1.1Background:

Aggregate is obtained from natural rocks. Mining of the aggregate leads to the reduction of natural resources. The countries having limited resources of natural aggregate are thinking of saving their natural resources for future generations. A large area of land is utilized for the disposal of such solid wastes, produced by industries. Factors like environmental, economic, technical, and deficiency of proper construction materials have diverted the attention of researchers to other alternatives [1]. As a result, they have explored a variety of recycled materials that can be used as an aggregate. According to Geiseler (1996), in 350 BC Aristotle indicated that during the purification of iron, a byproduct is generated like a stone called iron slag [2]. It has a number of advantages but is very effective for drying injuries. The byproduct is generated from the melting of a scrape to produce steel by an electric arc furnace (EAF), and through the conversion of iron to steel by a basic oxygen furnace (BOF). The steel slag obtained from these furnaces looks similar but the properties may differ based on the grade of steel produced and the furnace, while the chemical composition remains within the range. As compared to an electric arc furnace, the main problem with a basic oxygen furnace is the excess quantity of its free lime and free magnesia contents. Particular expertise is needed to handle it in a proper way to avoid volumetric expansion otherwise it may result in pavement failure [3]. According to the National Slag Association iron and steel slags have been used in engineering constructions for more than 150 years. It is being used as aggregate in replacement of natural aggregate, for bounding applications (BFS) instead of Portland cement, fill material, railroad ballast, and subgrade soil stabilization. According to John Emery iron slag was used for the construction of roads during the Roman Empire also [4]. In 1998 up to 97% of the total generated steel slag was used in different ways for the construction of high-trafficked roads in Germany. It is utilized as aggregate for the surface layer, road base, and sub-base. It is also utilized in earthworks and hydraulic structures as well [5]. Because of a significant amount of free iron, steel slag becomes hard and dense to provide high abrasion resistance [6]. Currently, the annual production of SS exceeds 100 million tons in China [7-11]. In the next few decades, SS waste will continue to be at a high level, although its utilization rate will remain at much less than 30% (mainly in road construction). Conversely in the U.S., the utilization rate for SS in road construction is over 80% [12-13]. Meanwhile, SS for road engineering, can on one hand realize the resource utilization of SS, reducing the damage to the ecological environment caused by natural sand and gravel mining. On the other hand, road construction costs can also be reduced, and promote the green development of traffic engineering [14–16]. Compared with natural aggregates, SS has the advantages of high density, high strength, and good wear resistance. In roads, the use of larger particlesize Steel Slag, within a certain particle size range, has three advantages. On the one hand, it increases the size of the Steel Slag to be used and speeds up the construction process. On the other hand, it reduces the precipitation of heavy metal elements from the Steel Slag in the base. It increases the size of the aggregate, improves the strength of the mixture, and reduces road deformation. Steel Slag outperforms natural aggregates in terms of mechanical properties, which has attracted the attention of engineering and academic communities. Generally, steel slags consist of CaO, MgO, SiO2, and FeO oxides, which are found within the range of about 88% to 90 %. The total concentration of these oxides in liquid slags is in the range of 88%– 92%. These oxides fluctuate based on the material used, the type of steel being manufactured, and the condition of the furnace [17]. The use of dolomite instead of lime as a flex highly influences the chemical composition which provides a higher content of MgO [18]. Both BOF and EAF slags are dicalcium silicate, dicalcium ferrite, and wustite. Dicalcium silicate provides stability, which prevents the disintegration of steel slag. Several studies show that the dissolved lime and MgO do not affect the volume of steel slag, but the excess amount of "spongy-free lime" and MgO may cause volume instability [2]. Engineering properties influence the level of performance and suitability of the material being used for road construction [19]. Having an affinity with binders is known as "hydrophobic" and the aggregates that do not have such a property are called "hydrophilic." Steel slags are hydrophobic (strong affinity with binder), basic or alkaline in nature having a pH value of around 12. Whereas the bitumen binder is normally acidic, having a natural chemical affinity with steel slags and the pH value of bitumen binder is less than 7. This property of steel slag provides good adhesion and helps to resist stripping. A simple test is conducted by putting the sample into boiling water and the degree of stripping is evaluated [3]. Roads experience both static and dynamic stresses, as well as exposure to adverse environmental conditions such as rain, temperature fluctuations, freezing, and thawing.

