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Sustainable Mix Design of Cement Treated Sub-Base using Industrial Steel Slag for Flexible Pavement Applications

Subrat Kumar Sahoo [1] and Jyoti Prakash Giri[2]

[1]PG Student, Centurion University of Technology and Management, Bhubaneswar, Odisha, India, 752050.
Email: 230303230005@centurionuniv.edu.in
[2]Assistant Professor, Centurion University of Technology and Management, Bhubaneswar, Odisha, India, 752050.
Email: jyotiprakash.giri@cutm.ac.in

ABSTRACT

Cement Treated Steel Slag Sub-Base (CTSB) is a sustainable and innovative material used in flexible pavement construction, created by mixing steel slag—a by-product of steel manufacturing—with cement and water to form a strong, durable, and cost-effective sub-base layer that enhances pavement performance while addressing environmental concerns through the reuse of industrial waste. Steel slag, produced during the conversion of liquid iron into steel, contains metal oxides, silicates, and minerals, and is valued for its high strength, angularity, durability, and low thermal expansion, although it may contain free lime (CaO), magnesia (MgO), and trace elements like chromium, nickel, and lead, which require environmental assessment. This study examines the design and performance of CTSB with varying cement contents, focusing on compaction, strength, moisture resistance, and long-term durability through tests such as Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), resilient modulus, and porosity. The results show that CTSB with minimal cement content outperforms untreated slag in strength and stability, offering superior load-bearing capacity and resistance to moisture-induced distress, allowing for reduced pavement thickness and overall construction cost savings. Ultimately, CTSB presents an eco-friendly and structurally sound alternative to traditional sub-base materials, supporting sustainable infrastructure development when designed and treated appropriately.

Key Words: Steel slag, Industrial byproduct, different material, Coarse combination, Sustainable Infrastructure.

1. Introduction

In the field of pavement construction, the necessity for durable, cost-effective, and environmentally friendly materials is more vital than ever. Traditional materials utilized in flexible pavements, such as natural steel slags, face challenges related to the depletion of natural resources, environmental concerns, and the growing demand for infrastructure. As an alternative, industrial by-product like steel slag have gained attention for their potential as construction materials, particularly in road-based applications.

Steel slag is a by-product of the steel production process, is produced in massive quantities globally and has historically been disposed of in landfills or used for limited applications. Cement-treated steel slag sub base (CTSB) offerings a promising solution that incorporates cement as a stabilizing agent to enhance the properties of steel slag, thereby making it a feasible material for the construction of flexible pavements.

The process of cement treatment improves the mechanical properties of steel slag, enhancing its strength, durability, and overall performance under conditions typically encountered in pavement systems. By treating steel slag with cement, the material undergoes a chemical process that binds the particles together, reinforcing its bearing capacity and resistance to deformation. The use of CTSB in flexible pavements not only offers the potential to replace traditional steel slags but also addresses environmental issues by using steel slag, reducing landfill waste, and conserving natural resources.

Moreover, the incorporation of cement improves the material's stability and its resistance to wet conditions and freeze-thaw cycles—critical factors for the longevity and performance of pavement structures. This innovation has the potential to contribute to the development of more sustainable infrastructure, providing a creative solution to material shortages while minimizing the environmental footprint of construction.

1.1 Objective:

This study aims to outline the role of Cement Treated Steel Slag Base (CTSB) in the perspective of flexible pavements. It will discuss the material used and its Characterization, Physical and Chemical properties of the material and mix design. Also discussed advantages, and challenges associated with its use, as well as explore the potential for integrating CTSB into current pavement design practices.

2.0 Literature Review:

Flexible pavements are increasingly utilized in road construction because of their cost-effectiveness and versatility. An essential component of these pavements is the Cement Treated Sub-Base (CTSB), which acts as a supportive and load-distributing layer. Recent developments in sustainable construction have promoted the incorporation of industrial by-products, such as steel slag, into pavement layers, aiming to enhance mechanical properties while mitigating environmental impacts.

Studies on CTSB with Steel Slag involves: -

Several studies have explored the use of steel slag in pavement layers, particularly CTS , due to its favorable physical and chemical properties:

i) Material Characterization and Mechanical Performance:

- Liu et al. (2020): Steel slag, though underutilized in road bases, shows promise as a partial cement replacement. This study evaluates base mixtures with 30%, 50%, and 70% steel slag, analysing mechanical, durability, and microstructural properties. The 50% slag mix with 4% cement showed optimal strength, stiffness, and shrinkage resistance(Figure-1). Higher slag content improved freeze resistance and reduced dry shrinkage but slightly reduced temperature shrinkage performance. SEM/EDS analysis confirmed better hydration and lower porosity, while molecular simulations indicated stronger cement bonding. Thus, 50% steel slag is a technically and environmentally viable option, provided slag quality is controlled.

