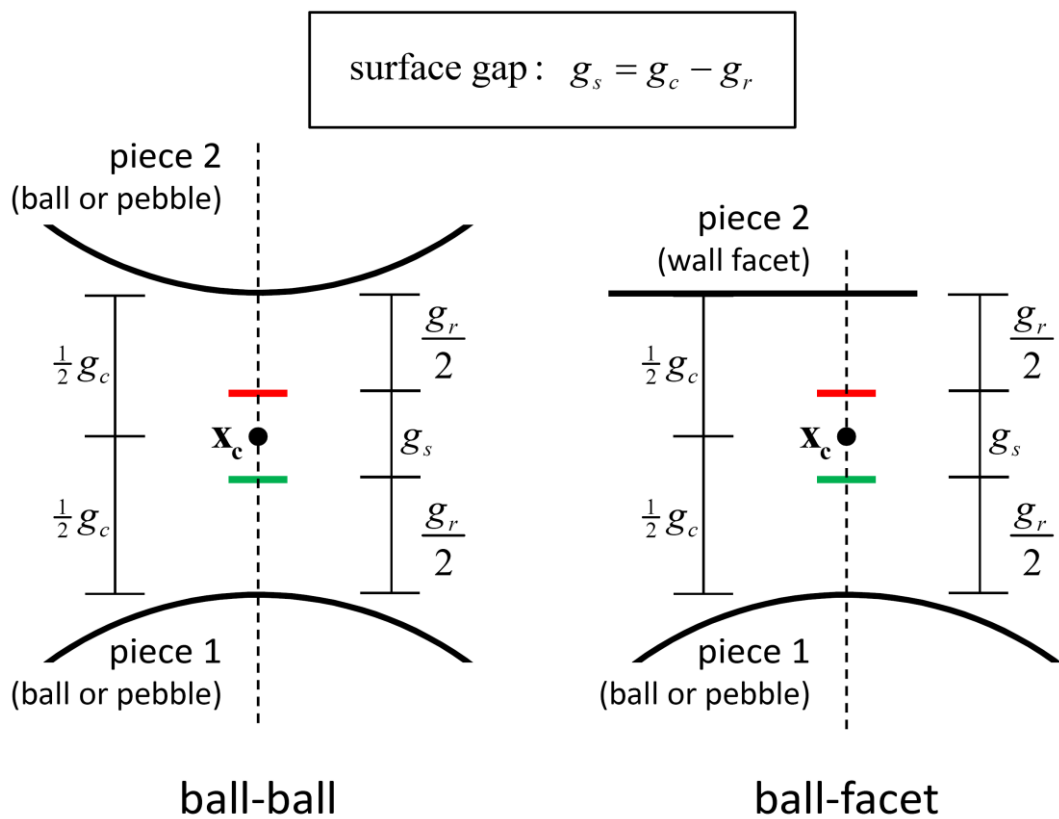


Figure 2-12. Surface gap for the linear contact models (Itasca, 2014)

The Hertz Contact Model (HCM) provides a non-linear simulation for forces and their correlative extensions, drawing from the hypothesis of Mindlin & Deresiewicz (1953). It theoretically analyses the smooth elastic deformation of spheres at frictional contacts for both normal and tangential force-displacement relationships (Figure 2-13). The model employs the shear modulus to calculate the shear force, which is also relates to the normal force. The model permits relative rotation at the contact, resulting in zero moment ($M_c = 0$). The total contact force (F_c) is decomposed into a Hertz component (F_h) and a dashpot component (F_d).

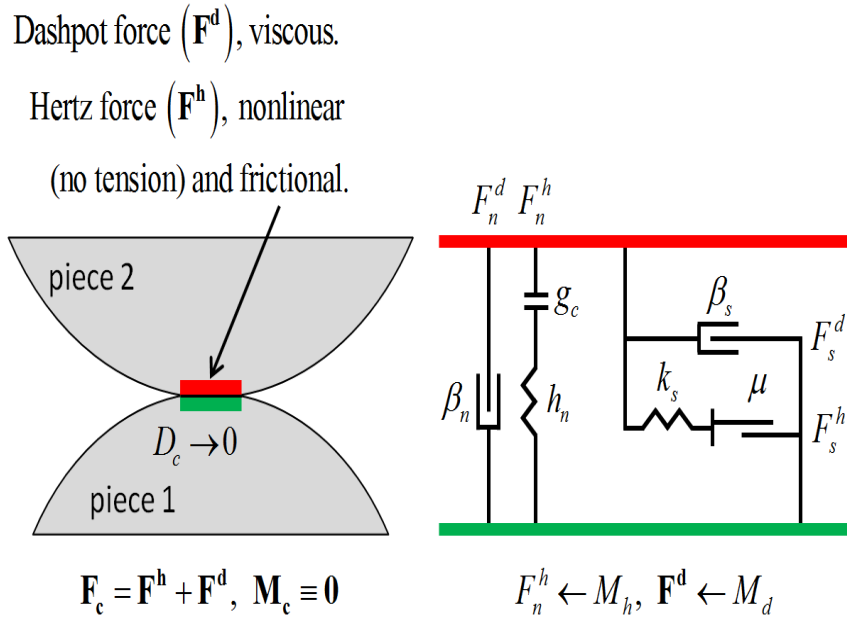


Figure 2-13. Hertz Contact Model (Itasca, 2014)

The Rolling Resistance Linear Model (RRLM) builds upon the LCM by incorporating a rolling resistance algorithm. The RRLM uses a torque to the contact point to oppose relative moment. In the PFC implementation of the RRLM, an additional variable called rolling friction is introduced compared to the LCM. Specifically, this rolling friction distinguishes the two models by resisting particle rotation, with the maximum resistance equal to the product of the rolling friction coefficient and the correlative normal force. This resistance can be likened to rolling stiffness (k_r), analogous to a clockwork spring in Figure 2-14. It should be noted that the RRLM only resists relative bending at the contact areas.

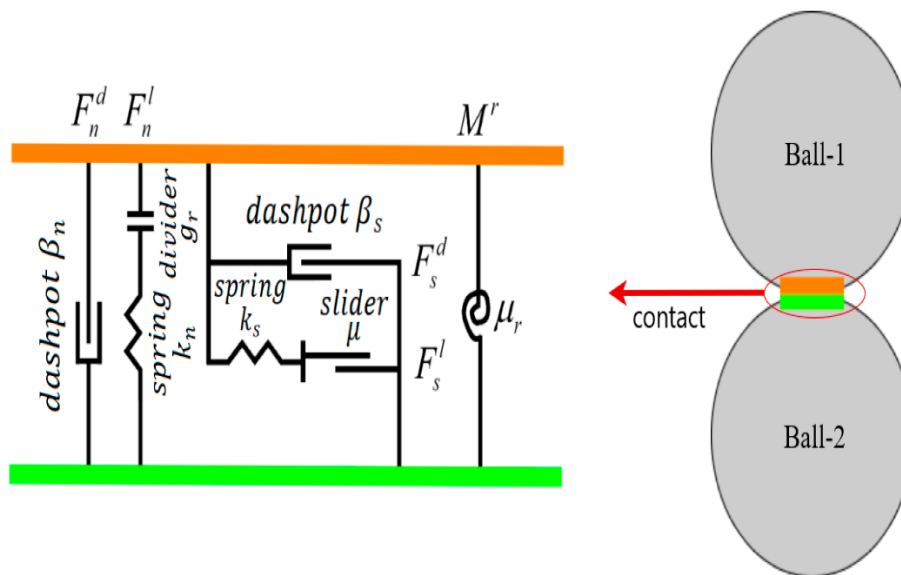


Figure 2-14. Rolling Resistance Contact Models (Benmebarek & Movahedi Rad, 2023)

The adhesive rolling resistance linear (ARRLinear) model is a contact model in PFC designed to simulate the response of cohesive granular particles by combining rolling resistance with short-range adhesion (Figure. 2-15). It is an extension of the conventional rolling resistance linear model by adding a cohesive parameter that represents a simplified form of the van der Waals attraction between particles. Unlike bonded contact models, this attraction does not break; it is always active when particle surfaces come within a specified attraction range. The model is governed by two key parameters: the optimum attractive force and the attraction range (Figure 2-16), which together control the strength and spatial extent of cohesion.

This model capable of reproducing the key features of cohesive powders and wet granular materials, which are able to create loose but mechanically stable structures at a much lower solid fraction than non-cohesive materials. The force-displacement law contains normal, tangential, and rolling forces, as well as the cohesive force, which acts in the normal direction. Energy considerations in the model also consider the adhesive energy, which corresponds to the work of the attractive forces during particle interaction. The ARRLinear model is a physically sound and computationally efficient tool for analyzing the mechanical behavior, packing density, and stability of cohesive granular materials.

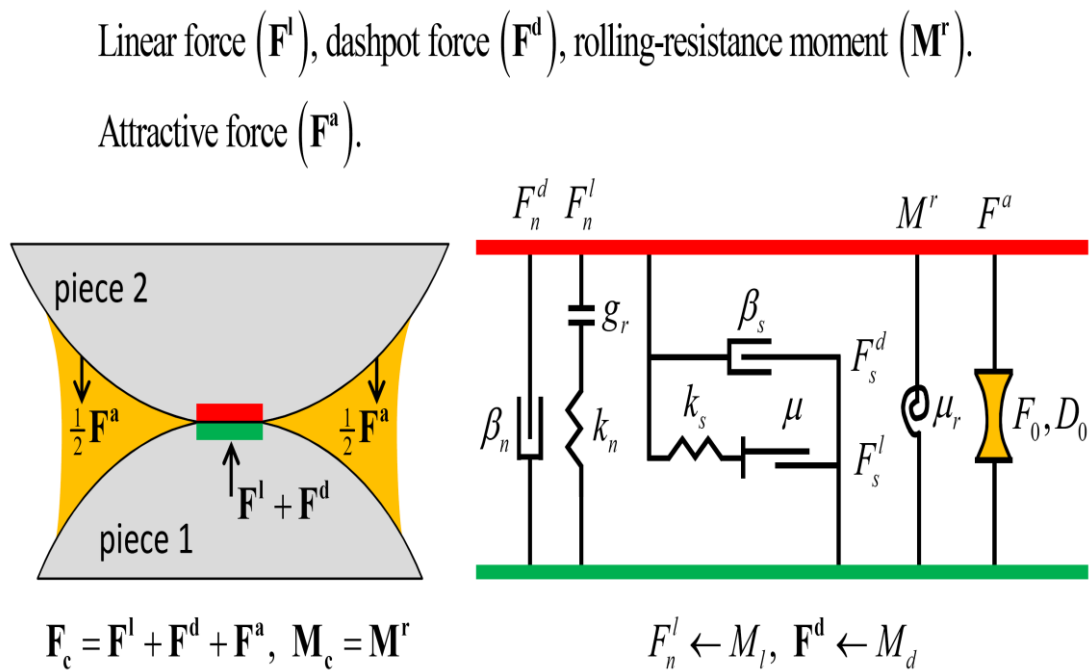


Figure 2-15. The adhesive rolling resistance model (Itasca, 2014)

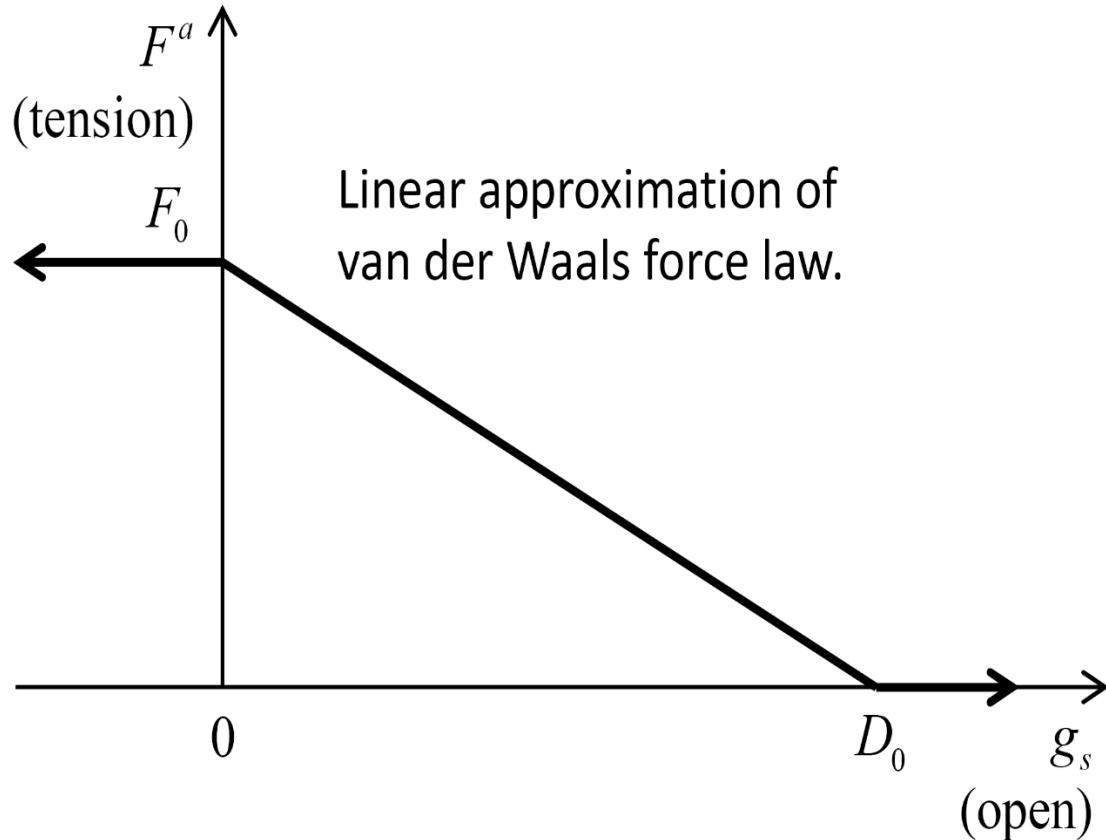


Figure 2-16. Attractive forces against the surface gap for the ARRLinear model (Itasca, 2014)

The Flat-Joint (FJ) model is a contact model in PFC that describes the mechanical behavior of bonded or frictional interfaces between particles (Figure 2-17). The flat-joint model is a realistic means of simulating angular, interlocked granular materials such as marble or cemented rock. Unlike other contact models, the flat-joint model introduces finite-size interfaces that are made up of multiple micro-elements, each of which can sustain normal, shear forces and moments. The elements are linear elastic while bonded. Once the strength boundary is reached, the bond fails, allowing frictional sliding and rotation to take place. The element breakage results in partial damage, allowing the model to smoothly transition from a fully bonded to an unbonded and frictional interface.

In a flat-jointed material, each contact between grains is modeled as a flat joint, resulting in a microstructure of grains facing each other through flat interfaces that are disk-shaped. This microstructure reflects the anisotropy of strength and stiffness that is characteristic of natural geomaterials. The model is capable of simulating the process of fracture initiation, crack growth, and post-failure behavior at the microscale, making it highly appropriate for modeling brittle fracture, fracture mechanics, and damage evolution in rock-like materials. The flat joint

model is an extremely effective tool for relating microcontact mechanics to macroscopic mechanical behavior.

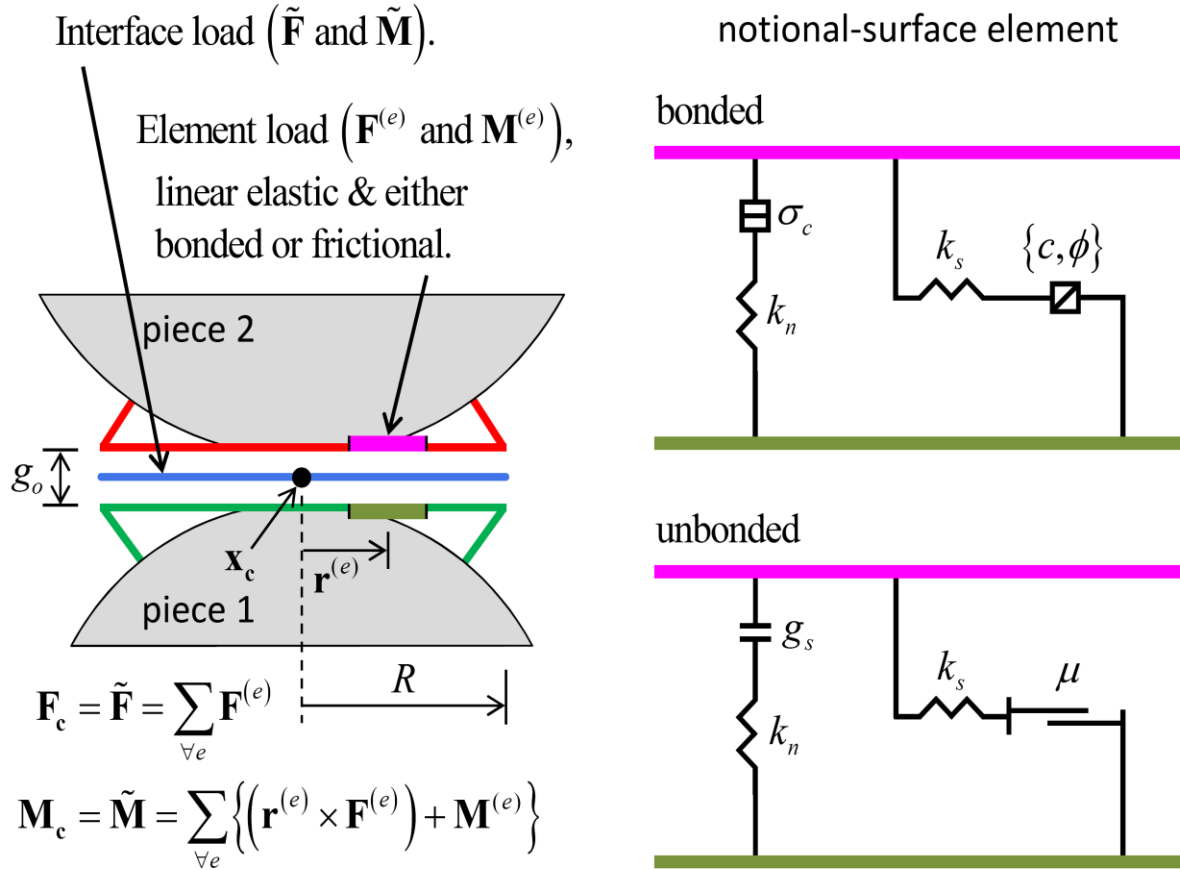


Figure 2-17. Behavior and working mechanism of the Flat joint model (Itasca, 2014)

The Smooth-Joint (SJ) model in PFC is intended to capture the behavior of planar interfaces, such as geological joints or bedding planes, without reference to the actual orientations of the particle contacts that constitute the interface (Figure 2-18). By assigning smooth joint contacts to particles on opposite sides of a joint plane, the model captures the macroscopic mechanical behavior of a frictional or bonded discontinuity that can dilate during shear.