The proposed material should possess sufficient physical and mechanical qualities to effectively withstand and function optimally. The physical and mechanical parameters include aggregate crushing value, loss angles abrasion, aggregate impact value, soundness, polished stone value, water absorption, surface texture, stripping, specific gravity, and flakiness. The physical and mechanical characteristics of steel slag effectively satisfy the criteria for a superior-grade material. Compared to natural aggregate, it offers superior durability, permeability, stability, and resistance to abrasion, cracking, and irreversible deformation.

With the development of highway and road construction technology, the laboratory specimens prepared by the traditional static compaction method (SCM) have little correlation with in-field specimens. The reason is that the aggregates cannot move during static compaction, which causes some of the aggregates to be crushed and affects the performance of the specimens [20]. Therefore, SCM is deficient in guiding the design and engineering application of cement-stabilized crushed stone mixtures. Due to the relative displacement between the aggregates during vibratory compaction, the aggregate rearranges more fully to form a stable skeleton structure. Given that the vibration compaction method (VCM) reduces aggregates being crushed. In addition, the correlation between specimens prepared in the laboratory using the VCM with infield specimens reaches up to 90% [21]. With the rapid development of computer hardware and related scientific theories, numerical simulation techniques have also been introduced into the study of cement-stabilized SS bases by some researchers. Using the finite element method. However, the majority of the research primarily concentrates on the technical study of enhancing the performance of pavement by improving the method of paving with steel slag. Insufficient research has been conducted on the technological aspects of producing steel slag aggregate. The size and performance of steel slag are significantly influenced by processing technology. Therefore, it is essential to develop an integrated process for producing steel slag aggregate. This will enhance the properties of the aggregate, ensuring that they meet technical requirements more effectively and are more suitable for road construction.

Figure 1. Steel slag sample

Figure 2. Vibratory drum compactor

1.2 Problem Statement

This research topic originates:

1) To improve the understanding of how Steel slag subgrade materials respond to vibration rolling, a common method for compacting roadbed fillings.
2) To fill existing research gaps and provide valuable insights into the behavior of steel slag subgrade materials under dynamic loading conditions.

1.3 Research Objective:

The finite element software will be used in this research:

1) To comprehensively investigate the response of steel slag subgrade packing under vibration rolling.
2) To analyze the physical and mechanical properties of steel slag,
3) To examine the impact of various vibration parameters on the response characteristics.
4) To optimize key parameters to enhance the bearing capacity and stability of steel slag roadbeds.

1.4 Theoretical Significance:

The theoretical significance of this research lies in its contribution to the understanding of the response behavior of iron slag subgrade materials to vibration rolling. By providing insights into the mechanical and dynamic characteristics of steel slag, this study will enrich the theoretical knowledge in the field of road engineering. It will facilitate the development of improved roadbed construction techniques and parameter optimization for better subgrade performance.

1.5 Practical Application Value:

The practical application value of this research is substantial. It will benefit the road construction industry by:

1) Offering insights into the selection and modification of steel slag particles to enhance their suitability as subgrade materials.
2) Optimizing vibration parameters to improve roadbed packing efficiency and performance.
3) Enhancing the long-term stability and load-bearing capacity of roadbeds, leading to cost savings and reduced maintenance needs.
4) Contributing to sustainable and environmentally friendly construction practices by promoting the use of steel slag, a recycled material.

Ultimately, the research will have a positive impact on the quality and sustainability of road engineering, reducing maintenance costs and ensuring the safety and longevity of transportation infrastructure.

Literature review, domestic and foreign research development trends (with main references and citations).