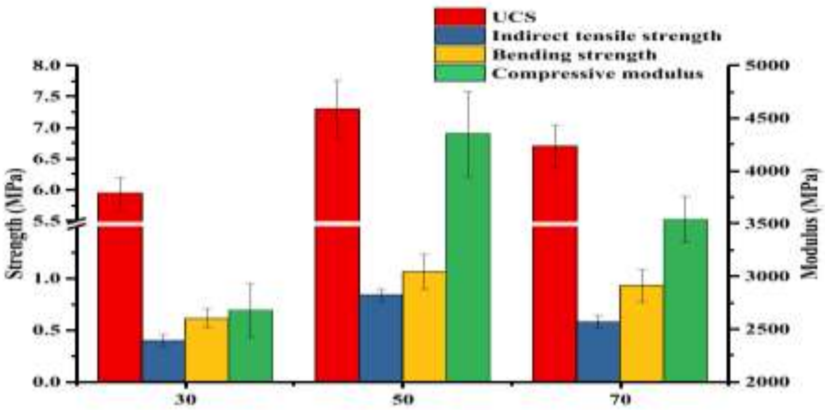


Figure-1 Co-relationship of strength, stiffness and replacement content (Liu et al. (2020):

- Ho and Huynh (2023): Steel slag (SS), a by-product of the steel industry, can fully replace natural coarse aggregates in high-performance concrete (HPC), reducing resource consumption and environmental impact. This study assessed the complete substitution of coarse aggregates with SS and partial replacement of cement with fly ash (FA) and ground granulated blast-furnace slag (GGBFS). The optimal mix—15% FA and 35% GGBFS (S100F15G35)—showed excellent performance: 110.3 MPa compressive strength, 11.1 MPa flexural strength, improved durability (5328 m/s UPV, 113.3 kΩ·cm resistivity, 203 Coulombs chloride penetration), and 15.7% lower drying shrinkage. It also reduced material costs by 24.4% and environmental impacts, cutting global warming potential by 43.5% and ozone depletion potential by 29.2%. These results underscore SS's potential, especially when combined with FA and GGBFS, for producing durable, cost-effective, and eco-friendly HPC.

- Song et al., (2024): This study investigates the mechanical behavior of cement-stabilized steel-slag materials under freeze–thaw and fatigue loading for a highway project in Xinjiang, using 3D scanning to model real slag shapes, revealing a non-linear relationship between macro- and micro-parameters, three stages of compression damage dominated by shear, and significant flexural modulus loss—especially a 50% drop within the first two years under freeze–thaw–fatigue coupling.

- Gao et al., (2023): Steel slag has traditionally been stored in the open air, posing significant safety and environmental concerns, including land occupation and the leaching of heavy metals into surrounding soil. In recent years, however, there has been growing interest in the utilization of steel slag across various industries, leading to a marked expansion in its applications. This paper reviews the current state of steel slag utilization in sectors such as building materials, agriculture, wastewater treatment, marine engineering, ceramics, and CO_2 mineral carbonation and sequestration, both domestically and internationally. It also examines the factors limiting its broader application. In response, the paper introduces the concept of Steel Slag and Slag Composite Micro Powder (SSCM) technology, which enhances both the added value and utilization efficiency of steel slag in industrial contexts. This review aims to provide valuable insights for the selection and development of secondary resources from other metallurgical solid wastes.

- Kalane and Shekokar (2023): In India, large quantities of steel slag from the steel industry are underutilized and cause environmental issues, but this review highlights that steel slag—with its high strength, durability, and heat retention—can effectively replace up to 40% of natural steel slag in concrete, improving strength, reducing costs, and promoting sustainable construction.

ii) Environmental Aspects:

- Hiltunen and Hiltunen (2004) Blast furnace and BOF slags, widely used in construction and soil conditioning due to their physico-chemical properties, have seen near-complete utilization, though ongoing research and environmental regulations continue to raise questions about their classification as waste or product, given both their resource-saving benefits and potential environmental risks.
- Piatak et al., (2015): Slag, a industrial waste from ore processing, varies in mineralogy and geochemistry based on origin—ferrous (steel, blast furnace) or non-ferrous (Cu, Zn, Pb, etc.)—with ferrous slag typically rich in Ca and Si, and non-ferrous slag in Fe and Si, both posing environmental risks due to potential leaching of toxic elements, though ferrous slag is more commonly reused in construction due to its alkaline, less metal-rich leachate, while non-ferrous slag, often acidic, is less favored for reuse but both are studied for secondary metal recovery and environmental impact.

iii) Durability Characteristics:

