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Eco-Friendly Alternatives to Natural Aggregates in Road Construction: A Case Study Using Slag and Moorum

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Abstract—The increasing scarcity of natural aggregates has become a pressing issue in the road construction industry, primarily due to the high demand for materials and the energy-intensive processes involved in their extraction and processing. This study focuses on sustainable alternatives by examining the use of steel slag, a by-product of the steel manufacturing industry, and locally available hard moorum (gravel) as partial replacements for conventional aggregates in pavement sub-base construction. The research includes a detailed analysis of the chemical composition and phase structure of slag using XRD techniques, as well as an evaluation of toxic and heavy metal content through leachate testing. Physical characteristics such as gradation, specific gravity, and impact resistance are assessed according to MoRTH guidelines. Experimental blending with crushed aggregates helped establish optimal usage rates of up to 80% slag and 50% moorum, both of which met the necessary gradation standards. To enhance the strength of moorum-based mixtures, cement stabilization was also introduced. Tests like Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) demonstrated the mechanical viability of these materials in base and sub-base layers. The study concludes that both slag and moorum are not only technically suitable but also environmentally beneficial for use in road construction, offering a sustainable and cost-effective solution to the growing need for alternative construction materials.

***Index Terms*—Steel Slag, Hard Moorum, XRD Analysis, Leachate Toxicity, Unconfined Compressive Strength, Sustainable Road Construction, Aggregate Replacement, Pavement Materials, Sub-Base Layer.**

1. Introduction

A. General

Road transportation continues to serve as a fundamental catalyst for a nation's economic growth, industrial expansion, and socio-cultural development. In India, which boasts the second-largest road network in the world, various government-led infrastructure programs such as the National Highways Development Programme (NHDP) and Pradhan Mantri Gram Sadak Yojana (PMGSY) have significantly improved connectivity across urban and rural landscapes. These initiatives contribute to the construction of thousands of kilometers of road annually, addressing regional accessibility and mobility needs.

Pavement systems form the structural foundation of roadways and are generally classified into three main types: flexible, rigid, and semi-rigid pavements. Flexible pavements are composed of multiple layers namely; the soil sub-grade, sub-base, base course, and surface course that collectively transmit surface loads downward to the sub-grade. These layers rely on a well-compacted and graded granular structure to effectively distribute stresses, enhance durability, and ensure service performance. The sub-base, in particular, plays a dual role in load transmission and drainage management and is often constructed in two parts: a filter layer to prevent fine soil intrusion, and a drainage layer to remove water through surface cracks.

In contrast, rigid pavements primarily consist of a cement concrete slab underlain by a granular base or sub-base, with structural strength derived mainly from the concrete's flexural capacity. These pavements distribute loads differently, with flexural stress becoming the critical design parameter. Although rigid pavements offer long-term durability, their higher initial costs and less comfortable riding surfaces often make flexible pavements the preferred choice in many developing regions, including India.

Semi-rigid pavements, an intermediate solution, incorporate bonded base or sub-base layers stabilized with binders such as lime, cement, or fly ash, combining the benefits of flexibility and improved load-bearing strength.

B. Problem Statement

The growing demand for natural aggregates in highway construction driven by rapid infrastructure development has led to their excessive extraction, causing environmental degradation, energy consumption, and resource depletion. Simultaneously, industries such as steel and coal are generating large volumes of solid waste, including steel slag, which pose serious disposal and environmental challenges. This dual concern shortage of natural aggregates and underutilization of industrial waste calls for sustainable alternatives. Despite the

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potential of materials like steel slag and hard moorum, their application in road sub-base layers remains limited and underexplored, especially under Indian conditions. This study specifically addresses the need to evaluate and optimize the use of these non-conventional materials in compliance with performance and environmental standards for pavement construction.

C. Locally Available Materials

India's push for sustainable, cost-effective road building has prompted the use of readily available non-conventional aggregates particularly steel-plant slag and hard moorum to supplement or replace scarce natural stone. Steel slag from the Bhilai Steel Plant, a dense, chemically stable by-product rich in Ca-Si-Fe-Al-Mg compounds, offers high load-bearing capacity and, when cement-stabilized, minimizes leaching hazards, easing long-standing disposal and land-use problems. Hard moorum, a locally abundant weathered rock–silt–clay mix with traditionally low bearing capacity and high-water absorption, can likewise be upgraded through cement modification. This study rigorously characterizes the physical, chemical, and mechanical behaviour of both materials and benchmarks their performance against Ministry of Road Transport & Highways (MoRTH) criteria, aiming to demonstrate that such industrial and marginal resources can furnish durable, eco-friendly base and sub-base layers while reducing construction costs and environmental impacts.