2.1 Literature review:

The chosen research topic is "Response of Steel Slag Subgrade Packing Under Vibration Rolling," aimed at investigating the response characteristics of steel slag roadbed fillings to vibration rolling. Steel slag, as an environmentally friendly and cost-effective recycled material, finds wide application in road engineering. However, the optimization of the performance of steel slag subgrade fillings under vibration rolling to enhance road carrying capacity and stability is a critical issue in current road engineering. The land transportation system, which includes railway and road transportation, has been extensively used as a convenient and flexible means of transport over several decades. However, the development of highspeed road transportation and the increasing weight of high-speed trains particularly induce strong ground and structural vibrations, especially in densely populated urban areas [22]. The ground vibrations caused by vehicles can impact human life and activity nearby, and even impact the normal operation of some precision instruments. The study of vibration propagation under traffic loads is thus very important to environmental protection. Theoretical and experimental studies have been conducted to investigate the characteristics of ground vibration induced by traffic loading.

With the development of the high-speed railway and road network, design, construction, and maintenance technologies have developed significantly. In China, only the railway lines with operation speeds higher than 250 km/h are named as HSRs [23]. There are very strict requirements for HSRs to ensure safety and serviceability. For a ballast-less track railway, the settlement of the subgrade after construction should be smaller than 15 mm, and the heave of the subgrade should be smaller than the adjustable value of the fastening system—5 mm [23]. To fulfill these requirements, researchers and engineers in China have made a series of developments for the HSR, especially for the subgrade, which is the foundation of track and controlling the behavior of HSR. The developments of technologies include but are not limited to, these five aspects: subgrade fill materials, dynamic behavior of subgrade, ground improvement technologies, retaining structures, and smart construction of subgrade engineering. Firstly, proper subgrade fill materials must be used in HSR based on the static and dynamic mechanical behavior of fill materials. As for the design of the subgrade of HSR, it is based on the dynamic strength, deformation, and strain of the subgrade [23], it is very important to understand the dynamic behavior of fill materials properly, e.g. shakedown performance [24-26], small strain stiffness [27-28], etc. During the operation of HSR and road construction, the subgrade is always under the dynamic loading of trains. As well as knowing the dynamic behavior of fill materials, it is also very important to understand the dynamic responses of the geo-structure, and subgrade, which includes the propagation of vibrations in the field caused by the operation of trains [29-30], the long-term cumulative deformation [30-31]and corresponding problems (mud-pumping, differential settlement) [31-32], and the dynamic stability analysis of subgrade [33-34]. Then, as special soils are widely distributed in China, including soft clays, loess, expansive clays, etc. the HSR will inevitably cross areas containing special soils. However conventional foundation treatment methods used in railways cannot satisfy the strict requirements in both deformation and dynamic stability control of HSR subgrade. In this case, a series of new foundation treatment technologies have been developed, e.g. geosynthetic reinforced pile supported embankment [35-36], pile-raft structure [37-38], pile-plate structure [39-40], etc. The corresponding reinforcement mechanisms, performances, and application scenarios have also been widely studied by researchers and engineers [41-43]. Occasionally along railway lines, the main body of the subgrade is built on the slopes. To ensure the stability of subgrade and slopes, retaining structures must be used. Recently, a series of new types of retaining structures have been developed and used, including a cantilever retaining wall [44-45], geosynthetic reinforced soil retaining walls [46-47], anchored retaining structures [48-49], retaining walls reinforced by soil nailing [50-51], etc. The performance of these new types of retaining structures has been thoroughly studied by many researchers, e.g., load transfer [52-53], dynamic stability [54][49], etc.

The ground vibrations caused by vehicles can impact human life and activity nearby, and even impact the normal operation of some precision instruments. The study of vibration propagation under traffic loads is thus very important to environmental protection.