A smooth joint is a linear elastic interface that may be either bonded or frictional. When it is bonded, it resists both normal and shear deformation elastically until the strength boundary is attained; after the bond is broken, the interface becomes frictional, following the Coulomb slip criterion, which permits shear displacement with dilation. The model does not resist relative rotation between particles, enabling realistic sliding behavior along joint surfaces as displayed in Figure 2-19.

The joint orientation is characterized by an invariant normal vector by dip and dip direction angles to ensure that smooth-joint contacts share a common geometric reference plane. This

makes the model very appropriate for modeling pre-existing rock masse discontinuities, such as fractures, faults, or bedding planes, and for simulating shear strength, dilation, and failure mechanisms along these interfaces.

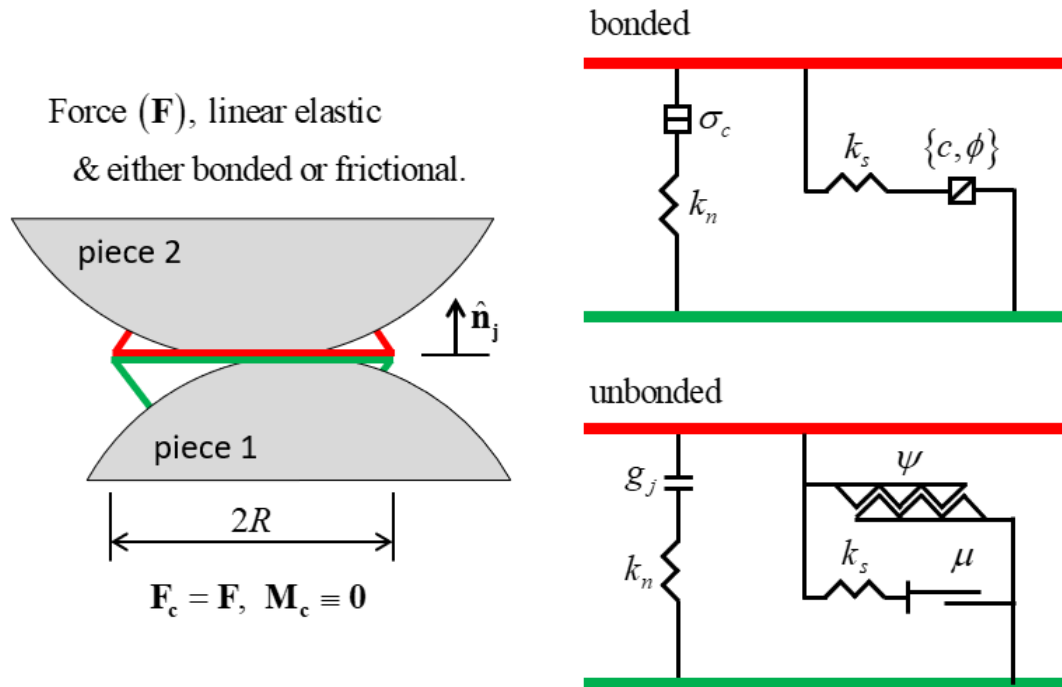


Figure 2-18. Behavior and working mechanism of the smooth-joint model (Itasca, 2014)

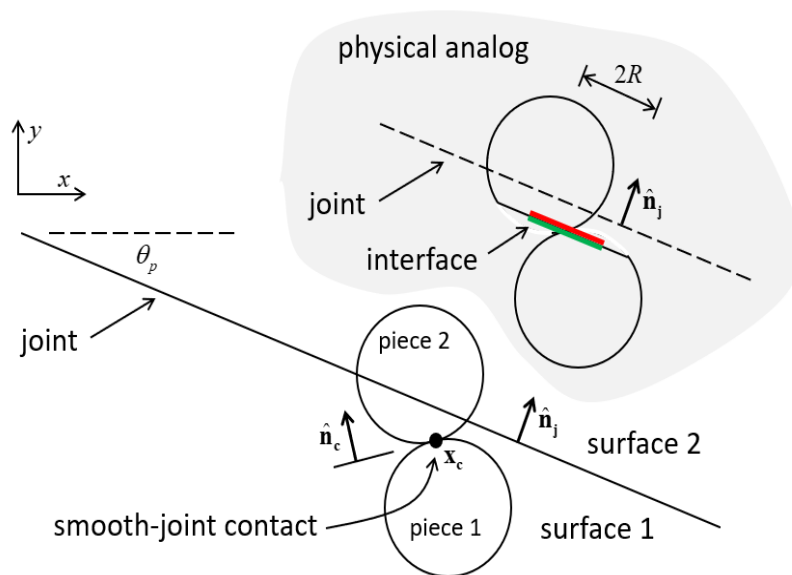


Figure 2-19. Sliding mechanism of smooth-joint model (Itasca, 2014)

For the purpose of this study, the LCM was adopted because it is computationally efficient, easy to calibrate, and has been widely used in railway ballast DEM simulations. When ballast particles are represented as clumps, the LCM provides reliable macroscopic responses without

excessive computational cost. Its simpler parameter set (k_n , k_s , μ) also allows straightforward calibration against laboratory experimental results.

2.7. Sustainable Approach to Railway Ballast Materials

The construction sector is largely dependent on quarries and gravel pits for the production and upkeep of railway ballast. The reduction in raw material reserve availability reduces the proportion of quality material, making it more challenging to produce railway ballast annually (Ezsias et al., 2023). The exploitation of natural ballast material has also created different environmental challenges such as habitat destruction and increased carbon emissions. Hence, researchers and railway infrastructure managers are actively searching for eco-friendly alternatives to the conventional railway ballast. They are mainly involved in recycling of ballast materials, recycling from industrial waste products, innovative processing techniques, and reinforcement that enhances the longevity of railway ballast coupled with reducing environmental impacts.

Two primary methods that have been employed over time in relation to sustainability of railway ballast are reusing and recycling existing material. In the past, whenever ballast fouling happens (contamination of fine particles, rubbish, coal or organic material), they are usually discarded and replaced with new clean material replaced in the course of maintenance. This has generated a great deal of waste generation and continuous exploitation of natural resources. Previous research has indicated that well-treated recycled ballast can retain a significant amount of its mechanical properties. High-pressure jet washing equipment, up-to-date screening, contaminants removal, and restoration of drainage effectiveness have all been factors in reusing ballast as a feasible and effective solution (Anderson et al., 2003). In addition, mixing clean ballast materials with recycled ballast materials in controlled amounts has been shown to have been effective in maintaining the mechanical characteristics while reducing over-reliance on natural material sources. Studies show that using 10-30% recycling ballast can strike a balance between sustainability and long-term track performance (Jia et al., 2019; Leus et al., 2021).

Industrial wastes have also been found to be a suitable choice for railway ballast material. Steel slag, a by-product of steel manufacturing, is becoming increasingly popular as an alternative to natural stone because of its high abrasion resistance, high grade and durability, economic efficiency and high bearing capacity. Some of the significant examples of these byproducts are blast furnace (BF) iron slag, BOF steel slag, and EAF slag (Koh et al., 2018). Jing et al. (2020) presented a numerical and experimental investigation of the response of ballast mixed with

steel slag in ballasted tracks. They employed a 50m test track and a FEM model to evaluate the impact of different percentages of steel slag on stone ballast. Their findings show that there was a notable increase in the behavior of ballast layer as the percentage of steel slag increased. Other industrial byproducts like bottom ash from coal combustion, tire derived aggregate, neo-ballast and crushed concrete debris from demolition waste, have also be examined as alternative railway materials. Duraisamy et al. (2023) noted if these materials are adequately processed, they possess similar drainage and strength properties compared to traditional ballast aggregates, representing a viable secondary source for railway construction.

Table 2-5. Overview of material used as a replacement to traditional ballast materials

Material	Outcome	Reference
Neo Ballast	Neo ballast offers improved damping capacity, stress reduction and reduced settlement over a long period of time	(Sol-Sánchez et al., 2018)
Tire Derived Aggregate	A mixture of 5% tire-derived aggregate (TDA) with ballast was identified as the optimal combination for balancing breakage resistance and stiffness.	(Wu et al., 2021)
Recycled Ballast	The decrease in shear strength and coordination number of the combined mix is minimal when the proportion of recycled ballast is kept below 30%.	(Jia et al., 2019)
Steel Slag (Electric Arc Furnace)	Experimental findings indicate that incorporating steel slag into ballast enhances the elastic modulus and friction angle of the ballast layer, thereby improving the mechanical behavior of the railway track	(Jing et al., 2020)

2.8. Basic Oxygen Furnace (BOF) slag as railway ballast material

Slag is a by-product generated from the manufacturing of steel. Basically, there are three types of slag that can be formed including EAF slag, Granulated Blast Furnace Slag (GBFS) and BOF slag. BOF slag is formed during the conversion process of pig iron into steel. During the process, pig iron reacts with lime, silicates, aluminum oxides, manganese oxides, magnesium oxides and ferrites with specific composition varying based on the target quality of steel (Kambole et al., 2017). The presence of free oxides and the chemical oxide composition of

EAF and BOF slags makes them similar, however, BOF is distinct because of its higher levels of CaO, FeO and SiO₂ content (Yildirim & Prezzi, 2011). According to report by Netinger Grubeša et al. (2016), the equivalent weight of BOF slag generated is about one ton for every metric ton of steel produced. If this persists and not properly managed, it will bring about sustainability issues relating to environmental degradation and landfill capacity concern. The viability of utilizing BOF slag as ballast material has piqued the interest of researchers because of some tremendous properties it possesses. Extensive research has been done to assess the potential use of BOF slag in railway ballast applications by evaluating its physical and mechanical properties, durability and environmental impact. A feasibility study by Koh et al. (2018) on the use of BOF slag as a railway ballast material reached the following conclusions.

- BOF slag is expected to offer great resistance to lateral pressure from centrifugal forces on curved tracks because its unit weight is higher compared to natural aggregate
- The wear rate of BOF slag was lower while hardness was higher when compared with natural aggregate. This suggests that BOF slag, when used as railway ballast material, offers advantages in relation to maintenance, exhibiting superior resistance to abrasion and hardness under continuous train loading.
- The unconfined compressive strength (UCS) of BOF slag exceeds the standard and natural aggregate. This will ensure reduced particle breakage and excess deformation
- The immersion test proved that BOF slag met the required standard
- The chemical analysis results also showed no existence harmful substance in the aggregates.
- The three aging period used (up to 6months) had minimal impact on the physical properties of BOF slag. This suggests that aging phenomenon can be disregarded for up to six months. Although, the long-term effect of expansion needs to be studied.

Currently, Kazakhstan, just like other nations of the world are experiencing challenges in adequately managing industrial wastes. Additionally, environmental concerns about CO₂ emissions, land scarcity, and high cost of managing and treating industrial wastes is on the increase. As a result, Kazakhstan is looking into the development of an industrial byproduct management capacity that transcends national needs and pollution prevention (Kareken et al., 2023). The BOF slag in Kazakhstan has been evaluated through physical, mechanical, chemical, and environmental experiments to estimate its compliance to the GOST standard for railway ballast in Kazakhstan. The table below outlines the summary of the results of the evaluation.

Table 2-6. Properties of BOF Slag in Kazakhstan (Olawaju Olagunju et al., 2023)

Test type	Value	Limits	Method	Standard
Specific Gravity	3.29	>2.4	GOST 7392–2014	GOST
Absorption Capacity (%)	1.18	<2	GOST 7392–2014	GOST
Flakiness Index (%)	9.67	<15	GOST 7392–2014	GOST
Lightweight Particles (%)	0.5	<3.5	ASTM C123M-11	AREMA
LA Abrasion (%)	11.7	<12	GOST 7392–2014	GOST
Micro-Deval (%)	8.4	<9	CS LS-618	CN
ACV (%)	19.3	<22	BS 812–110: 1990	BS EN
AIV (%)	16.1	<22	BS 812–112:1990	BS EN

Chapter 3 – Materials and Methods

3.1 Materials

Figure 3-1 presents the aggregates utilized in the present study. BOF slag was collected from a steel factory in the Karaganda region of Kazakhstan. The BOF slag comprises mainly the oxides of iron, calcium, and silicon, with proportions of 20.24%, 29.18%, and 8.69%. Normal crushed aggregate was sourced from broken lateritic bauxite, a sedimentary deposit that is renowned for its pisolitic structure and distinctive reddish-brown color, a testament to its high iron oxide content. To satisfy railway ballast specifications, the two aggregates were screened into various fractions and mixed to conform to the AREMA #4A (American Railway Engineering and Maintenance-of-Way Association, 2004) grading curve. The resultant grain size distribution is plotted in Figure 3-2. The particle diameter was restricted to a maximum of 37.5 mm in an effort to achieve a shear box-to-particle diameter ratio of around 7-8. As demonstrated by Indraratna et al. (1993), this requirement minimizes boundary effects.

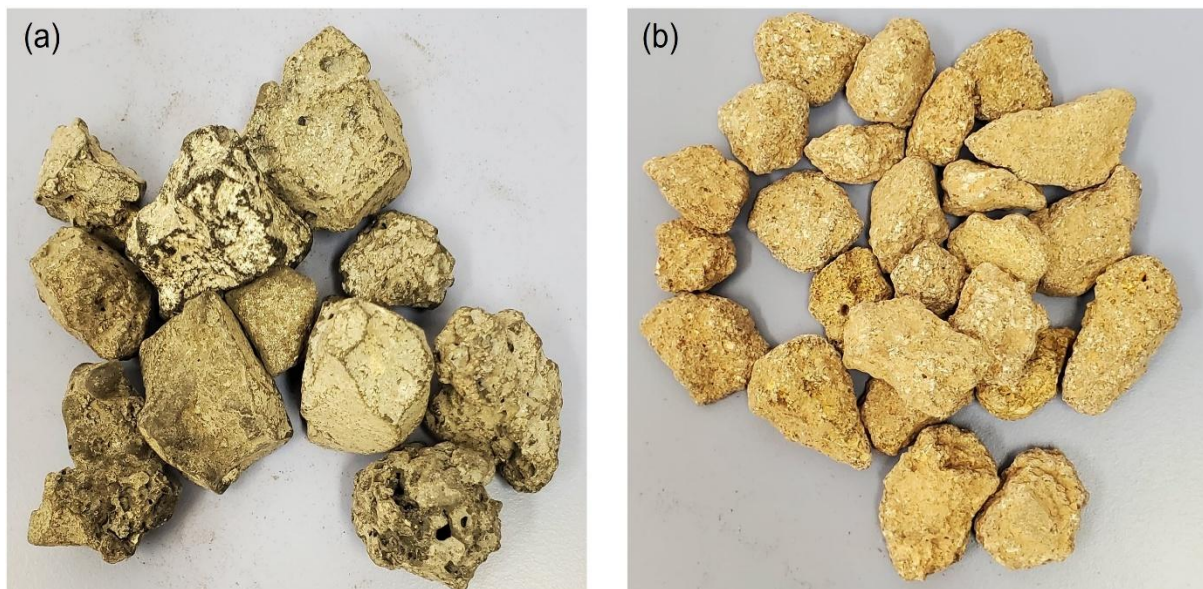


Figure 3-1. Ballast material: (a) BOF slag; (b) Natural crushed stone

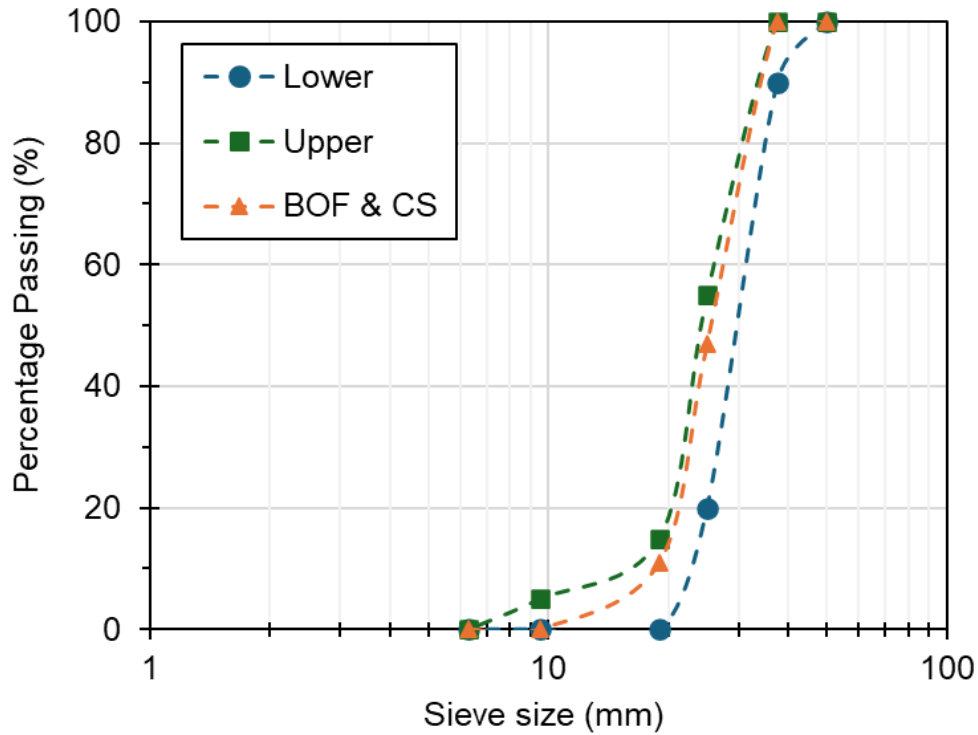


Figure 3-2. Particle size distribution curve. (note: CS is crushed stone)

3.2 Experimental Testing Program

The laboratory experiment of this study was done via a Wille Geotechnik large direct shear test apparatus (ADS-160-500-EM) as displayed in Figure 3-3. The schematic of the equipment is depicted by Figure 3-4. The equipment comprises two independent boxes of the same size. The bottom box is 300mm x 300mm x 150mm and it's free moving. The upper box that is fixed at the top is 300mm x 300mm x 150mm. The two boxes have a shear gap so that the lower box can move freely without coming into contact with the top box. There are also high-precision displacement sensors and force measurement system in the machine in order to facilitate real-time estimation of the shear force, vertical displacement, and horizontal displacement. The displacement sensors are four linear variable differential transformers (LVDTs), which give precise measurements of the vertical and horizontal displacements. The equipment is linked to a computer that can automatically store the data for the test. Samples were made by placing them in three even layers, with a light compaction to achieve a levelled surface. Experiments were performed under low normal stresses (30, 50 and 70 kPa), which is typical for a railway track under low confinement conditions (Lackenby, 2006). This level of stresses were picked to simulate targeted low-confinement range specified in the ASTM-STP1605 standard for ballast applications (Estaire & Santana, 2018). Each sample was sheared until it reaches a maximum horizontal movement of about 45mm (15% shear strain).