D. Objectives

The present work focuses on the utilization of a combination of slag, locally available hard moorum, and conventional crushed aggregates of different nominal sizes for use in the base or sub-base layers of pavement. The objectives of this work are:

- To determine the chemical composition, phase composition, and presence of hazardous materials in slag and its leachate water.
- To evaluate the physical properties of slag and assess its suitability for use in the sub-base layer of pavement.
- To examine the physical characteristics of locally available hard moorum and determine its suitability for use in the base or sub-base layer of pavement.
- To investigate the effects of cement stabilization in base or sub-base layers incorporating natural aggregates and locally available gravel (hard moorum).
- To explore the overall potential of utilizing regionally available materials to enhance the performance of pavement sub-base layers, thereby promoting sustainable road construction practices.

2. Literature Review

A. Characterization of Slag

Basic oxygen furnace (BOF) steel slag is a residue obtained from the basic oxygen converter during steel-making operations. It can be partially used as a construction material for roads. Though it is an attractive construction material, before the application its long-lasting behaviour and the related environmental influences should be considered into account. BOF slag is generally composed of silicon, calcium, iron and some potential toxic elements or known as toxic elements, like chromium and vanadium. [P. Chaurand., et al. (2006)].

B. Physical Properties of Slag and Moorum

Slag as a residual or by-product is often utilized in the construction of cementitious applications to optimize the utilization of natural available aggregate materials and conservation of natural resources. Ferrous slag (blast furnace slag, steel making, manufactory and ferroalloy) are the industrial by-products can be used in pavement construction because of their wide convenience and scope of applications. [J. J. Emery (1982)]. In an European stabilized base layer 60% blast furnace slag (0 to 60 mm), 25% steel slag (0 to 15mm) and 15% granulated blast furnace slag mixture was compacted with 10% water by mass using standard highway equipment that showed excellent results.

Industrial wastes and by-products are also utilized in recycling processes, manufacturing of new products, or as construction materials to minimize their environmental effects. The steel slag aggregate (SSA) was utilized in road construction in Saudi Arabia, which is a by-product of the steel manufacturing process [Saad Ali Aiban (2006)]. Two types of SSA materials were taken: material finer than 5 mm (labelled 0-5 mm) and material having sizes up to 37 mm (labelled 0-37 mm). Several gradations were tried taking mixture of SSA, locally available marl, marl fines, and sand and the gradation corresponding to the maximum CBR (as per ASTM method) was taken. The CBR value of proposed gradation was found to be 119 at moulding moisture content of 5%. In a modified gradation, 10 % SSA fines were added to the proposed gradation gave highest CBR value of 383. Similarly different percentages of dune sand were added to SSA and compacted at 5% moisture content. The highest CBR value of 406 was obtained at a sand percentage of 15 %. Locally available marl (having maximum CBR value of 224) was used to reduce the consumption of SSA, taking a blend of equal proportions of SSA and marl produced CBR values reaching 400.

C. Critical Review

From various research studies, it is clear that steel slag has strong potential for use in road construction. Its physical and strength properties are often better than those of natural aggregates. Chemical and leaching tests have shown that steel slag contains very low or no harmful elements, making it safe for the environment. It can be used effectively in unbound or stabilized sub-base layers, especially when it follows the required specifications and environmental safety standards.