- Himanshu et al., (2024): In recent years, the use of steel slag in various construction applications has grown significantly; however, its application as a base course material in pavements remains limited. This study investigates the potential of cement-stabilized weathered steel slag (WSS) for use as a cement-treated base (CTB) layer in road pavements. A range of laboratory tests—including unconfined compressive strength (UCS), flexural strength (FS), scanning electron microscopy (SEM), and ultrasonic pulse velocity (UPV)—were conducted on WSS samples with varying proportions of Portland pozzolana cement (PPC). Preliminary results suggest that cement stabilization with a moderate PPC content of 4% meets the performance criteria for CTB layers. At a lower PPC dosage of 2%, visible cracking was observed, whereas higher cement contents yielded stable specimens. Further durability assessments are recommended to fully establish the suitability of WSS as a CTB material in pavement construction.
- Dondi et al., (2021): This study highlights the effective use of construction and demolition materials, particularly steel slag, as a sustainable substitute for natural steel slags in road pavements, improving stiffness and performance across both cementitious and bituminous layers through laboratory evaluations like Marshall stability and ITSM tests.

3.0 Material and Methodology:

3.1 Material Used-

Material considered in this study are- Crushed Steel Slag, Crusher dust, Water and Cement.

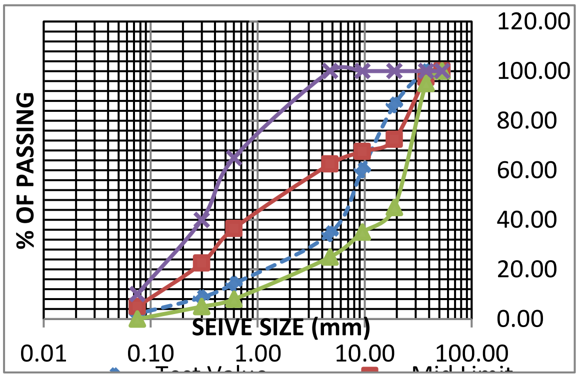
Figure-2 Crushed Slag

Figure-3 Crusher Dust

Figure-4 Cement

3.2 Mix Design Methodology-

- **Sieve Analysis:** The grading of the steel slag conducted as per the table 400-4 of MORT&H specification (5th Revision).



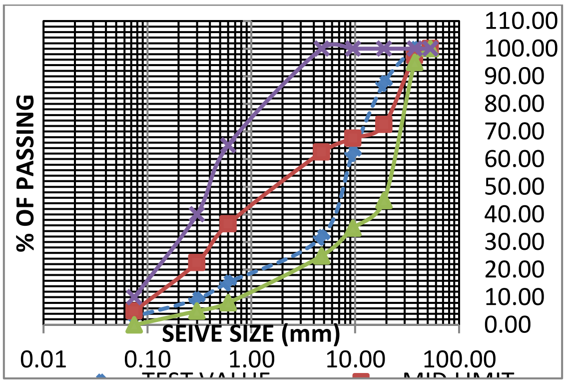


Figure-5 Theoretical Gradation Figure-6 Actual Gradation

- **Standard Proctor Test:** Standard Proctor is a laboratory experiment to determine Optimum Moisture Content(OMC) and Maximum Dry Density(MDD) at which a given mix type will become most dense and become dense and achieve its maximum dry density. Test conducted as per IS:2720(Part-8)-1980.From this test we have got MDD and OMC for the mix. We have taken 5nos trial for the test and the suitable result is given below-

Table-1

Summary of Standard Proctor Test Trials			
Trial No	**Cement Content**	**MDD(gm/cc)**	**OMC(%)**
1	2.00%	2.236	6.62
2	2.25%	2.248	6.74
3	2.50%	2.265	6.86
4	2.75%	2.282	6.96
5	3.00%	2.276	7.14

- **Unconfined Compressive Strength:** This test represents the highest axial compressive stress that a cylindrical sample can resist without any lateral support. It serves as a crucial measure of the mix's strength and its capacity to bear loads in pavement construction. Unconfined Compressive Strength (UCS) of the material to be tested of the samples after curing for 7, 14, and 28 days. But here we have tested after 7days.We have taken 5nos trials with different percentages of cement content and the results are below-

Table-2

Unconfined Compressive Strength Test Results at various Cement Content.		
Sample No	**Cement Percentage**	**Strength Gained in N/mm2**
1	2.00	0.91
2	2.25	1.45
3	2.50	2.14
4	2.75	2.76
5	3.00	2.40

4. Result and Discussion:

After conducting all required tests we have got the actual gradation of CTSB mix as shown in Figure-6. We have got Optimum Moisture Content and Maximum Dry Density are 6.96% and 2.282 gm/cc at trial-4. We have got cement percentage 2.75% and UCS achieved 2.76 MPa.