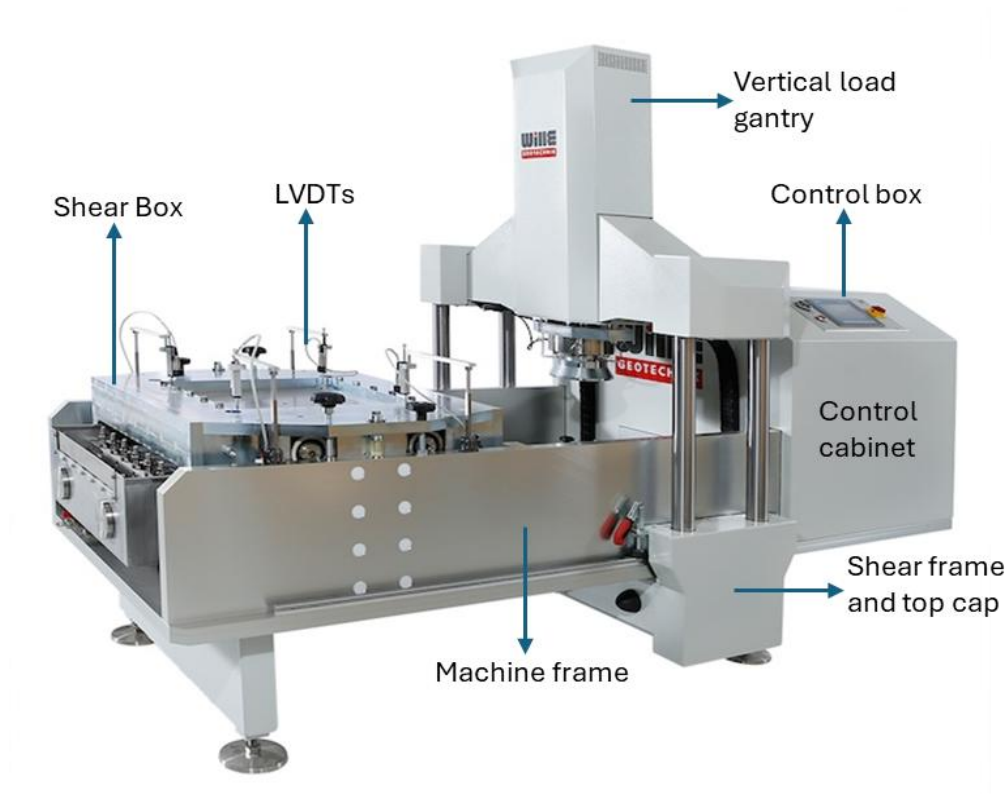


Figure 3-3. Large-Scale Direct Shear Test Machine

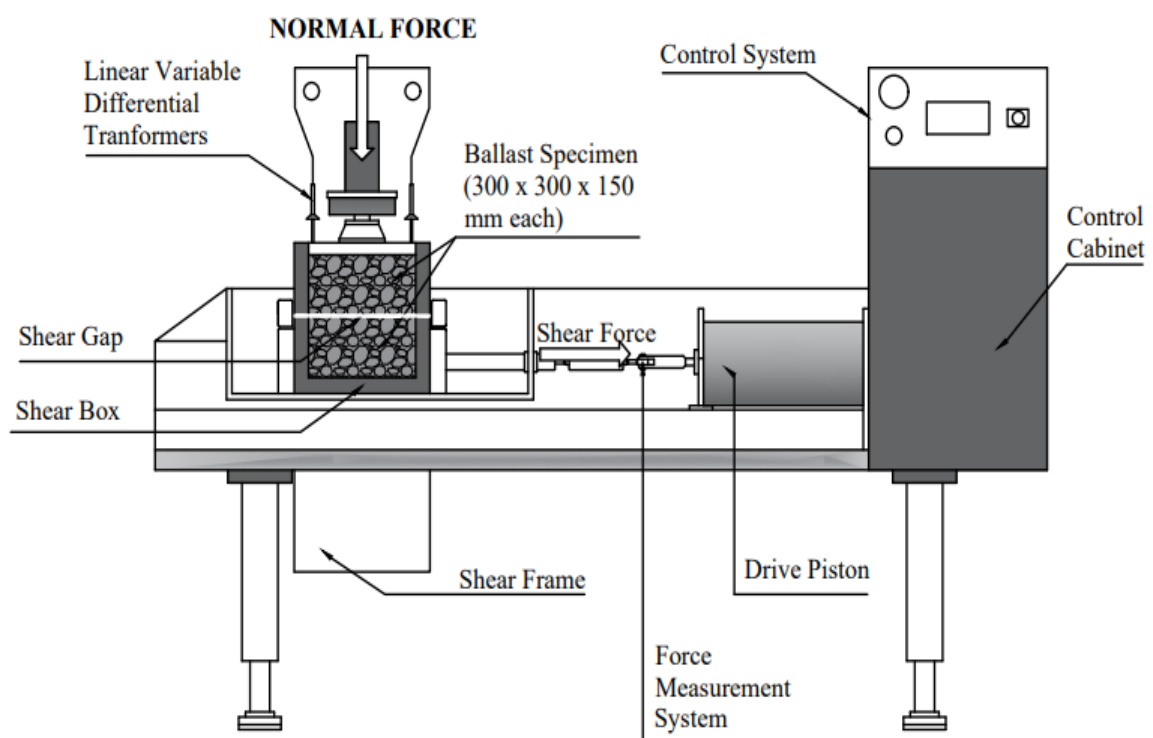


Figure 3-4. Schematic representation of the automatic large-scale direct shear machine

3.3 Shape Quantification

Recent advances in three-dimensional scanning techniques now allow ballast particles to be digitally reconstructed with high geometric fidelity, enabling systematic and reproducible shape characterization. Particle shape is an important parameter in determining the mechanical property of ballast subjected to varying loading conditions, and the measurement of these parameters provides important information on ballast behavior. In this study, the shape of ballast particles was determined via four basic parameters: aspect ratio, convexity, Wadell sphericity, and angularity. A total of thirty-two individual particles representing different size groups were examined, consisting of sixteen crushed stone particles and sixteen BOF slag particles. Each particle was scanned using a 3D EinScan-SE scanner, resulting in the generation of surface meshes in STL format. Geometric analysis of the reconstructed particles was performed using a Python-based script, incorporating custom computational geometry libraries. The mathematical formulations adopted for each shape descriptor are presented in the following formulas:

$$\text{Aspect ratio } (A_r) = \frac{1}{2} \left(\frac{w_f}{l_f} + \frac{t_f}{w_f} \right) \quad (3.1)$$

$$\text{Wadell sphericity } (S_w) = \frac{\sqrt[3]{36\pi V_p^2}}{A_p} \quad (3.2)$$

$$\text{Convexity } (C_v) = \frac{V_p}{V_c} \quad (3.3)$$

$$\text{Angularity Index } (AI) = \frac{|V_d|}{V_p} \quad (3.4)$$

where w_f is the Feret width (Intermediate dimension); t_f is the Feret thickness (Shortest dimension); l_f is the Feret length (Longest dimension); V_p is the particle volume; A_p is the particle surface area; V_c is the volume of convex hull; and $|V_d|$ is the absolute difference between the volume of the particle and the equivalent scalene ellipsoid (Potticary, 2018; Wadell, 1935). The description and parameter values of various shape representation for the 32 selected samples are presented in the appendix. Figure. 3-5 illustrates the average value of individual shape parameter for crushed stone and BOF slag. The aspect ratio, an indicator of elongation, is larger for BOF slag than for crushed stone. This implies that, on average, BOF particles are less elongated and more equidimensional than crushed stone particles. The sphericity of both materials is remarkably similar but slightly larger for crushed stone than for BOF slag. This implies that crushed stone particles, although more elongated, have a 3D shape

that is marginally closer to a sphere. The convexity result reveals that crushed stone particles have smoother boundaries and less complex surface micro-geometries than BOF particles. The angularity index reveals that crushed stone particles have sharper edges and more accentuated angular details, while BOF particles are relatively more rounded at their edges. These fundamental differences in particle morphology are anticipated to directly translate to differences in interparticle friction and microstructural trend under shear stress, which will be explored in subsequent sections.

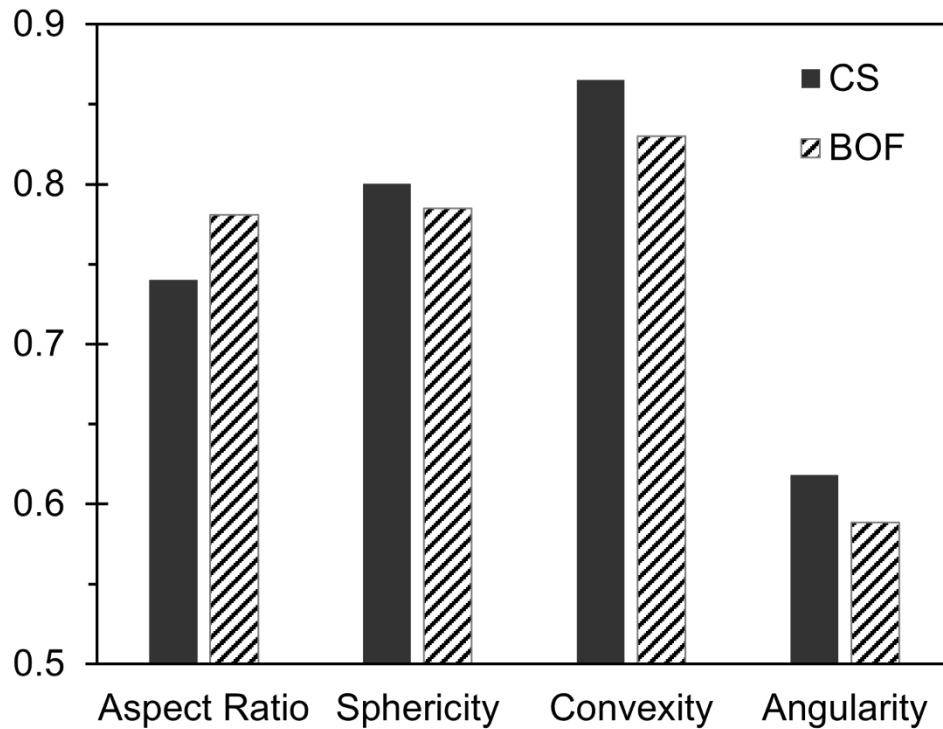


Figure 3-5. Mean particle shape characteristics of crushed stone (CS) and BOF slag

3.4 Discrete Element Modelling

3.4.1. Overview and Contact model

In this study, the linear contact model (LCM) was employed since it is straightforward and can bridge macroscopic and micro-mechanical behaviors (Bathurst & Rothenburg, 1990), which is a key focus of this research. It was also proven to be a good model in predicting ballast behavior subjected to varying loading conditions by several studies (Jing, Aela, et al., 2019; Khatibi et al., 2017; Mishra & Mahmud, 2017; Ngo et al., 2017; Zhang et al., 2017).

The LCM includes two parts: the linear (F_l) and dashpot (F_d) components that work in parallel to transfer forces. The linear component gives linear elastic behavior, while the dashpot component gives viscous behavior (Itasca Consulting Group Inc., 2021). The dashpot component is not used in this study since no viscous behavior occurs at ballast particle contacts

(Y. Guo et al., 2020). The linear component, which combines normal (F_l^n) and shear forces (F_l^s), is best described by three parameters: normal stiffness (k_n), shear stiffness (k_s), and friction coefficient (μ). The stiffness properties at particle contacts are defined in terms of particle size, effective elastic modulus (E^*), and stiffness ratio (k^*), as shown in Equation (1) below:

$$k_n = \frac{\pi R^2 E^*}{L} \quad (3.5)$$

$$k_s = \frac{k_n}{k^*} \quad (3.6)$$

where R is the least radius of two particles in contact and L is the sum of the radii. Using the parameters defined above, the normal and shear forces can be calculated as follows:

$$F_l^n = k_n \delta_n \quad (3.7)$$

$$F_{l*}^s = (F_l^s)_0 + k_s \Delta \delta_s \quad (3.8)$$

where (δ_n) is the relative displacement in the normal direction, ($\Delta \delta_s$) is the shear displacement increment, and (F_l^s)₀ is the shear force from the preceding timestep. The Coulomb sliding criterion is used to estimate the shear force at the contact interface. Initially, the shear force develops elastically; however, it cannot exceed the frictional limit defined by (μF_l^n). Once this limit is reached, sliding takes place, and the shear force follows the Coulomb law as shown below:

$$F_l^s = \begin{cases} F_{l*}^s, & \text{if } F_{l*}^s \leq \mu F_l^n \\ \mu F_l^n, & \text{if } F_{l*}^s > \mu F_l^n \end{cases} \quad (3.9)$$

3.4.2. Generating realistic ballast shape

Particle shape is vital in determining the performance of granular assemblies. It affects such key features as packing, bulk density, number of contacts, and breakage of particles, which are all crucial for granular behavior (Coetzee, 2016). For ballast particles, special care should be taken to model their shape since it is irregular and complicated. In PFC3D, a sphere can be used as the unit basis of a particle. Spherical particles facilitate simpler particle interaction computations, especially contact detection and force computation. Spheres, however, cannot mimic the real shape of ballast particles, which is essential to effective interlocking and reduced slipping (Indraratna et al., 2014). To create DEM models that preserve particle shape, several methodologies have been used, such as ellipsoids (B. Yan et al., 2010), polyhedrons (Bian et al., 2019b), spheropolyhedrons (Ji et al., 2017), and clump logic (Indraratna et al., 2014).

Representation of real ballast particles as collections of connected and overlapping spheres is popular practice, and the computational expense is affordable due to the ease of sphere-to-sphere contact detection (Angelidakis et al., 2021).

Therefore, clumps were used in this study to create realistic shapes of ballast materials. The clump acts as a rigid body, and contacts between its constituent spheres are ignored (Itasca Consulting Group Inc., 2021). Thirty-two different particle shapes were selected, with sizes from 12.5 to 37.5 mm (matching the lab size and distribution), to represent realistic forms. Sixteen shapes modeled BOF slag, while the rest modeled crushed stone. Converting real ballast particles into DEM models involves a multi-stage process (Figure. 3-6). First, ballast samples were scanned with a 3D EinScan-SE scanner to produce high-resolution point cloud data capturing the irregular particle surfaces. The raw scans were then converted to triangulated surface meshes in STL format. These scanned meshes are typically large, with thousands of triangles, making them computationally expensive for DEM. To simplify while keeping key geometry, the meshes were processed using a Python script with the Open3D library, creating a clean closed surface mesh exported as an ASCII STL file for PFC3D. In the software, the Bubble-Pack algorithm by Taghavi (2011) was applied to produce clumps from the simplified surface geometry. This algorithm is notable for its easy use as a built-in PFC3D feature and its effectiveness (Fan et al., 2025). It packs small spheres, called "pebbles," around a central point to form a clumped model that approximates the particle's complex shape.

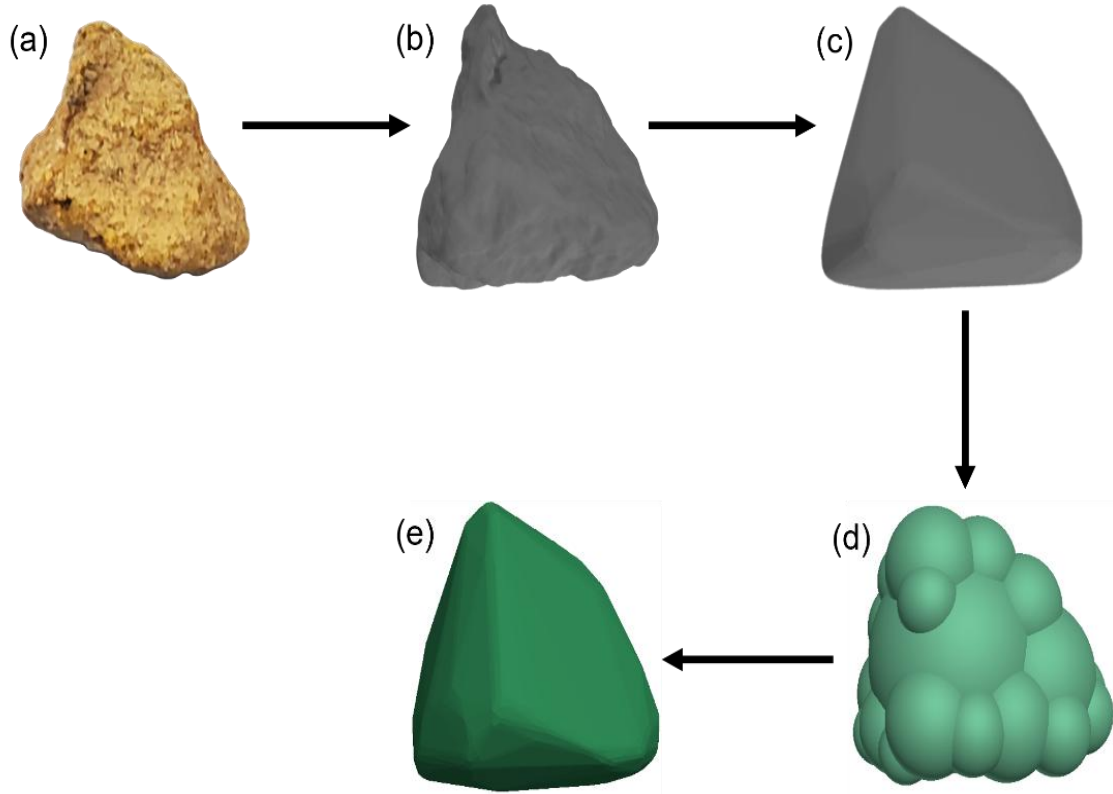


Figure 3-6. Workflow for ballast particle transformation: (a) Actual ballast particle; (b) 3D scanned ballast surface; (c) Simplified 3D model of ballast; (d) Clump of spheres representation in PFC; (e) Surface representation of ballast in PFC.