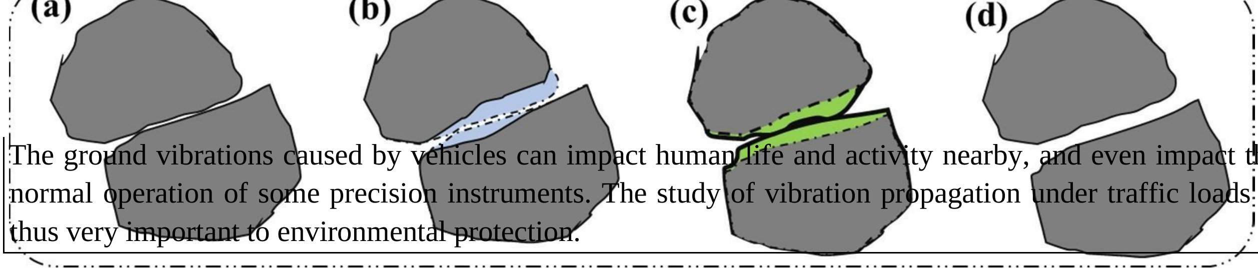

Figure 3. Steel slag "hard-to-hard" effect in compaction.

(a) The particles are initially relatively close to each other.

(b) Deformation takes place under external strong vibration.

(c) an elastic recovery expansion occurs successively.

(d) Eventually, the displacement of the particles results in a macroscopic decrease in density.

2.2 Previous Studies:

Theoretical and experimental studies have been conducted to investigate the characteristics of ground vibration induced by traffic loading. There have been various studies on related fields of vibration rolling and steel slag subgrade both domestically and internationally. Some studies focus on the fundamental principles and techniques of vibration rolling and its application in road engineering. Others concentrate on the physical and mechanical properties of steel slag and the improvement effects of vibration rolling on steel slag roadbeds.

- Siddharthan et al. (1993) used the Fourier series expansion method to solve the dynamic problem of a layered subgrade. The work of Siddharthan et al. (1993) also contributed to the development of an improved subgrade soil model, wherein the soil was simplified as a two-phase medium interacting with water [55].

- Hunt and Boyle (2000) described that in 1994, steel slag test and control sections were constructed in Oregon to evaluate the use of steel slag in hot mix asphalt concrete (HMAC). The research covers the construction and five-year performance of a pavement constructed with 30% steel slag. Asphalt concrete can be produced and the pavement is constructed readily when crushed steel slag is used as a portion of the aggregate. If the unit cost of steel slag-modified mixes is the same as conventional dense-graded mixes, overall project costs may increase because of the decrease in coverage by the heavier steel slag mix. For the test section of HMAC constructed with 30% steel slag, the coverage was 15% less than a conventional 'B' mix. Reported increased resistance to rutting and improved skid resistance were not measured during the five years the pavements have been monitored. The differences between the two sections may not be measurable because only 30% steel slag was used in the test mix and the slag was finer than the conventional ½- to ¼-inch (12.7÷6.3 mm) material it replaced. To date, both the control and test sections are performing satisfactorily [56].

- Huang and Thambiratnam (2001) investigated the dynamic response characteristics of soil, which was regarded as a Winkler elastic medium under a moving load [57]. The dynamic response of the simplified soil under the action of a moving load was solved by Theodorakopoulos (2003) [58].

- Chai and Miura (2002) proposed an empirical method for predicting the permanent traffic-loadinduced deformation of a road on a soft subsoil with a low embankment. Based on an examination of the response frequency and stress amplitude of saturated soft clay under the vibration load of a subway tunnel, Tang et al. (2008) proposed an equation for calculating the fluctuation attenuation of soil under dynamic pressure. Kelly et al. (2008) constructed an embankment on top of a 25m deep soft clay layer using vacuum consolidation, in conjunction with additional surcharge filling. They compared the performance of the vacuum consolidation with that of an adjacent area constructed using surcharge filling [59-61].

- Mooney and Rinehart (2009) evaluated soil stiffness via roller vibration monitoring, they found that roller-measured stiffness decreased with increasing excitation force on vertically homogeneous clayey sand [62].

- Chen and Shen (2010) presented a detailed measurement scheme for analyzing the ground vibration induced by trains passing over bridge structures [63].

- Lopes et al. (2014) investigated the effect of soil stiffness on the assessment of vibrations induced by railway traffic in tunnels [64].

- Deng and Ren (2017) presented a theoretical method based on a single-degree-of-freedom vibration equation for estimating the accumulated plastic deformation of soft clay subjected to cyclic loads [65].