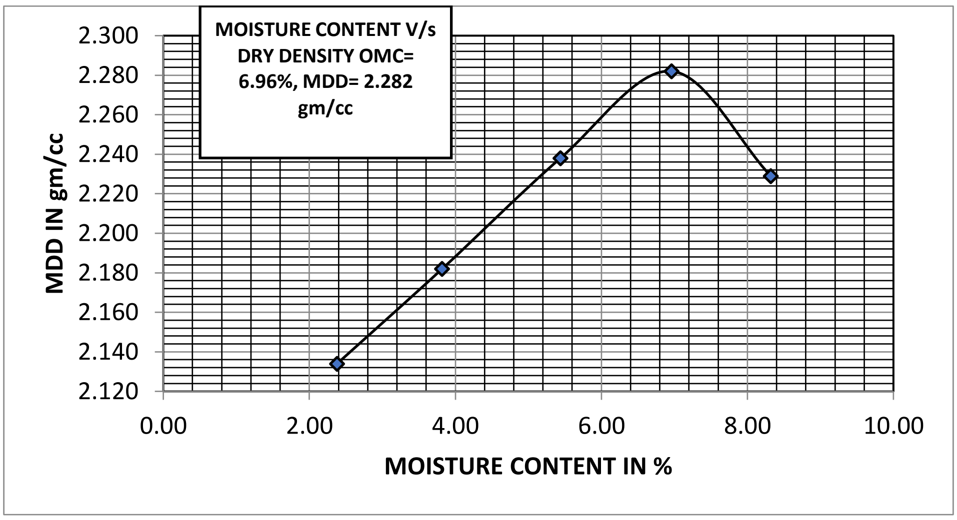


Figure-7 Standard Proctor Test Final

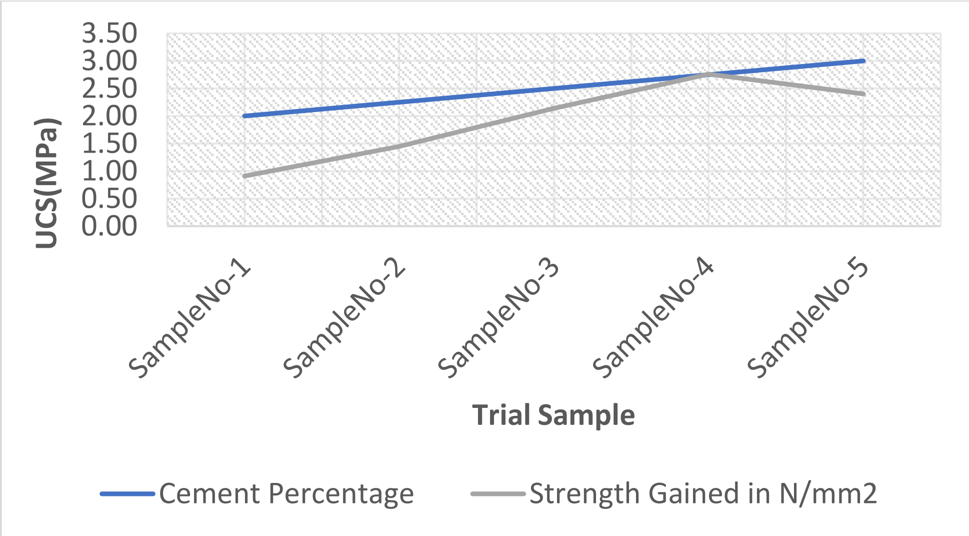


Figure-8 UCS with different cement content

5. Conclusion:

The utilization of steel slag in the design of Cold Mix, Steel Slag, and Bitumen (CTSB) offers significant benefits in terms of improving the mechanical properties of road pavements. This study has shown that steel slag, when incorporated as an steel slag, enhances the strength, durability, and resistance of the CTSB mixture compared to conventional materials. The addition of steel slag contributes to a more robust and sustainable pavement system, as it not only recycles industrial by-products but also reduces the reliance on natural steel slags.

Key findings include in this study are follows:

- **Strength and Durability**: The CTSB mixture incorporating steel slag demonstrated superior compressive strength, abrasion resistance, and overall durability, making it a viable alternative to traditional materials.
- **Environmental Impact**: The use of steel slag significantly reduces the environmental footprint by recycling waste from the steel industry, minimizing the need for mining natural steel slags, and reducing landfill waste.
- **Cost-Effectiveness**: The study highlighted that the incorporation of steel slag could lower material costs due to its availability and reduced need for natural resources.
- **Performance in Pavement Applications**: Steel slag-based CTSB mixtures showed excellent performance in terms of load-bearing capacity, making it suitable for both low and high-traffic areas in road construction.

In conclusion, the design of CTSB using steel slag is a promising solution for sustainable and high-performance road construction, aligning with modern goals for both environmental sustainability and cost-effectiveness in civil engineering.

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