The Bubble-Pack algorithm works based on two key parameters: the size ratio (ρ) and the intersection angle (β). The size ratio ρ is the ratio of the least pebble to the largest pebble in the clump (ranging from 0 to 1), while the intersection angle β is the maximum angle between two intersecting pebbles (ranging from 0° to 180°). A simplified diagram of these parameters is shown by Jia et al. (2019). Figure 3-7 displays the effects of varying β against ρ . The parameter β controls the particle surface texture. A high value produces smoother and denser clumps, while a lower value creates a rougher surface. The parameter ρ affects the range of pebble sizes in a clump. A high value generates pebbles of similar size as it approaches 1, while a lower value produces a wider size range with more small spheres and a finer clump shape. For computational efficiency, many spheres are needed to accurately match the real clump shape. However, too many spheres become impractical, causing high computational demand and increased simulation cost. Therefore, a balance is required between the number of pebbles for efficient contact detection and stability, and the overall simulation cost (L. Wang et al., 2021). In this study, an intersection angle (β) of 120° and size ratio (ρ) of 0.3 were chosen based on prior research that found these parameters suitable for representing ballast shape (J. Chen et al., 2019; Jia et al., 2019). With these settings, natural crushed stone clumps contained about

162,465 pebbles, while BOF slag clumps contained about 148,309 pebbles across the entire granular assembly. For other mixtures, 20%, 40%, 60%, and 80% BOF slag contains 162081, 157581, 152083, 150241, and 148309 pebbles respectively. These parameters indicate that natural crushed stone has more angular, irregular, and complex shapes than BOF slag.

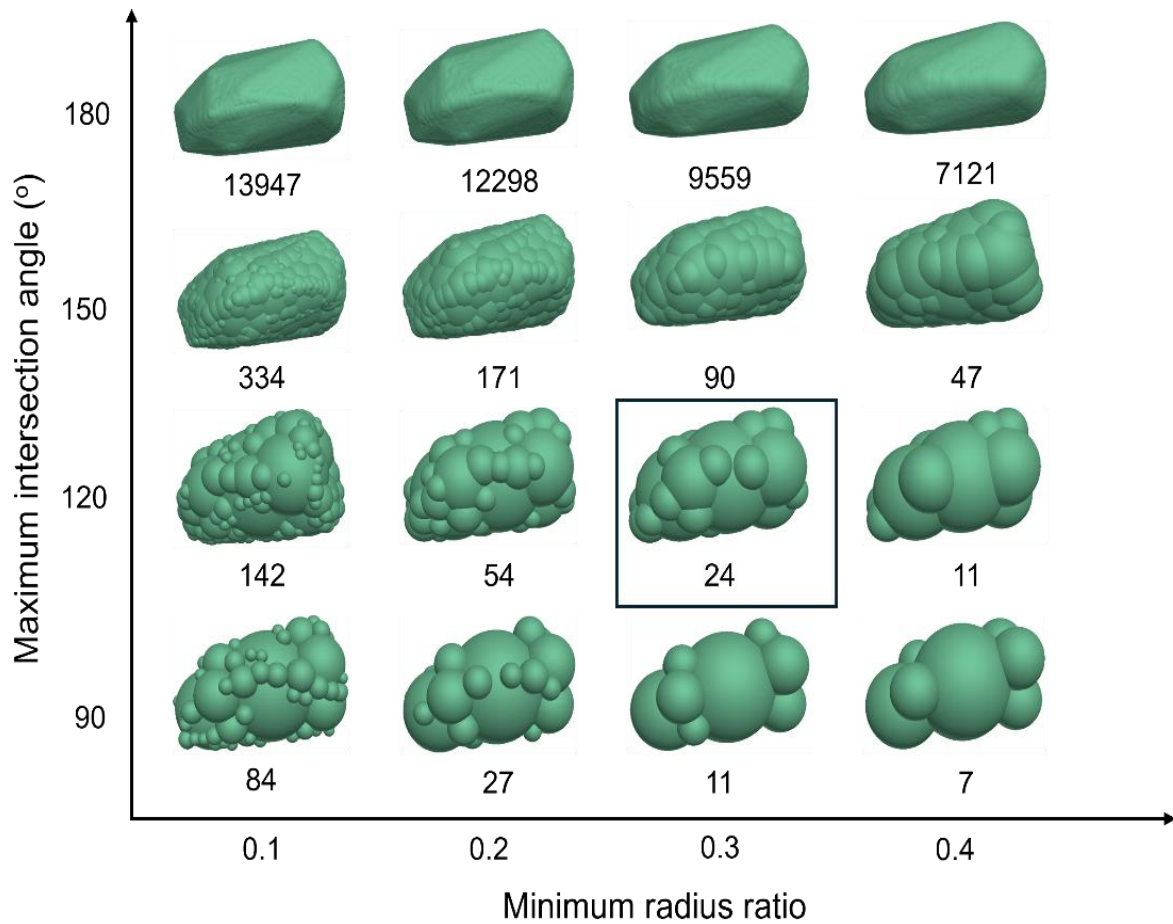


Figure 3-7. Geometric effects of varying sphere size ratios and intersection angles in spherical clump templates

3.4.3. Model setup

A 3D numerical model was developed in PFC3D to simulate the response of ballast subjected to monotonic direct shear loading conditions. The numerical model employed a large shear box with a size of $300 \times 300 \times 300$ mm. The shear box was split horizontally into two equal parts, with rigid walls representing the boundaries to confine the particle assembly. Two rigid flanges were also included on each side of the shear box to prevent ballast particles from escaping. A schematic illustration of the numerical shear box model in the XZ-plane is presented in Figure 3-8. The particle size distribution (PSD) of the assembly was represented via a multi-bin clump approach, which matched the target PSD from experimental tests. In the DEM simulations, the mixture compositions were specified on a volumetric basis. To ensure that the same volume

fractions were represented in both the physical and numerical assemblies, the experimentally measured masses were transformed into corresponding volumes based on the measured particle densities.

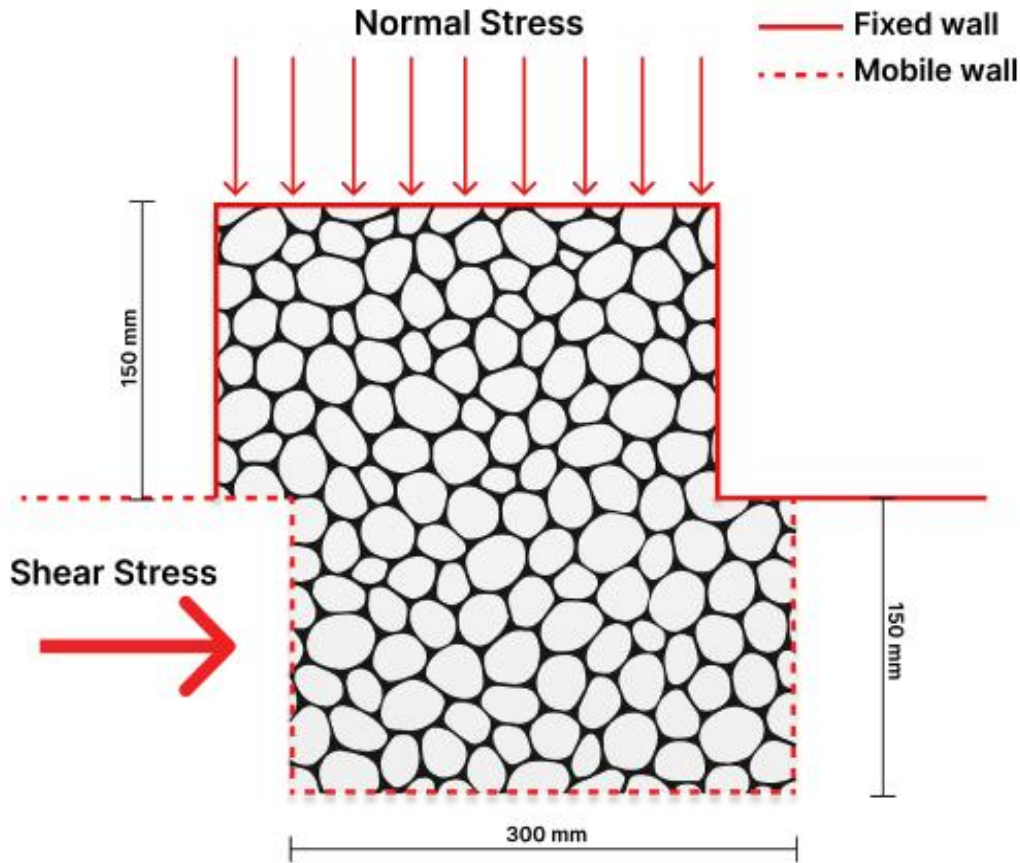


Figure 3-8. Schematic illustration of the shear box configuration viewed in the XZ plane

The particles were randomly generated using an in-built random generation algorithm. The value of the random seed was set to ensure that the models had randomly generated but repeatable positions and orientations of the particles. The particles then settled due to the force of gravity and cycled until they reached equilibrium with the rigid boundaries through particle contact. The equilibrium was achieved by setting the average force ratio to 1×10^{-5} with zero friction and targeting a porosity value of 0.21. The average force ratio is the ratio of unbalanced forces to the total applied forces at a given time (Itasca Consulting Group Inc., 2021). The particle-particle and particle-wall contact forces were calculated using the linear contact model explained above. Normal stress was applied using a servo-control system that controlled the velocity of the top wall until the reaction stress reached the target value within $\pm 0.1\%$. The shear stage was initiated by translating the lower part of the shear box at a steady velocity of 0.01 m/s while ensuring constant normal stress. The velocity was set to ensure that the simulation stayed in the quasi-static state, where the inertia forces are negligible (Sun et al.,

2024). The average number of clumps generated in the granular assembly is approximately 6091. The shear stress, τ , was measured by tracking x-direction reaction forces on all lower box boundaries and calculated using the expression below:

$$\tau = \frac{\sum_{i=1}^n F_{xi}}{A} \quad (3.10)$$

where F_{xi} is the reaction force in the x-direction of the i^{th} wall, and A is the shear plane area (H. Gong et al., 2019).

3.4.4. Model calibration and verification

In DEM, technical limitations make it impossible to directly translate macroscopic parameters into the microscopic inputs needed for simulations. As a result, the material's micro-parameters require gradual calibration until the model matches the behavior observed in physical tests (S. Li et al., 2021). This calibration process is crucial to make sure the numerical model correctly predicts the mechanical behavior of the material (Yu et al., 2021). Based on this procedure, three sets of reference experiments were employed: 100% BOF slag, 100% natural crushed stone, and 80% BOF slag. These were the standards for the calibration of the model. Calibration using the trial-and-error procedure as outlined by M. Wang et al. (2021) was employed. In the course of this, certain microscopic parameters were customized, while others were chosen as per provided guidelines in previous studies. For example, a normal-to-shear stiffness ratio of 1.33 was picked as it lies within the practical range of 1.0 to 1.5 for granular materials (Goldenberg & Goldhirsch, 2005; Lu et al., 2024). The effective modulus for the shear wall was set higher than that of the particles to reduce particle-wall overlap (Potyondy & Cundall, 2004). Moreover, a local damping coefficient of 0.7 was used to quickly achieve equilibrium by removing kinetic energy from the system and to support quasi-static deformation modeling (J. Chen et al., 2025; Itasca Consulting Group Inc., 2021). The calibration graphs are presented in the appendix. Parameters within the minimal calibration set were varied individually over their specified ranges while all remaining parameters were fixed at their baseline values. The obtained response curves show how each of the important parameters affects the calculated shear stress-strain behavior of the individual-material samples (100% stone and 100% slag). These results demonstrate the sensitivity of the model to the chosen parameters and provide a reason for choosing the values of the parameters. It is also crucial to point out that the interparticle friction coefficient for stone-slag interactions was considered to be the smaller of the two friction values, as suggested by the method proposed by Potyondy & Cundall (2004). Figure 3-9 and Table 3-1 present the stress-strain response of the calibrated model and the

calibrated microscopic parameters, respectively. It can be deduced that the numerical model is in good agreement with the laboratory results for all normal stresses.

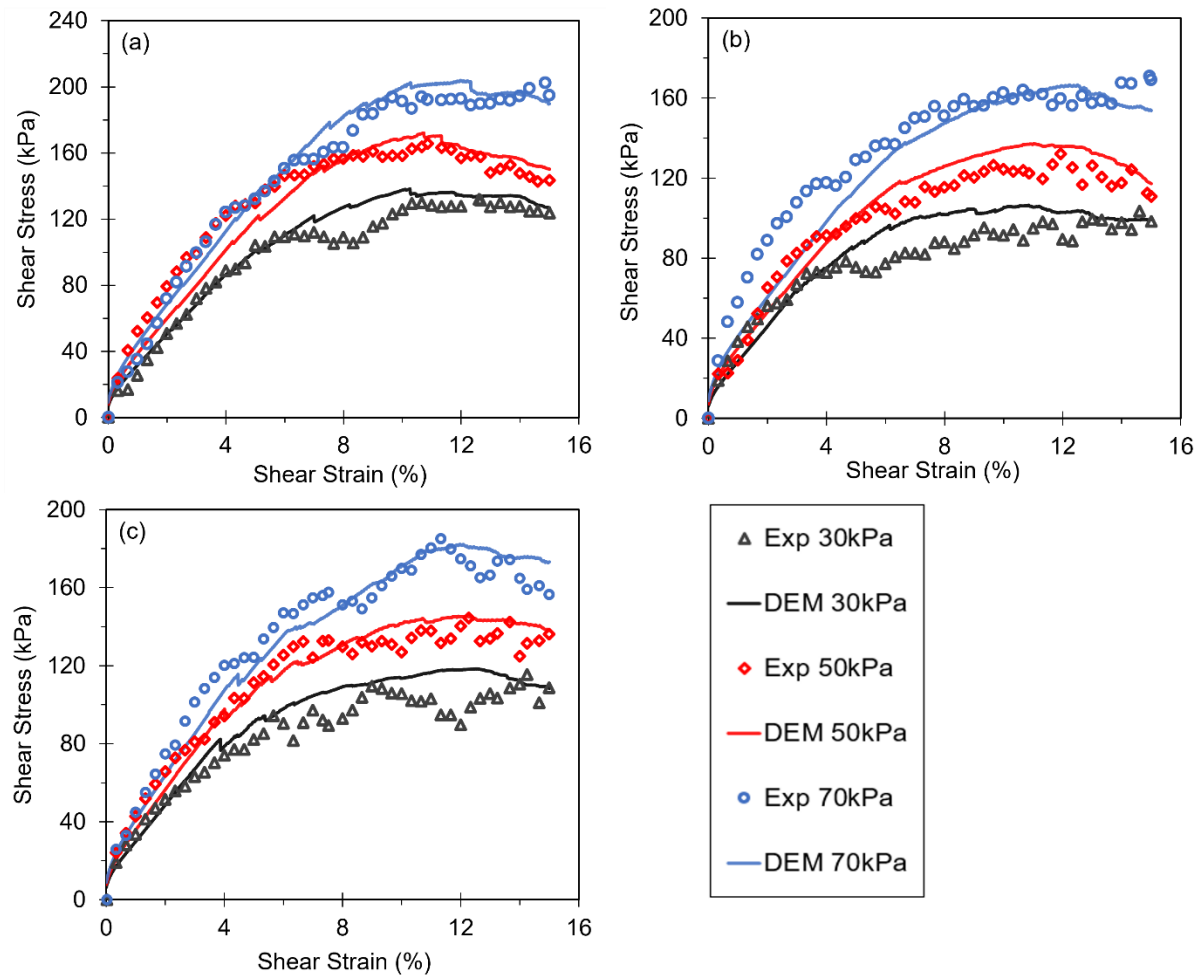


Figure 3-9. Validation of experimental results with DEM simulation: (a) Crushed Stone; (b) BOF slag; (c) 80% BOF slag.

Table 3-1. Proposed model parameters for the numerical simulation.

Parameters	Value
Particle density (kg/m^3)	2750 (Stone) / 3290 (slag)
Effective Modulus of crushed stone (Pa)	1.1×10^7
Effective Modulus of BOF slag (Pa)	1.1×10^7
Effective modulus of elasticity of wall (Pa)	1.5×10^7
Stiffness ratio (k_n/k_s)	1.33
Interparticle friction coefficient of stone-stone ($\mu_{\text{stone-stone}}$)	0.52
Interparticle friction coefficient of slag-slag ($\mu_{\text{slag-slag}}$)	0.46
Interparticle friction coefficient of stone-slag ($\mu_{\text{stone-slag}}$)	0.46
Interparticle friction coefficient of stone-wall ($\mu_{\text{stone-wall}}$)	0.4
Interparticle friction coefficient of slag-wall ($\mu_{\text{slag-wall}}$)	0.4
Local damping coefficient	0.7

Figure 3-10 shows the particle arrangement in the stone-slag mixtures prepared for direct shear tests. The assemblies were created to examine the effect of different BOF slag and crushed stone proportions. Six typical mixtures are displayed, with slag contents of 0%, 20%, 40%, 60%, 80%, and 100%.

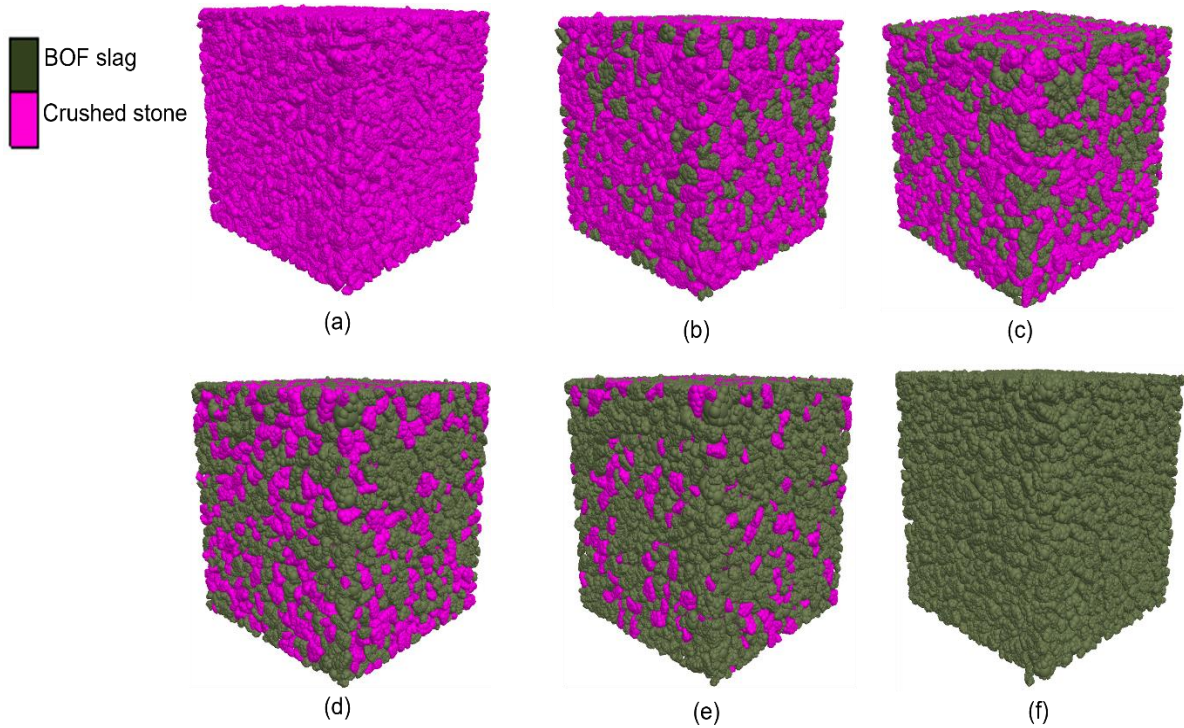


Figure 3-10. BOF slag content the stone-slag blends: (a) 20% BOF content; (b) 40% BOF content; (c) 60% BOF content; (d) 80% BOF content.