- Autelitano and Giuliani (2016) (Barišić et al. 2016, 2019) demonstrated that cement-stabilized EAF SS can be used effectively in base and sub-base pavement layers. Compared with mixtures containing only natural aggregates, cement-stabilized base mixtures with EAF SS aggregate as a replacement have a higher dynamic modulus of elasticity and improved frost susceptibility [6668].

- Al-Homidy et al. (2017) investigated that dune sands mixed with 20–30% EAF SS fines and stabilized with 2% cement have favorable engineering properties for use as sub-base in rigid and flexible pavements [69].

- (Skaf et al. 2017) (and Santamaria et al. 2018) investigated that the favorable frictional characteristics and volumetric instability is an issue for the fine fractions of EAF Steel Slag Use of fine fractions of EAF SS (natural fines or those obtained through crushing of large particles), increases the surface area and exposure of free lime. This can activate swelling that can be detrimental in fine aggregate and filler applications [70-71].

- Pasetto and Baldo (2018) showed that various mixtures containing foundry sand, bottom ash, and EAF Steel Slag (with EAF Steel Slag contents in the 20–40% range by weight of the mixtures) stabilized with 3% cement have suitable strength characteristics to be used as hydraulicallybound layers in road construction [72].

- (Xiao et al., 2021a). In terms of numerical simulation, the methods used to analyze the dynamic response of subgrade includes the vehicle-track-subgrade coupling dynamic model, dynamic finite (or finite difference) method based on the elastic–plastic theory, and some extended method (for example, infinite element method). However, these methods cannot reflect the influence of granular characteristics of subgrade filler under cyclic loading. To consider this, the discrete element method based on the granular medium mechanic's theory has been gradually used, and some achievement has been made in revealing the meso-vibration behavior of subgrade filler under different speed levels [30].

2.3 Development Trends:

Development trends for steel slag subgrade under a vibration roller involve ongoing advancements in material engineering, construction techniques, and technology applications. Here are some potential trends in this area:

1) Material Modification and Optimization: Ongoing research may focus on modifying and optimizing the properties of steel slag to enhance its suitability for use in subgrades. This could involve treatments or additives that improve compaction characteristics, strength, and long-term stability.
2) Advanced Compaction Methods: Continued exploration of advanced compaction methods using vibration rollers. This includes studying the impact of vibration frequency, compaction energy, and roller design on the effectiveness of the compaction process for steel slag subgrades.
3) Smart Construction Technologies: Integration of smart technologies into construction processes, such as real-time monitoring and control systems. This allows for better management of compaction parameters, quality control, and the overall construction process.
4) Environmental Sustainability: Increasing emphasis on the environmental sustainability of construction materials. The use of steel slag in subgrades aligns with sustainable practices, and future trends may involve further exploring the environmental benefits and life cycle assessments associated with its use.
5) Performance Monitoring and Evaluation: Continued focus on monitoring the long-term performance of steel slag subgrades under different conditions. This involves assessing how these subgrades withstand traffic loads, environmental factors, and potential degradation over time.
6) Standardization and Guidelines: Development and refinement of industry standards and guidelines specific to the use of steel slag in subgrades. Standardization helps ensure consistent and reliable practices in design, construction, and quality control across various projects.
7) Integration with Other Materials: Exploration of how steel slag subgrades can be integrated with other construction materials to create composite systems with enhanced properties. This could involve combining steel slag with geosynthetics or other materials to improve overall performance.
8) Research into Long-Term Durability: In-depth research into the long-term durability of steel slag subgrades, considering factors such as fatigue resistance, resistance to environmental conditions, and potential aging effects. This knowledge can inform better design practices.

9) Education and Training: Increased focus on educating engineers, construction professionals, and stakeholders about the benefits, challenges, and best practices associated with using steel slag in subgrades under vibration rollers.
10) Global Collaboration and Knowledge Sharing: Collaboration among researchers, engineers, and industry experts on a global scale to share insights, research findings, and successful case studies. This collaborative approach can accelerate the adoption of steel slag subgrades in various regions.

Additionally, research using digital and simulation technologies may see further development to accurately simulate and predict the response characteristics of steel slag roadbed fillings.