3.5. Quantifying microstructural evolution

To develop a clear understanding of the mechanical response of granular materials like ballast under loading, it is essential to study their behavior from the microstructural level. Specifically, the evolution of fabric anisotropy during shearing to a large extent controls the strength, deformation, and load transfer mechanisms within the granular assembly. Fabric anisotropy is defined as the directional dependency of the spatial distribution and orientation of particles and voids within the assembly (Oda, 1972). It can be measured through the assessment of the favored direction of particle bodies, surfaces, void spaces, and contact normal (Kuhn et al., 2015). The distribution of contact normal has proven to be the most effective and straightforward measure of the behavior of granular materials (J. Shi & Guo, 2018). The fabric

tensor (ϕ_{ij}) is a mathematical tool for quantifying fabric anisotropy in granular materials (Satake, 1978), and it is defined as follows:

$$\phi_{ij} = \frac{1}{N} \sum_{k=1}^N n_i^k n_j^k = \begin{bmatrix} \phi_{xx} & \phi_{xy} & \phi_{xz} \\ \phi_{yx} & \phi_{yy} & \phi_{yz} \\ \phi_{zx} & \phi_{zy} & \phi_{zz} \end{bmatrix} \quad (3.11)$$

where n^k is the contact unit normal vector for contact k with i and j representing the x, y , and z directions. The N represents the sum of contacts in the overall contact network. The fabric tensor above describes the entire contact assembly. However, Radjai et al. (1998) suggested dividing the contact assembly into two subgroups: strong sub-network and weak sub-network. The strong sub-network includes contacts where the normal contact force exceeds the average normal contact force ($\bar{F}$), while the weak sub-network includes contacts where the normal force is below the average ($\bar{F}$). The average normal contact force is defined as:

$$\bar{F} = \frac{1}{N} \sum_{k=1}^N f_n^k \quad (3.12)$$

where f_n^k is the normal force for contact k . Therefore, the fabric tensors for the subnetworks can be expressed as:

$$\phi_{ij}^s = \frac{1}{N^s} \sum_{k=1}^{N^s} n_i^k n_j^k, \quad \phi_{ij}^w = \frac{1}{N^w} \sum_{k=1}^{N^w} n_i^k n_j^k \quad (3.13)$$

where N^s and N^w are the sum of contacts in the strong and weak sub-networks, respectively. In the direct shear test setup, the z -axis represents the normal loading direction, while the x -axis aligns with the horizontal shear direction. The principal stress state and resulting particle contact network primarily develop within the X - Z plane (J. Chen et al., 2021; L. Gong et al., 2020). By projecting contact orientations onto the X - Z plane, the main anisotropic features of the ballast assembly can be captured effectively without the added complexity of full 3D analysis. The fabric tensor was simplified to two dimensions to measure anisotropy in the X - Z plane, as shown below:

$$\phi_{ij} = \begin{bmatrix} \phi_{xx} & \phi_{xz} \\ \phi_{zx} & \phi_{zz} \end{bmatrix} \quad (3.14)$$

The magnitude of fabric anisotropy for each contact network can be described by the corresponding fabric deviator, ϕ_d , which is the difference between the major principal value ϕ_1 and the minor principal value ϕ_2 of the fabric tensor. These principal values can be obtained from the tensor's eigenvalues.

Chapter 4 – Results and Discussion

4.1. Shear stress parameters

The shear stress-strain relationships for the simulated mix ratios of BOF slag under normal stresses of 30, 50 and 70kPa are presented in Figure 4-1. At all levels of confining pressures, the stress-strain curves demonstrate the characteristics behavior of granular materials: initial increase in shear strength until a peak value is reached, followed by strain-softening where the shear stress gradually reduces with further displacement. The strain-softening for all curves begins between 10% and 12% shear strain, indicating that the maximum strain applied was enough to fully characterize the material's mechanical response. As expected, the peak shear stress increased with increasing normal stress for all the test samples. Generally, the peak shear stress is strongly dependent on both the applied normal stress and the proportion of BOF slag in the assembly. Additionally, it can be observed that at the onset of shearing, when the strain level is still very low, the assembly behaves in a linear elastic manner; hence, the shear stress is primarily governed by the contact stiffness of the particles. After reaching a certain level of strain, the samples become unlocked and relatively mobile, and the shear stress becomes essentially independent of the interparticle stiffness. Furthermore, the trends observed before and after the peak shear stress are influenced by the mobilized friction at contacts, the coordination number and particle angularity. This observation is consistent with the findings Bathurst & Rothenburg (1990) from their numerical simulations of biaxial compression on a planar assembly of 1000 discs.

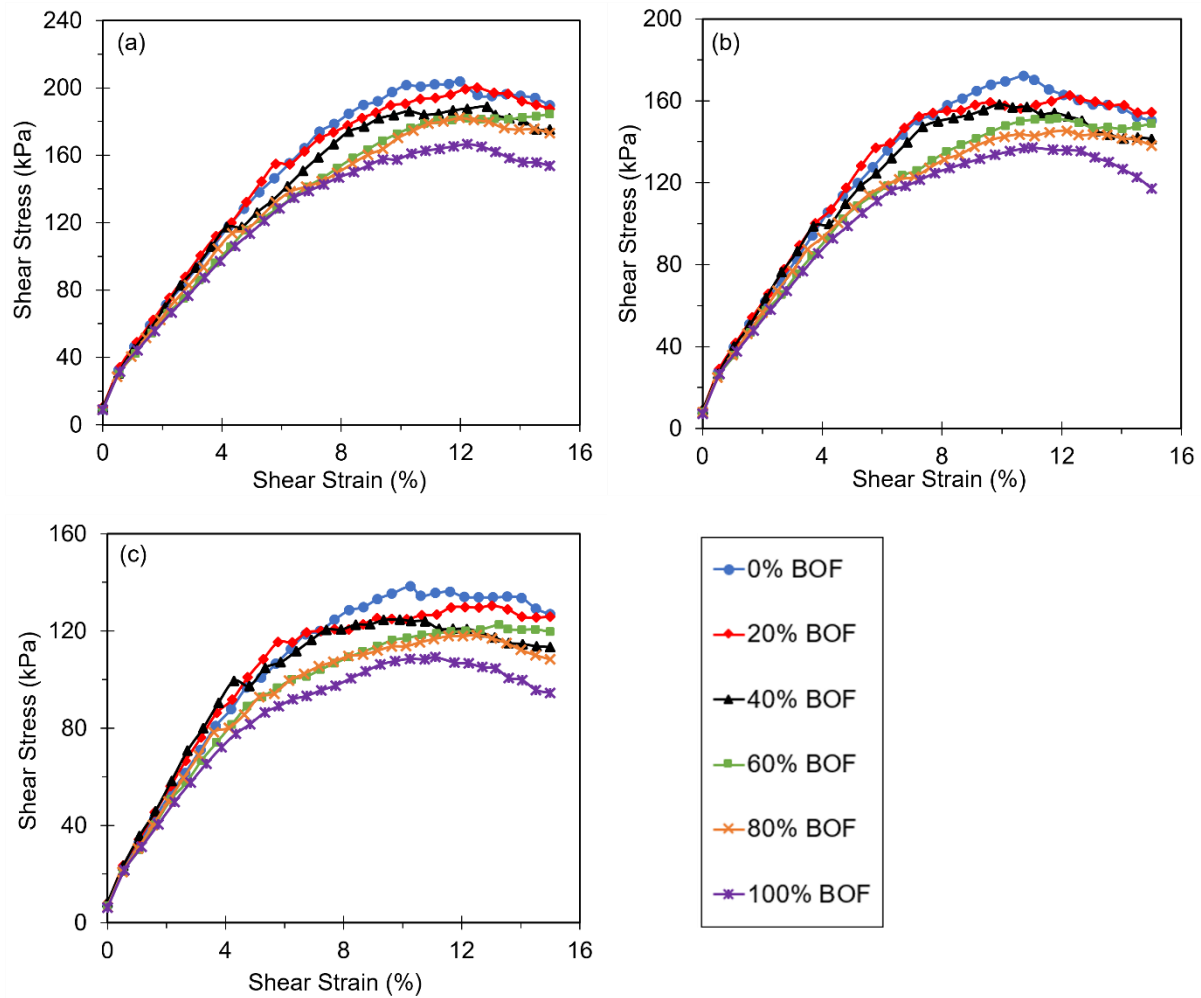


Figure 4-1. Shear stress vs shear strain for various mix ratio of BOF slag: (a) 70kPa; (b) 50kPa; (c) 30kPa.

The maximum shear strength and the corresponding peak friction angle for all mix ratios are presented in Figure 4-2. The maximum shear strength represents the peak shear stress before failure or the onset of strain softening. At all normal stresses, the sample containing 0% BOF slag mobilized the highest strength. A gradual reduction in shear strength was observed with increasing BOF content, with the lowest resistance recorded for the 100% BOF slag mixture. An increase in the BOF slag content from 0% to 20%, 40%, 60%, 80% and 100% resulted in a mean reduction of 4%, 8%, 11%, 14% and 20%, respectively, in the maximum shear strength across all normal stresses. This reduction may be attributed to a decrease in interparticle frictional resistance as natural crushed stone is reduced in the mix. When BOF slag is used in its entirety, the material exhibits weaker interlocking and a reduced ability to sustain shear stresses. However, mixtures containing 20-40% BOF has relatively high shear strength, performing only marginally lower than the natural crushed rock. This suggests that a limited addition of BOF slag does not significantly compromise shear resistance.

The peak internal friction angle ϕ' of the ballast samples was estimated using the following formula:

$$\phi' = \tan^{-1} \frac{\tau}{\sigma_n} \quad (4.1)$$

where τ is the shear stress, and σ_n is the normal stress. Cohesion is assumed to be negligible due to the granular, non-cohesive nature of ballast. The internal friction angle follows the same trend as the maximum shear strength of the mix, as it is the primary factor governing shear failure of granular materials. An increase in the BOF slag content from 0% to 20%, 40%, 60%, 80% and 100% resulted in an average reduction of 1%, 2%, 2%, 3% and 5%, respectively, in the peak internal friction angle across all normal stress levels. Microscale observations provide further insight into this reduction. These results confirm the influence of the number of pebbles generated for each material, as discussed earlier. Natural crushed stone generated more pebbles than BOF slag, resulting in greater particle angularity and enhanced interparticle interlocking. The progressive incorporation of BOF slag into the mix reduces the degree of mechanical interlock among particles and promotes greater particle sliding and reorientation, which in turn results in a lower mobilized friction angle.

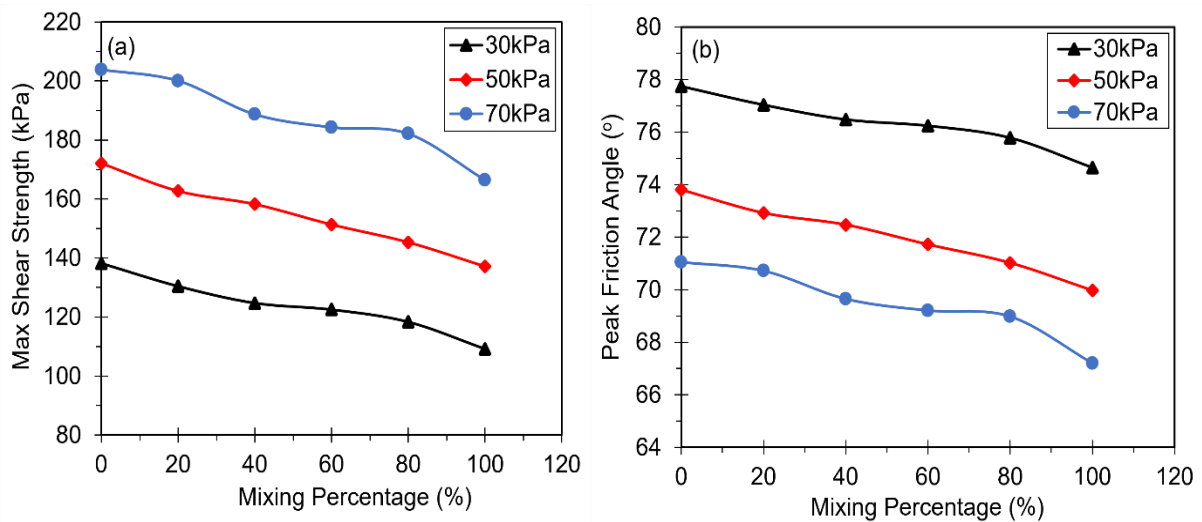


Figure 4-2. Shear stress parameters with various BOF slag mix ratio: (a) maximum shear strength. (b) peak friction angle.

4.2. Comparative evaluation of shear stress parameters

The shear strength parameters obtained in this study contribute meaningful insight into the performance of BOF slag and its mixtures with bauxite for potential use as railway ballast. However, it is important to note that there is no universally accepted standard for rating the performance solely based on shear strength and internal friction angle. Instead, evaluation is

often conducted through a comparative assessment with direct shear parameter values and trends reported in previous works. Based on the literature, there is a general agreement that the strength and friction angles of steel slags are higher than those of natural aggregates (Esmaeili et al., 2025; Godson et al., 2025; Jia et al., 2021; Jing et al., 2020). On the other hand, different results were obtained by Jing et al. (2022), who found that basalt has stronger shear strength properties than EAF slag. The reason for this is that the strength of ballast materials is strongly influenced by the parent rock, shape, and manufacturing process.

In the current study, it was anticipated that the shear strength of BOF slag would be greater than that of natural bauxite aggregate, as has been observed in the majority of previous studies. However, the opposite was observed, and the bauxite aggregate was found to have higher shear strength and friction angle than BOF slag under all testing conditions. This indicates that the parent material has a significant effect on the overall shear characteristics of ballast aggregates. Nevertheless, it is noteworthy that the BOF slag in the current study also performed well, with similar values of shear strength to those reported for high-quality steel slag in previous studies (Esmaeili et al., 2025). Moreover, partial replacement can also be considered a good compromise. Mixtures containing BOF content between 20-40% have optimal properties and effective friction angles (ϕ') slightly reduced compared to the 0% BOF content condition, while also offering the chance to improve sustainability via resource utilization and waste reduction. Therefore, partial replacement of BOF content can be considered an optimal strategy that maintains shear strength within a very small range of reduction and has the potential to meet environmental compliance requirements.

4.3. Evolution of normal contact force

External forces in a granular assembly are maintained and propagated through the interconnected network of particle contacts. The contact force distribution is a crucial aspect in understanding the micromechanical mechanisms governing deformation (N. Guo & Zhao, 2013). In an attempt to explain the contact force transmission in the current study, the natural crushed stone and BOF slag assemblies were taken as case studies under a normal stress of 70kPa (Figure 4-3 & 4-4). In these figures, each line denotes a contact between two particle centroids, while the color scale represents the magnitude of the corresponding contact forces. These figures clearly indicate the progressive evolution and redistribution of contact forces within the particle assembly as the shearing process advances. At 0% shear strain, the contact distribution is relatively uniform with a low average contact force and number of contacts. The force chains are randomly distributed, indicating an isotropic contact distribution characteristic

of an undeformed granular assembly. At this point, most of the contacts are weak, with only a few force chains dominating the vertical stress applied.

With the increase in shear strain, the random force chains start to reorient, and a preferred direction emerges in the horizontal plane. Along with this, the number of contacts and the average contact force increase. This is because the mobilization of interparticle resistance increases as the particles reorient to resist the shear deformation. The force chains start to realign themselves in a diagonal manner, creating a continuous path from the top-left to the bottom-right of the shear box, which represents the direction of the major principal stress. At 10% shear strain, the force chain network becomes more organized and aligned. The average contact force and the total number of contacts both increase. This is because the interparticle resistance is maximized at this stage, and the particles are at their most aligned. Finally, at 15% shear strain, the average contact force slightly increases, but the number of contacts decreases. This indicates that the contacts are breaking, and the particles are rearranging themselves after the peak stress has been attained.

Overall, this progression clearly shows the change from an isotropic to an anisotropic structure as shear deformation develops. This evolution of contact forces is consistent with previous literature that shows how contacts orient preferentially in the direction of the major principal stress (N. Guo & Zhao, 2013; Indraratna et al., 2014b). A distinguishing feature between the BOF slag and crushed stone assembly is the number of contacts generated throughout the shearing phase. This difference demonstrates how the total number of contacts relates to the capacity of a granular assembly to accommodate external forces and shear deformation. Additionally, this explains further that the crushed stone assembly transmit force through a more concentrated but stronger chains, while the BOF slag assembly carries load through a more randomized network.