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The main research contents and key technologies to be solved.

3.1 Main Research Content:

The primary research content of this study includes the following aspects:

- Analysis of Steel Slag Properties: This involves a comprehensive examination of the physical and mechanical properties of steel slag, including particle size distribution, porosity, density, and compressive strength. Understanding these properties is fundamental to assessing the behavior of steel slag subgrade packing under vibration rolling.

- Response Characteristics Under Vibration Rolling: The study will focus on investigating how steel slag subgrade packing responds to different vibration parameters, such as frequency, amplitude, and compaction energy. The research will involve extensive experimentation to analyze the dynamic response of steel slag subgrade materials under various conditions.

- Optimization of Key Parameters: One of the key objectives is to optimize the parameters involved in the vibration rolling process. This includes determining the ideal vibration frequency and amplitude to achieve the best compaction and stability of the steel slag subgrade.

3.2 Key Technical Solutions:

The research will address key technical challenges, and the following are the proposed solutions:

- Optimization of Vibration Parameters: Through systematic experimentation, the study will identify the optimal vibration parameters for steel slag subgrade packing. This includes determining the ideal frequency and amplitude of vibration to achieve effective compaction while minimizing the risk of material damage.

- Selection and Modification of steel Slag Particles: To enhance the suitability of steel slag as a subgrade material, the study will explore the selection and modification of steel slag particles. This involves evaluating different particle sizes and assessing the potential benefits of particle modification to improve packing and stability.

- Development of Performance Prediction Models: Numerical modeling and simulation will be employed to develop models that predict the long-term performance of steel slag subgrade materials under various environmental conditions. These models will assist in making informed decisions regarding road construction and maintenance.

- The combination of theoretical studies, data analysis, and numerical simulations will enable the optimization of key parameters and contribute to the enhancement of steel slag subgrade performance under vibration rolling. These key technical solutions will help address the challenges related to road construction and subgrade stability.

The research methodology, technical route, and implementation scheme to be adopted.

4.1 Proposed Research Methods:

The research will employ a multifaceted approach, combining experimental studies with numerical simulations to comprehensively explore the response characteristics of steel slag subgrade packing under vibration rolling. The specific research methods include:

- Theoretical Studies: Theoretical Studies and Numerical analysis will be used by using computer and PFC software. A series of vibration rolling tests will be performed, considering various combinations of vibration parameters and steel slag particle sizes to collect response data.

- Material Property Analysis: Physical and mechanical property tests will be conducted on the steel slag samples, including particle distribution, porosity, density, and compressive strength. These tests will provide essential information about the material properties of steel slag.

- Numerical Simulations: Numerical simulation techniques, such as finite element analysis, will be employed to model the response behavior of steel slag subgrade fillings under different vibration parameters. This will aid in validating experimental results, predicting long-term performance, and optimizing parameters.

4.2 Technical Route:

The research will follow the following technical roadmap:

- Sample Collection and Preprocessing: Initially, representative steel slag samples will be collected and subjected to preprocessing, including screening and particle distribution analysis.

- Theoretical Studies: Theoretical Studies and Numerical analysis will be used by using computer, PFC software, and Data, including vibration parameters and Theoretical results, will be recorded.

- Data Analysis: Theatrical data will be analyzed to evaluate the impact of different vibration parameters and particle sizes on the steel slag subgrade, identifying key performance factors.

- Numerical Simulations: Finite element numerical simulations will be carried out to validate Theoretical results and perform parameter optimization. This will aid in better understanding the response behavior of steel slag subgrade fillings under vibration rolling.