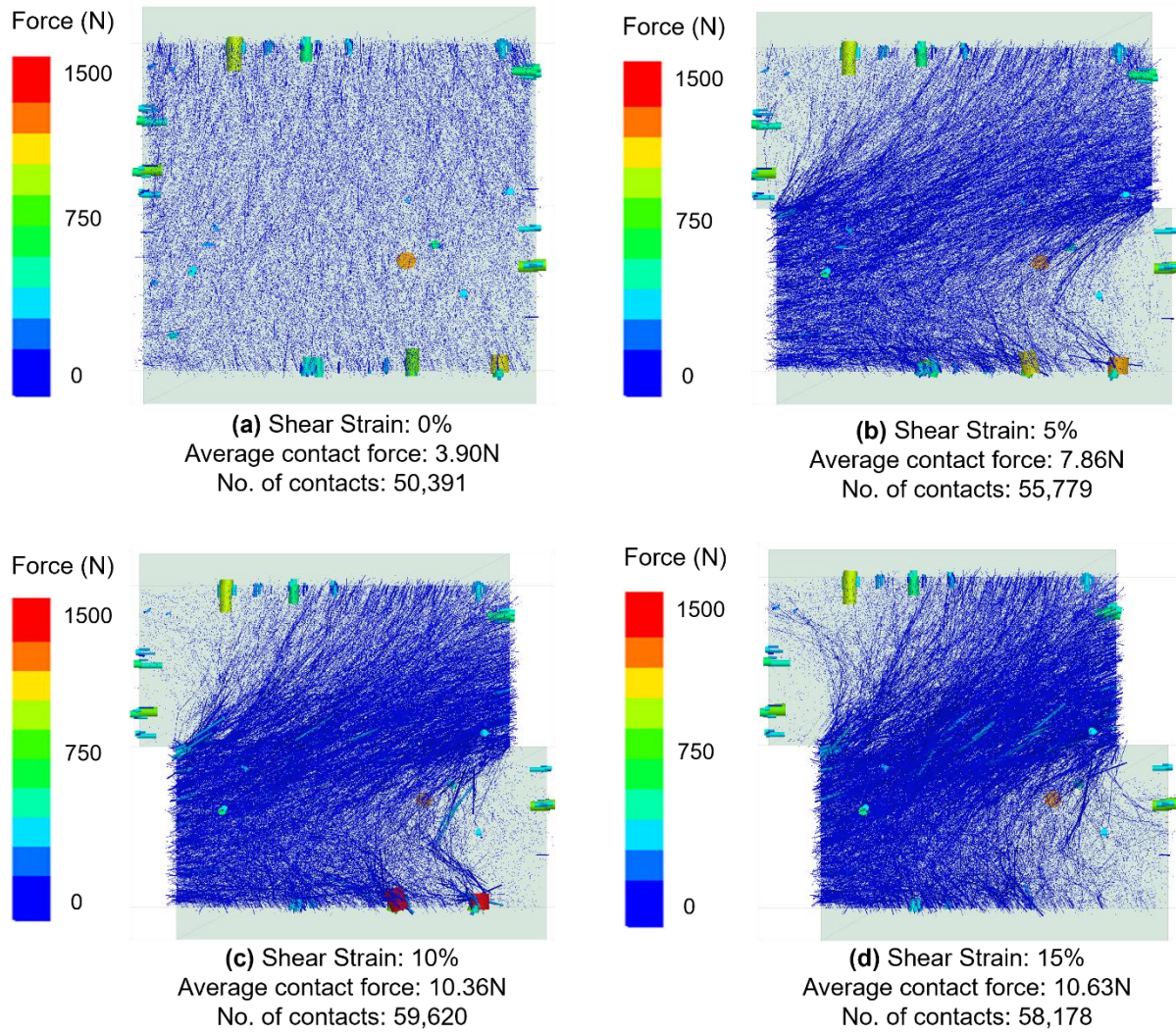


Figure 4-3. Development of force-chain networks in crushed stone specimens at various shear strain levels: (a) 0% shear strain; (b) 5% shear strain; (c) 10% shear strain; (d) 15% shear strain.

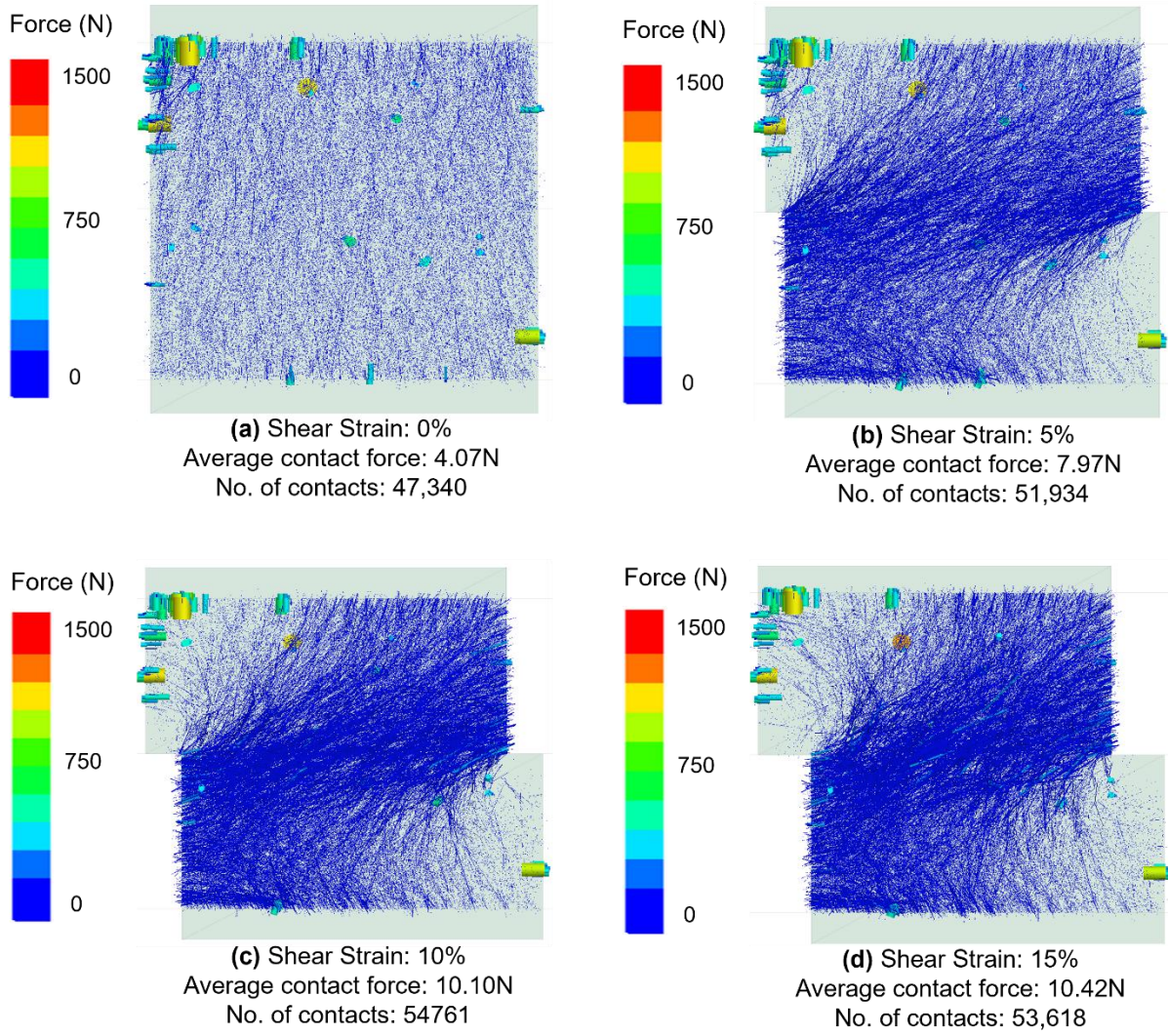


Figure 4-4. Development of force-chain networks in BOF slag specimens at various shear strain levels: (a) 0% shear strain; (b) 5% shear strain; (c) 10% shear strain; (d) 15% shear strain.

4.4. Coordination number

One of the major statistical quantities that describes the contact geometry of a granular assembly is the coordination number (CN) (Kruyt, 2003). It is a vital microstructural variable that characterizes the internal packing, network structure and rearrangement of particles (P. Zhang et al., 2022). It is estimated as the mean number of contacts per particle and can be computed mathematically using the following expression:

$$CN = \frac{2N_c}{N_p} \quad (4.2)$$

where CN is the average coordination number of the whole assembly, N_c is the total number of contacts and N_p is the total number of particles. The expression is multiplied by 2 because each contact is shared by two particles. Figure. 4-5 illustrates the development of CN with shear

strain for various mixing ratios of BOF slag. Initially, a small decrease in CN is noticed for all samples, which represents the initial particle rearrangement due to the applied shear stress. During this phase, some contacts are broken as particles rearrange to adapt to the imposed boundary conditions. As shearing proceeds, a steady rise in CN is noticed, which represents the phase where particle contacts are organized and stabilized. This is accompanied by the mobilization of shear resistance and the development of robust force chains in the sample. The maximum CN is reached at 8-10% shear strain, which is in close proximity to the maximum shear stress. After this stage, a steady decline in CN is noticed for all mixtures, which represents the loss of contacts as the sample undergoes large shear deformation. This is indicative of the development of shear bands in the sample, where particle rearrangement and void growth take place (Cheng & Wang, 2018; H. Gong et al., 2019).

The addition of BOF slag means there are fewer average contacts between particles, indicating less dense packing and lower interlocking between particles. The increase in the ratio of BOF slag mixture from 0% to 20%, 40%, 60%, 80%, and 100% led to a CN value decrease of 0.5%, 2%, 5%, 6%, and 8%, respectively. Nevertheless, the mixture of 20-40% has a peak CN value that is still close to the natural crushed stone, indicating that the presence of BOF slag does not affect the connectivity of particles to a great extent.

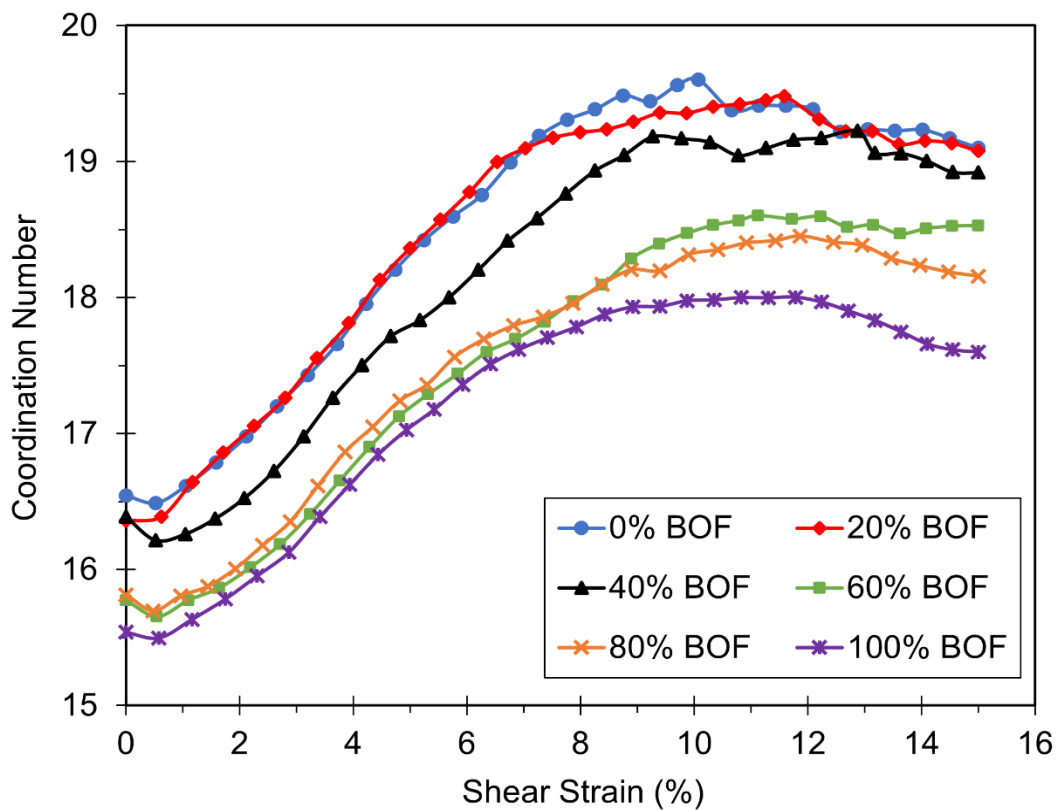


Figure 4-5. Evolution of coordination number with varying BOF slag contents.

4.5. Proportion of strong and weak contacts

The objective of this section is to analyze the development of the proportion of strong and weak contacts (Figure 4-6) in the granular assembly. This will assist in understanding the load transfer processes that develop during shearing. The difference between the strong and weak contacts has been explained in an earlier section (Section 3.5). Before shearing, all mixtures have a proportion of strong contacts between 21% and 24%. As the shear strain increases, this proportion increases until it reaches 6-8% strain, where it becomes stable at a critical state with values between 29% and 31%. It has been observed that the shear stress in a granular material is supported by the strong contact network, while the weak contact network acts as a support system that redistributes the forces (Radjai et al., 1998). This indicates that the rise in the proportion of the strong contacts is due to the development of force chains and their strengthening, where the number of load-carrying particles increases, and they support higher forces. The evolution of the weak contacts follows an inverse trend to that of the strong contacts. With increased strain, the proportion of weak contacts gradually decreases as they are either lost or converted into strong contacts until a stable state is reached. The prevalence of weak contacts throughout the shearing stage highlights that most particles in the mixture do not directly carry large loads but provide essential support that stabilizes the strong contact network. In terms of BOF slag inclusion, no consistent trend is observed in the peak values of either strong or weak contact proportions. However, all samples follow a similar evolutionary trend during shearing.

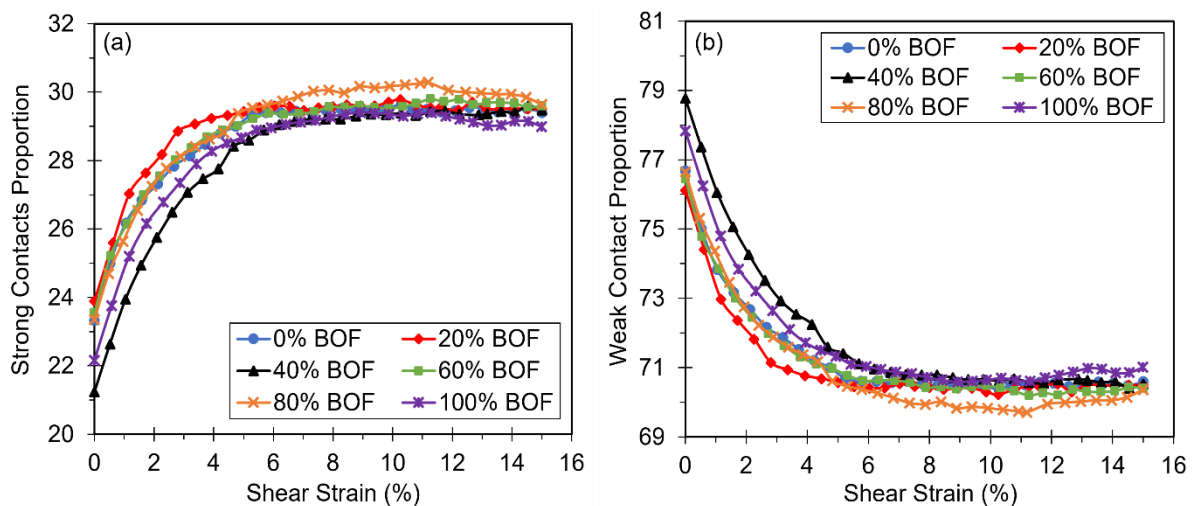


Figure 4-6. Variation in strong/weak contact fractions during shearing: (a) strong contacts; (b) weak contacts.

4.6. Fabric anisotropy evolution

The macro-scale behavior of granular materials is governed by particle-level interactions, including the evolution of particle spatial arrangement and the orientation distribution of inter-particle contact. This section focuses on the evolution of the degree of fabric anisotropy of the overall, strong, and weak contact networks (Figure. 4-7). For all contact networks, the observed anisotropy can be categorized as either inherent or induced. Inherent anisotropy results from the initial arrangement and preparation of the material, while induced anisotropy develops as a consequence of applied shear stress (Oda & Nakayama, 1989; J. Shi & Guo, 2018). In a typical direct shear test, a vertical load is applied prior to shearing to simulate in-situ overburden pressure and allow for initial consolidation. This loading sequence is crucial for capturing inherent anisotropy, which reflects the natural directional dependence of particles deposited under gravitational stresses. Khera & Krizek (1967) described this phenomenon as primary inherent strength anisotropy. Therefore, the inherent anisotropy in this study is a combination of the initial particle arrangement and the effect of normal loading.

At 0% shear strain, inherent anisotropy was observed for all contact networks. This occurred because the contact normal were preferentially oriented in the vertical direction, aligning with the vertical stress. As expected, the introduction of shear induced stresses alters the inherent anisotropy at an early stage as particles rearrange and align with the direction of shear. It can therefore be noted that when particles are inclined parallel to the major principal stress direction, they tend to resist shear deformations more effectively. These results align with those of Oda & Nakayama (1989) from biaxial compression test on rod assemblies. With the progression of shear strain, the fabric deviator rises to a maximum value and then decreases towards the maximum displacement. This trend mirrors the evolution of the stress-strain curve, confirming a link between fabric anisotropy and shear strength of the samples.

The results further indicate that stress-induced fabric anisotropy is most significant within the strong contact network, relative to the overall and weak networks. This further confirms the role of the strong contact network as the main load-bearing component of the assembly. The peak value of the fabric deviator is influenced by the addition of BOF slag. The general trend shows that the peak fabric deviator decreases with increasing BOF slag content across all contact networks. This reduction indicates that the inclusion of BOF slag tends to randomize and weaken the directional dependency of particle orientations. This suggests that the BOF slag promotes a slight deviation of contact normal, which weakens force chains and reduces the assembly's ability to mobilize shear strength. However, J. Chen et al. (2025) stressed that

growing anisotropy could lead to localized stress concentrations, potentially resulting in increased ballast breakage. An advantage the inclusion of BOF slag can provide is the reduction of stress buildup in these small, localized areas. This in essence means that a small addition of BOF slag to the mix can provide a balance between ballast breakage and fabric anisotropy.

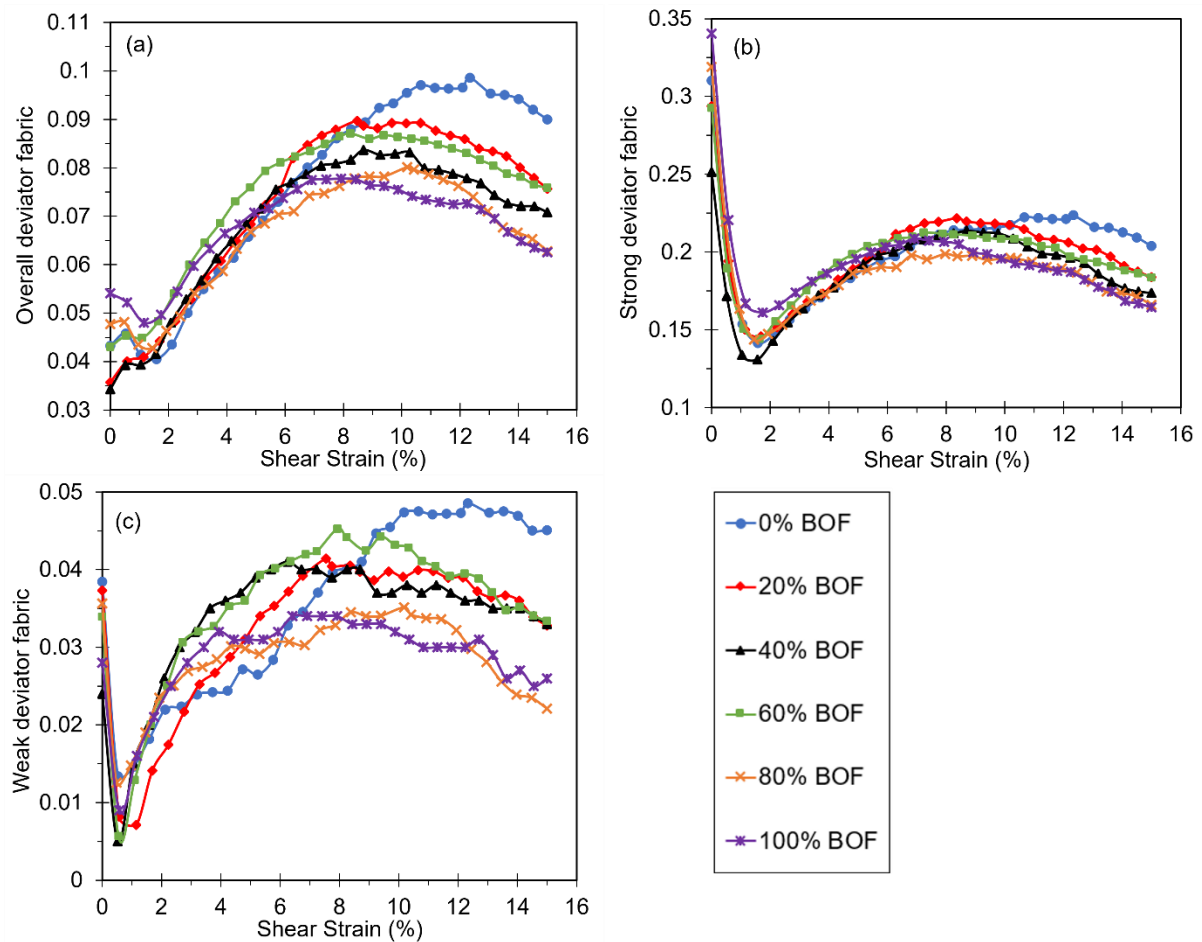


Figure 4-7. Evolution of deviator fabric against shear strain: (a) Overall contact network; (b) Strong contact network; (c) Weak contact network

4.7. Fabric anisotropy and applied stress ratio relationship

The evolution of microscopic fabric and macroscopic stress response reveals how granular media deform under shear, as the internal fabric directly influences macroscopic behavior. Monitoring these evolving fabric and stress parameters provides key micro-macro correlations, linking the particle-scale contacts and rearrangements to the resulting strength properties. Several constitutive models have been proposed to establish the relationship between fabric evolution and applied stress ratio (Antony et al., 2004; Shi & Guo, 2018). These models can predict the overall strength response of granular materials subjected to different conditions by relating the internal material structure (fabric) to its macroscopic strength. Despite significant progress in establishing these relationships, most models are limited to biaxial test

configurations. Therefore, this section attempts to establish a correlation based on the tests results from direct shear tests.

The evolution of the fabric deviator with the stress ratio is plotted in Figure. 4-8 for all contact networks. The stress ratio here represents the ratio of the shear stress to the normal stress. The graph was plotted by assuming that deformation begins from an isotropic state (neglecting inherent anisotropy), to capture the correlation for stress-induced anisotropy. Prior to attaining peak values, the stress ratio increases non-linearly with the fabric anisotropy for the overall and strong contact networks. After the peak, a reduction in the fabric deviator is observed as the stress ratio decreases. Unlike the other two networks, the weak contact network does not show a clear, consistent relationship. The curves are more scattered and exhibit irregular trends, which is expected because of their minor contribution to stress transmission compared to the strong network.

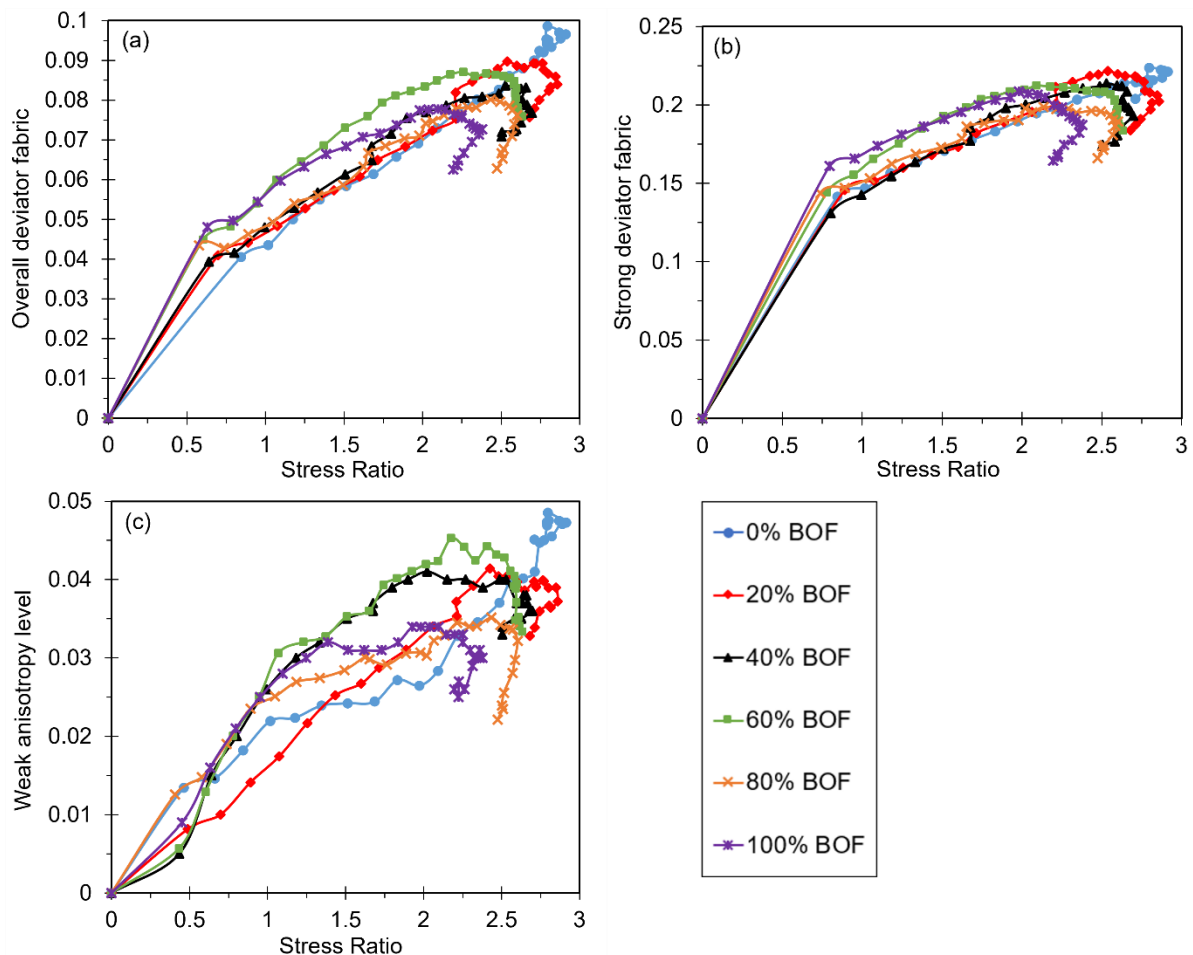


Figure 4-8. Relationship between fabric deviator and stress ratio: (a) Overall contact network; (b) Strong contact network; (c) Weak contact network

To establish a quantitative description of the pre-peak relationship between the fabric deviator and stress ratio for the strong and overall contact networks, a regression analysis was conducted. The relationship can be represented approximately with the power equation below:

$$\phi_d = a \left(\frac{\tau}{\sigma_n} \right)^b \quad (4.3)$$

where a and b are correlation constants that depend on the type of contact network and the proportion of BOF slag, as summarized in Table 4.1. The power equation provides an excellent approximation of the relationship between fabric deviator with the stress ratio, with all R^2 values exceeding 0.9, indicating a strong statistical correlation. The parameter a describes the initial build-up of fabric anisotropy at lower stress ratio, while b reflects the rate at which anisotropy builds up as a result of increased stress ratio. Generally, increased BOF slag content results in a decrease in parameter b , further highlighting the importance of shorter and randomized orientation of contact force chains on the evolution of anisotropy. For engineering applicability purposes, it is important to establish a functionalized relationship between each of the fitted parameters and the mixture of slag and stone in the granular assembly. Therefore, further equations were established that captures these relationship as described in Figure. 4-9. For the overall contact network, the equations are described as follows:

$$a = 0.0441 + 0.0001m_r \quad (4.4)$$

$$b = 0.7251 - 0.003m_r \quad (4.5)$$

The equations for the strong contact network are described as follows:

$$a = 0.1429 + 0.0002m_r \quad (4.6)$$

$$b = 0.4312 - 0.0014m_r \quad (4.7)$$

These mathematical equations shows that as BOF slag content increases, the parameter a increases and parameter b decreases. This trend shows a gradual move from an anisotropic stress state to a more isotropic stress condition, where contact force orientation becomes relatively less strongly aligned with the principal stress axis. This shift reduces the extent to which the internal friction angle and shear strength are mobilized in the granular assembly.

Table 4-1. Fitted parameters and R^2 for Equation (4.3) for the overall and strong networks at varying BOF slag proportions.

Overall contact network				Strong contact network			
Mix ratio (%)	a	b	R^2	Mix ratio (%)	a	b	R^2
0	0.043	0.754	0.996	0	0.147	0.378	0.999
20	0.046	0.667	0.989	20	0.146	0.433	0.994
40	0.050	0.564	0.990	40	0.146	0.418	0.995
60	0.058	0.521	0.995	60	0.162	0.367	0.996
80	0.050	0.522	0.990	80	0.155	0.302	0.994
100	0.057	0.435	0.998	100	0.171	0.273	0.999

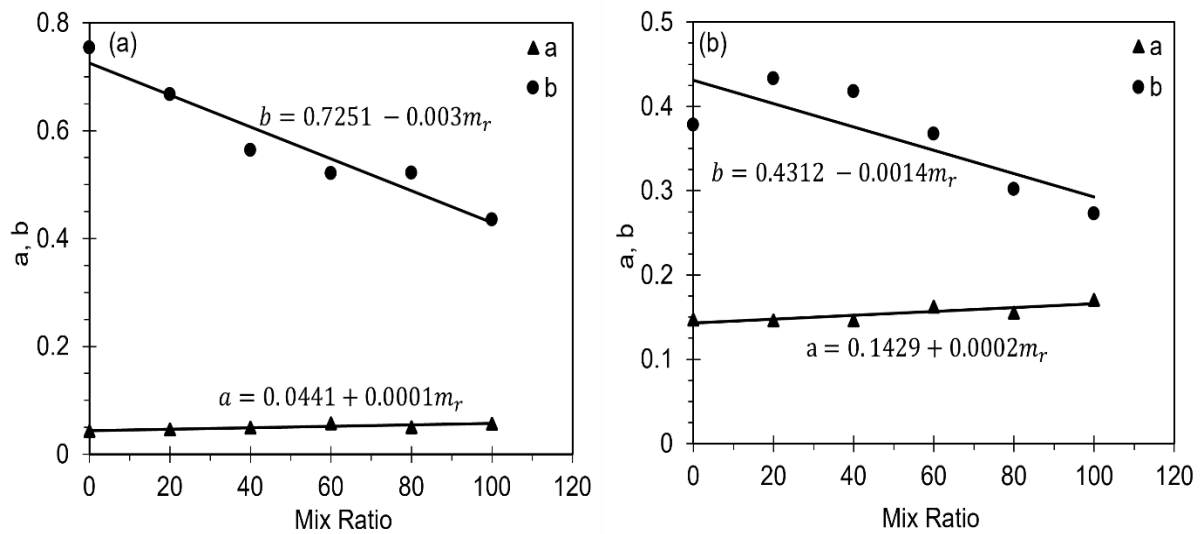


Figure 4-9. Correlation between fitted parameters and BOF proportions: (a) overall contact network; (b) strong contact network.

Chapter 5 – Conclusion

The research work used an integrated experimental and numerical method to assess the viability of BOF slag as a sustainable alternative to natural crushed rock for railway ballast. The macroscopic shear response and micromechanical structure development of different slag-stone mixtures were investigated through a series of large-scale direct shear tests and DEM simulations. The results show that the blending of BOF slag with bauxite provides a viable means for improving the sustainability of railway infrastructure. The following are the main conclusions drawn from this research work:

1. The numerical simulations of the stress-strain behavior were in acceptable agreement with the experimental results from the direct shear tests, capturing initial stiffness, peak strength, and post-peak strain hardening or softening.
2. The macroscopic shear strength and angle of internal friction are very much reliant on the BOF slag content. Although the pure form of BOF slag has the lowest resistance to shear, it was found that a combination of 20-40% BOF slag had a marginally lower shear strength than bauxite rock. This combination provides a good compromise between the use of a substantial amount of industrial waste and maintaining the required mechanical strength for ballast.
3. The CN decreases with increase in the proportion of BOF slag. This decline is due to less dense packing and weaker particle connectivity as the proportion of BOF slag increases. However, a moderate BOF slag ($\approx 20-40\%$) content does not significantly compromise particle interlocking.
4. The evolution of induced fabric anisotropy of all samples is consistent with the evolution of the stress-strain curve, following an initial increase as shearing progresses until a peak value is reached and then decreases. The magnitude of the fabric anisotropy is reduced systematically with the inclusion of BOF slag in the strong and overall contact network. However, while reduction in the magnitude of fabric anisotropy results in strength loss, it suggests a potential for reduced localized stress concentration and a potential reduction in ballast breakage, contributing to prolonged service life.
5. The study successfully established a quantitative power-law relationship $\phi_d = a(\tau/\sigma_n)^b$ between the fabric evolution and the applied stress ratio for the pre-peak behavior of the granular materials subjected to direct shear testing.

Chapter 6 – Limitations and future works

This study offers detailed insights into the macroscopic properties and microscopic properties of BOF slag and crushed stone for railway ballast applications, providing a clear pathway for the potential use of sustainable materials for railway ballast application. However, some limitations exist which restrict the general applicability of the conclusions drawn, and these are highlighted below.

1. These findings and constitutive models developed in this study are calibrated and validated exclusively for the tested materials: BOF slag from a steel plant in the Karaganda region of Kazakhstan and the crushed lateritic bauxite, under the specified gradation, chemical compositions and confinement range. Accordingly, the direct applicability of the conclusions to BOF slag with differing chemical compositions or to alternative crushed stone lithologies has not been established. Therefore, extension to other lithologies, gradations, and higher confinements should be undertaken with dedicated calibration.
2. The present simulations used rigid clumps; therefore, explicit particle breakage and intra-particle porosity in BOF slag were not modeled. Nonetheless, analysis of stress concentration and force-chain persistence identified the micromechanical factors governing breakage potential. Future work should incorporate breakable or bonded-particle formulations and account for porosity to directly quantify stress-mitigation effects.
3. While the study establishes the geotechnical viability of partial BOF substitution, a quantitative life-cycle assessment (LCA) was not performed. A dedicated LCA is recommended to evaluate potential reductions in carbon emissions, energy consumption, and landfill volumes achievable with 20–40% BOF substitution.

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APPENDIX

A1. Shape Quantification

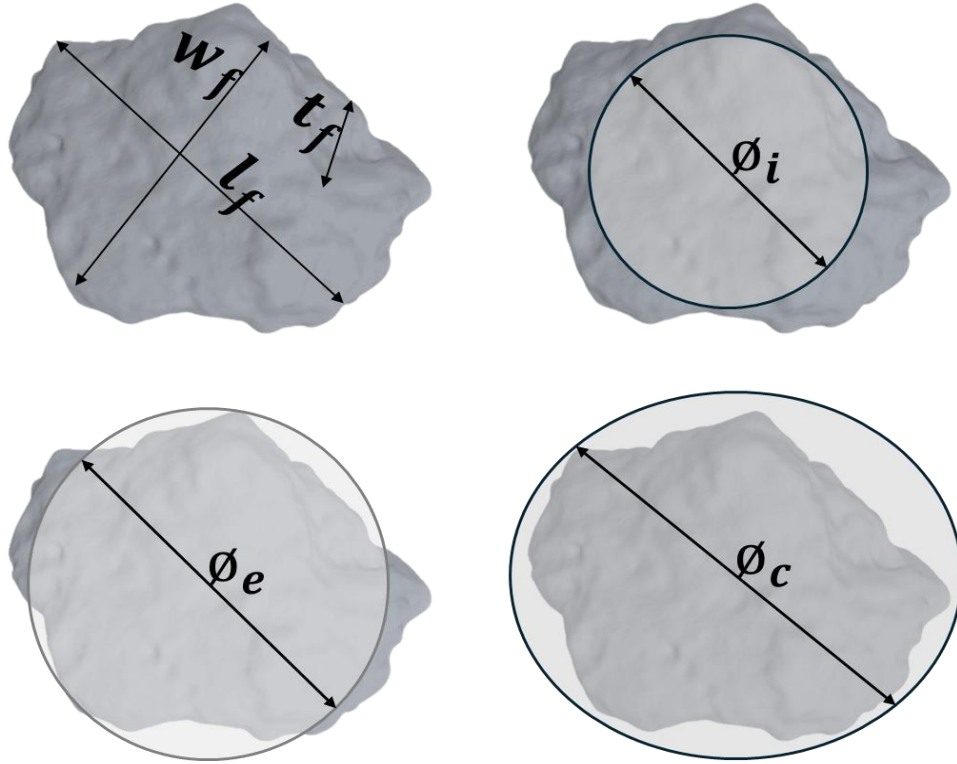


Fig. A1.1. Figurative description of shape parameters

Table. A1.1. Description of shape parameters

Shape Parameter	Meaning
w_f	Feret width
t_f	Feret thickness
l_f	Feret length
$\emptyset_e$	Volume equivalent sphere diameter
$\emptyset_i$	Inscribed sphere diameter
$\emptyset_c$	Circumscribed sphere diameter