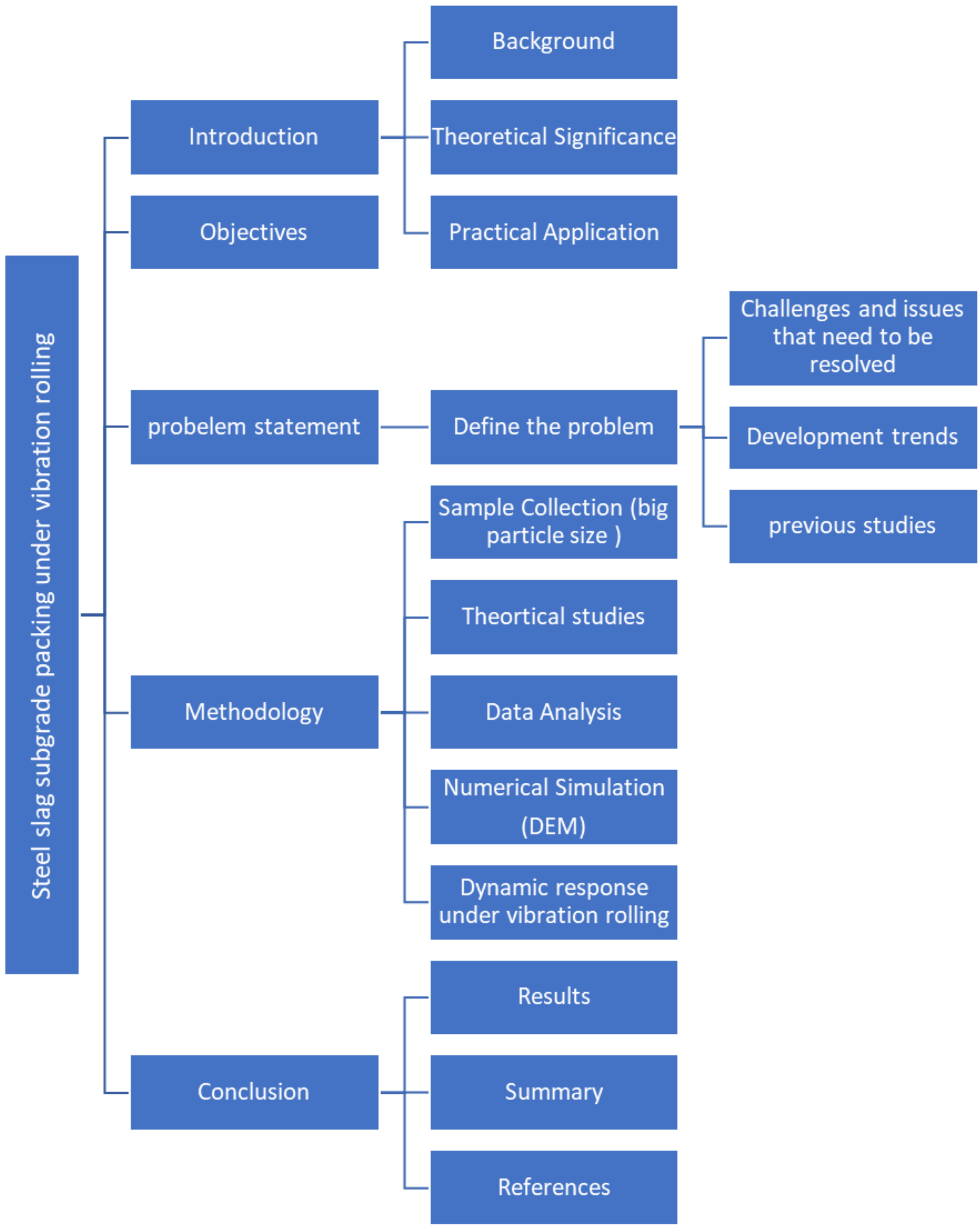

Figure 4. Technical Route

4.3 Implementation Plan:

The implementation plan for the research is as follows:

- Theoretical studies will be used under Selection and Modification of steel Slag Particles (Big particles) evaluating different particle sizes and assessing the potential benefits of particle modification to improve packing and stability.
- Material property analysis, Physical and mechanical property tests will be conducted on the steel slag samples, including particle distribution, porosity, density, and compressive strength. These tests will provide essential information about the material properties of steel slag.
- Numerical simulations will be performed on computers using finite element analysis software and specialized simulation tools.
- This implementation plan will allow for the comprehensive analysis of theoretical results and simulation data to gain in-depth insights into the response behavior of steel slag subgrade fillings. It will also provide guidance for further parameter optimization.