Table. A1.2. Shape parameter values of crushed stone

ID	$l_f(mm)$	$w_f(mm)$	$t_f(mm)$	$\phi_i(mm)$	$\phi_e(mm)$	$\phi_c(mm)$	$V_p(cm^3)$	$A_p(cm^2)$	$V_c(cm^3)$	$A_c(cm^3)$	A_r	S_w	C_v	AI
1	28.62	22.64	16.55	13.16	18.64	28.74	3.39	13.07	3.89	13.29	0.76	0.83	0.87	0.64
2	31.15	24.44	15.78	11.35	20.01	31.26	4.20	15.51	4.90	15.36	0.72	0.81	0.86	0.61
3	34.40	27.91	18.28	10.33	20.71	34.44	4.65	17.63	5.66	18.03	0.73	0.76	0.82	0.58
4	30.91	26.02	16.78	12.11	20.09	31.03	4.24	15.87	4.92	15.76	0.74	0.80	0.86	0.62
5	45.24	36.97	19.87	15.32	27.46	45.53	10.84	29.52	12.01	29.06	0.68	0.80	0.90	0.59
6	31.66	26.64	17.34	14.01	22.14	31.87	5.68	18.40	6.46	18.19	0.75	0.84	0.88	0.56
7	37.77	32.94	22.14	13.74	25.32	38.00	8.50	26.47	10.61	25.79	0.77	0.76	0.80	0.68
8	40.61	34.84	20.36	12.99	26.73	40.66	10.00	27.56	11.12	27.34	0.72	0.81	0.90	0.57
9	54.07	46.09	31.05	20.37	36.58	54.53	25.62	52.04	29.96	51.25	0.76	0.81	0.86	0.63
10	44.33	39.29	27.80	19.65	31.69	44.54	16.66	38.10	18.75	38.07	0.80	0.83	0.89	0.66
11	45.82	41.20	20.23	14.83	30.61	46.35	15.02	38.88	17.46	38.49	0.70	0.76	0.86	0.73
12	40.04	36.62	27.60	19.65	29.66	40.49	13.66	34.48	15.96	34.03	0.83	0.80	0.86	0.69
13	54.00	46.55	33.05	24.46	39.68	54.42	32.71	60.85	37.05	57.45	0.79	0.81	0.88	0.59
14	69.73	56.80	27.02	21.80	40.53	70.41	34.87	66.24	40.03	65.79	0.65	0.78	0.87	0.58
15	57.80	48.54	34.32	20.28	40.64	58.13	35.15	64.21	40.40	61.52	0.77	0.81	0.87	0.60
16	55.62	46.38	24.67	15.82	36.72	55.73	25.92	53.88	29.98	53.00	0.68	0.79	0.86	0.58

Table. A1.3. Shape parameter values of BOF slag

ID	$l_f(mm)$	$w_f(mm)$	$t_f(mm)$	$\phi_i(mm)$	$\phi_e(mm)$	$\phi_c(mm)$	$V_p(cm^3)$	$A_p(cm^2)$	$V_c(cm^3)$	$A_c(cm^3)$	A_r	S_w	C_v	AI
1	24.67	22.22	18.18	7.54	18.69	24.71	3.42	14.32	4.31	13.54	0.86	0.77	0.79	0.54
2	27.96	25.44	15.97	9.87	19.81	28.13	4.07	15.41	4.94	15.51	0.77	0.80	0.82	0.53
3	27.78	23.92	15.85	7.64	18.48	27.84	3.31	14.22	4.20	13.84	0.76	0.75	0.79	0.51
4	26.58	23.19	16.62	8.60	18.81	26.64	3.49	14.45	4.44	14.06	0.79	0.77	0.78	0.50
5	31.06	26.01	20.27	12.99	21.69	31.39	5.35	18.84	6.84	18.62	0.81	0.78	0.78	0.50
6	28.86	25.52	17.60	9.71	20.31	29.16	4.39	19.50	5.69	16.69	0.79	0.66	0.77	0.66
7	30.83	28.14	17.47	12.13	21.29	31.05	5.05	17.24	5.77	17.33	0.77	0.83	0.88	0.53
8	30.23	26.40	15.61	11.72	21.30	30.36	5.06	17.95	6.07	18.08	0.73	0.79	0.83	0.53
9	40.78	36.72	25.81	16.15	29.33	41.15	13.21	34.42	15.97	34.05	0.80	0.79	0.83	0.64
10	45.17	38.81	24.30	16.36	29.63	45.20	13.62	34.93	15.52	35.03	0.74	0.79	0.88	0.62
11	53.54	45.52	29.83	20.38	34.93	53.81	22.32	49.12	26.41	48.15	0.75	0.78	0.85	0.63
12	51.50	43.51	31.85	20.71	34.56	51.94	21.61	48.08	26.34	47.20	0.79	0.78	0.82	0.60
13	62.43	49.04	30.79	23.98	38.18	62.73	29.15	57.26	33.97	59.14	0.71	0.80	0.86	0.68
14	46.89	41.66	32.56	14.24	34.37	46.90	21.27	47.66	26.75	46.72	0.83	0.78	0.80	0.62
15	56.93	47.26	30.27	26.08	40.35	57.07	34.39	58.16	37.65	58.50	0.74	0.88	0.91	0.55
16	51.40	47.56	37.07	25.32	37.67	51.88	27.98	55.53	31.29	56.66	0.85	0.80	0.89	0.76

A2. Clump creation from bubble-pack algorithm

Table A2.1. Sub-pebbles generated for each simulated clump for crushed stone

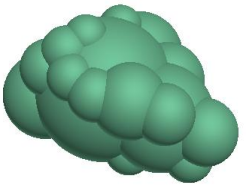
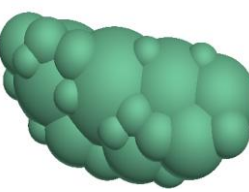
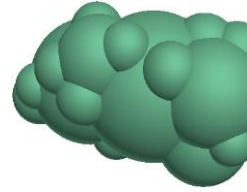
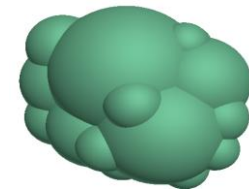
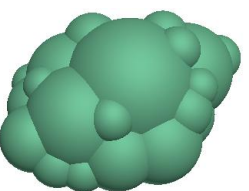
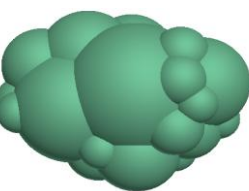
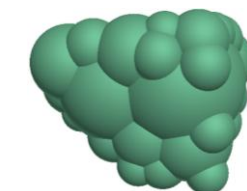
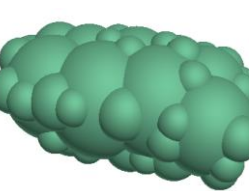
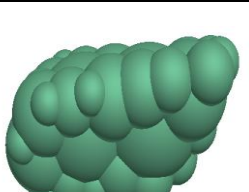
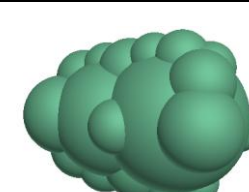
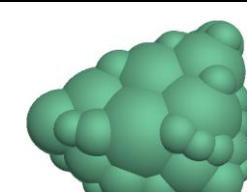
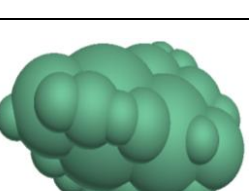
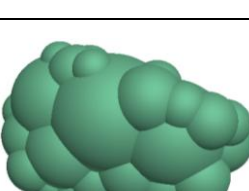
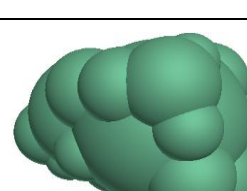
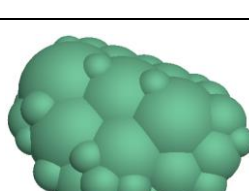
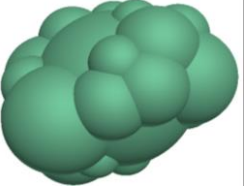
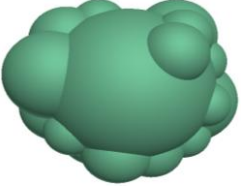
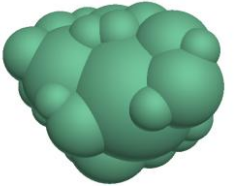
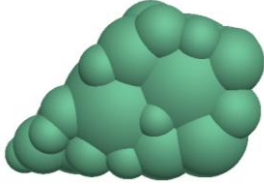
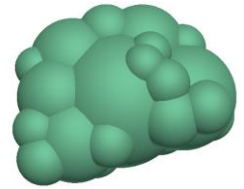
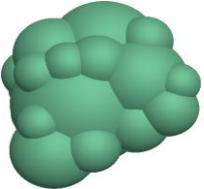
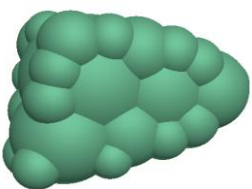
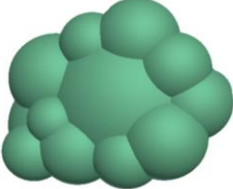
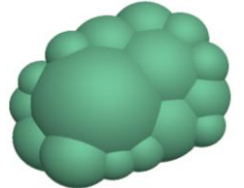
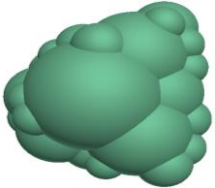
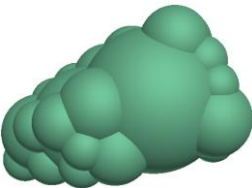
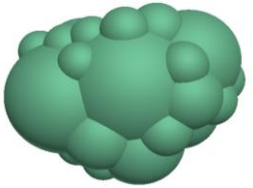
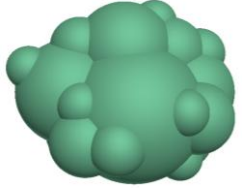
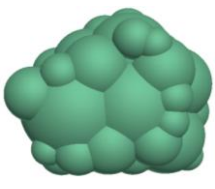
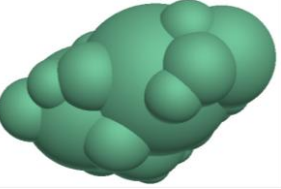
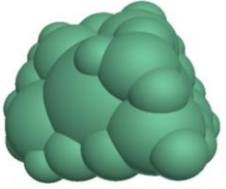
ID	Image of clump	Number of pebbles	ID	Image of clump	Number of pebbles	ID	Image of clump	Number of pebbles	ID	Image of clump	Number of pebbles
1		24	5		32	9		24	13		19
2		23	6		20	10		26	14		39
3		32	7		22	11		40	15		24
4		28	8		29	12		22	16		36

Table A2.1. Sub-pebbles generated for each simulated clump for BOF slag

ID	Image of clump	Number of pebbles	ID	Image of clump	Number of pebbles	ID	Image of clump	Number of pebbles	ID	Image of clump	Number of pebbles
1		23	5		20	9		24	13		33
2		26	6		22	10		30	14		21
3		19	7		24	11		28	15		28
4		21	8		35	12		24	16		29

A3. Sensitivity Analysis

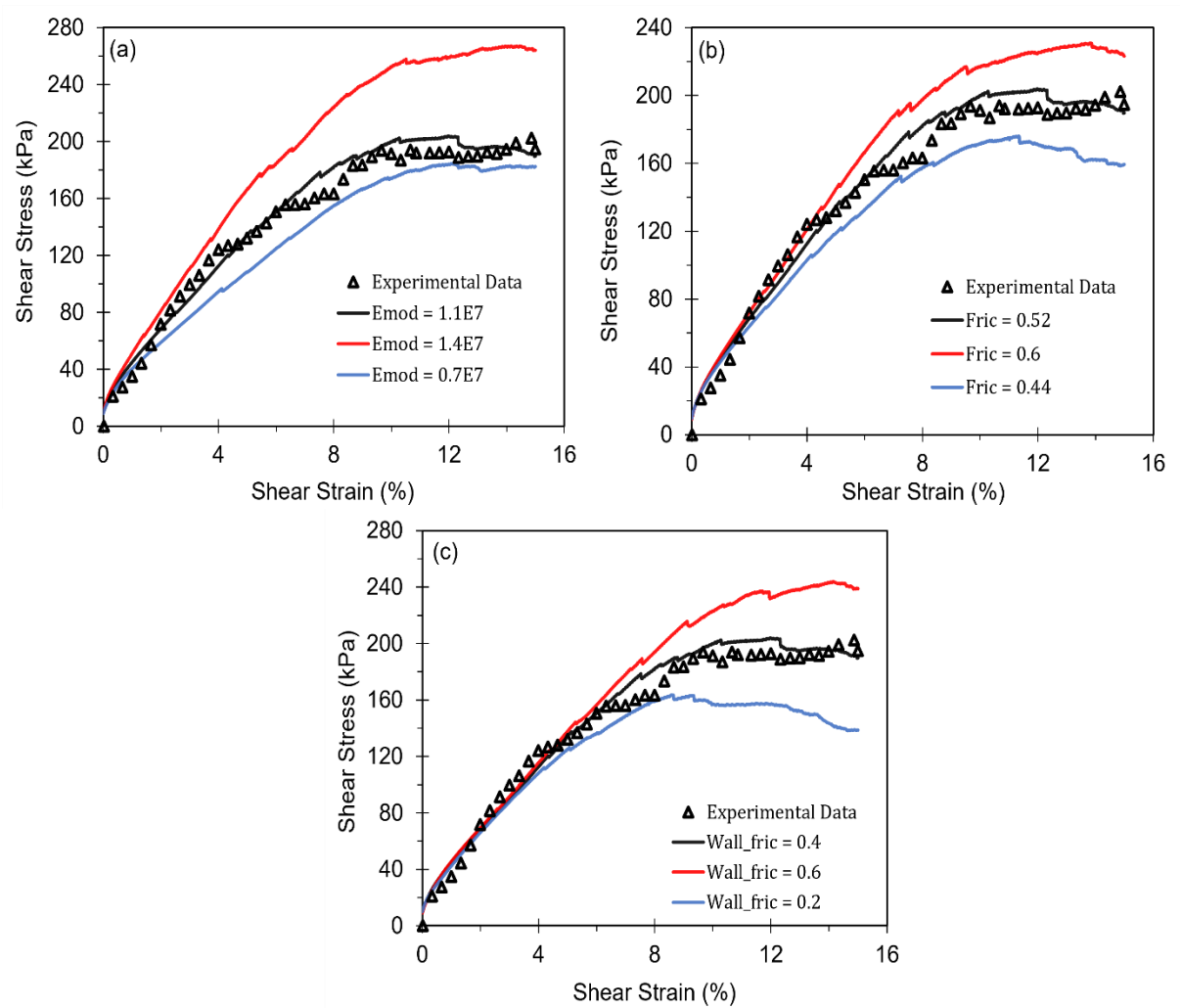


Fig A3.1. Stress-strain sensitivity analysis results for crushed stone: (a) Contact effective modulus; (b) Interparticle friction coefficient of stone; (c) Interparticle friction coefficient of wall.

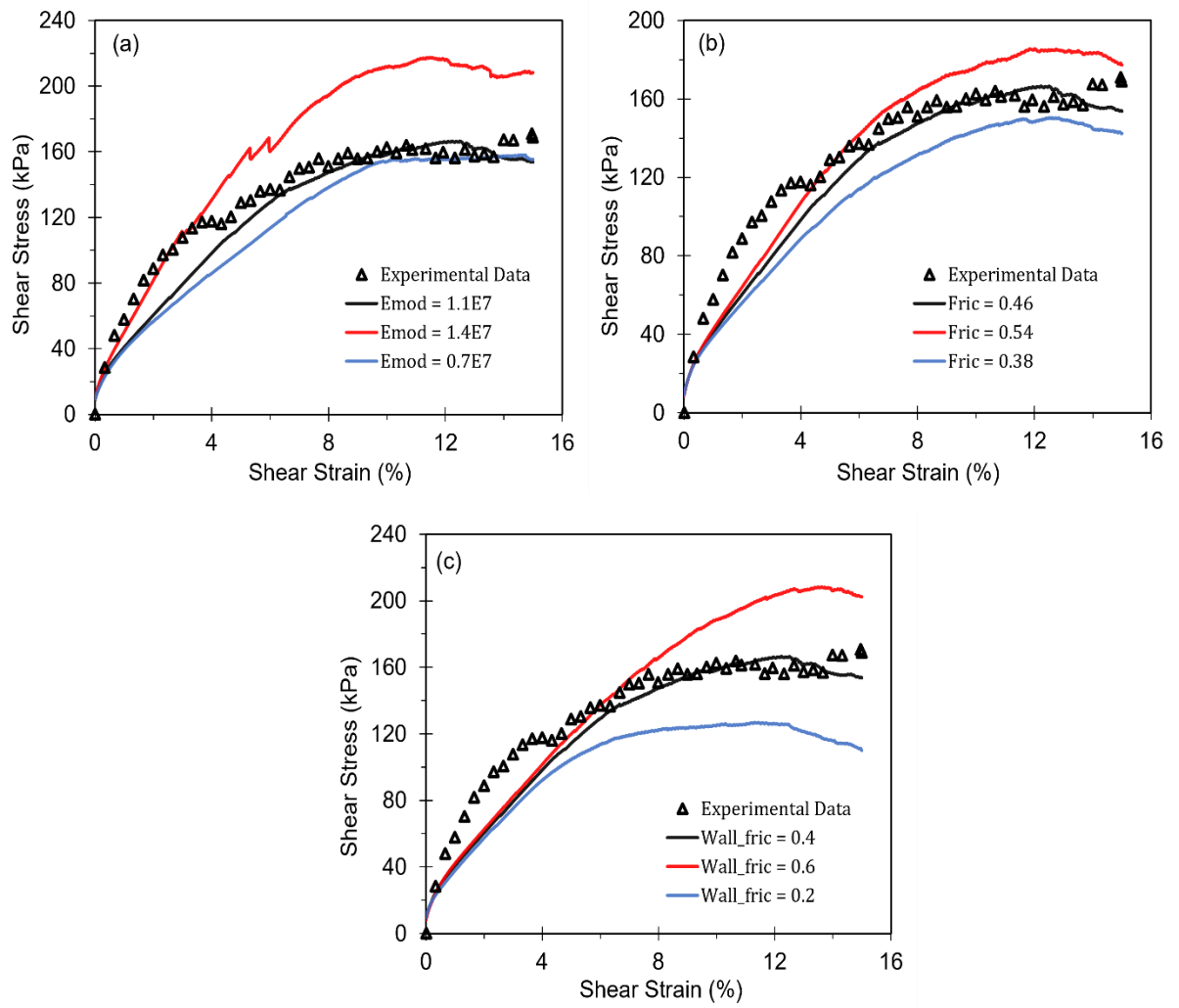


Fig A3.2. Stress-strain sensitivity analysis results for BOF slag: (a) Contact effective modulus; (b) Interparticle friction coefficient; (c) Interparticle friction coefficient of wall.