3. Methodology

A. Introduction

Whether using natural aggregates, industrial wastes/by-products, or locally available materials, it is essential that these materials satisfy the desired physical properties and strength parameters for application in the base or sub-base layer of road pavement. Additionally, materials with the potential to affect the environment are subjected to chemical tests and characterization to ensure they are environmentally acceptable. In this work, the chemical composition and characterization of slag were undertaken. The physical properties of slag, natural crushed aggregates, and moorum were determined according to relevant codes, specifications, and literature. The following test methods were carried out in this study:

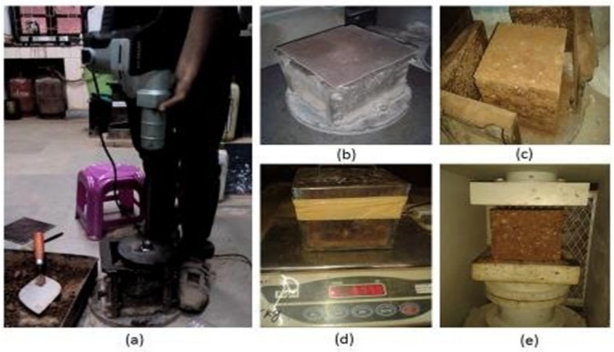

Fig. 1. Sequences involved in preparation and testing of UCS of cube specimens (a) Compaction of materials in a cube mould using a vibratory hammer, (b) cube mould covered with a metal plate (160 mm× 160 mm× 3 mm), (c) removal of specimen from the mould after 24 hours, (d) weight measurement of cube specimen inside a properly sealed curing tin (160 mm x 160 mm x 155 mm), (e) Unconfined compression test of specimen (after 7 days) using a Compression testing machine

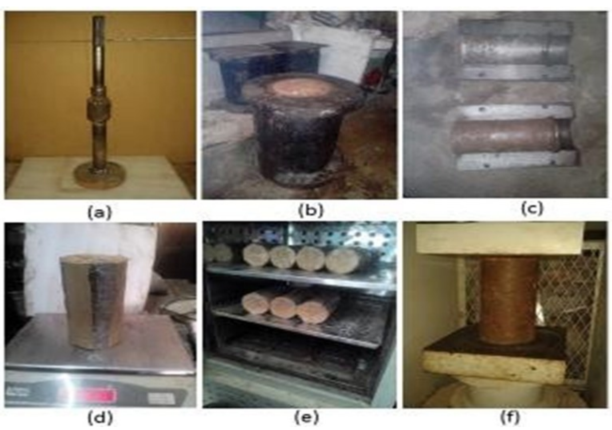

Fig. 2. Sequences involved in preparation and testing of UCS of cylinder specimens (a) Tamper used with vibratory hammer for compaction of cylindrical specimens, (b) Cylindrical mould (101.6 mm diameter and 203.2 mm height) used for compaction, (c) Removal of specimen from the mould after 24 hours, (d) Weighing of specimen after proper sealing, (e) Curing of specimens in the BOD incubator at a constant temperature (23±1.7°C) (f) Unconfined compression test of specimen (after 7 days) using a Compression testing machine

- Chemical composition analysis to determine the elements present in slag and their concentrations.
- Phase composition analysis to identify the mineral phases in the slag.
- Hazardous materials assessment in slag and its leachate water to ensure environmental safety.
- Physical property tests for slag, natural crushed aggregates, and moorum, including:
  - Gradation and particle size distribution
  - Specific gravity and bulk density
  - Moisture content and absorption
  - Compaction characteristics (Proctor test)
  - California Bearing Ratio (CBR) test for strength evaluation
- Cement stabilization effects on the mixture of natural aggregates and moorum to assess improvements in strength and durability.

4. Materials Used

The following materials were utilized for the study:

- *Slag*: Obtained as a waste material from the Rourkela Steel Plant premises.
- *Locally Available Hard Moorum*: Sourced from local regions for potential use in road construction.
- *Crushed Aggregates*: To be blended with slag or moorum to achieve the desired gradation, as per the Ministry of Road Transport and Highways (MoRTH) specifications.
- *Cement*: Used as a binder for cement stabilization to enhance the strength and durability of the mixtures.
- *Chemicals*: Required for performing various chemical analyses to assess the properties and environmental impact of the materials.

These materials were selected to evaluate their effectiveness in road base and sub-base applications, with a focus on achieving desired performance standards and environmental safety.

5. Result and Discussion

A. Characterization of Slag

1) Chemical Composition

The chemical composition of the slag samples was determined by the XRF technique and is presented in table 1.

The basicity (CaO/SiO_2) of the slag samples was found to be 1.

Table 1
Chemical composition of the slag samples determined by XRF technique

Chemical Composition	Percentage
SiO_2	27.33
FeO	20.91
Al_2O_3	6.03
CaO	31.03
MgO	9.24
MnO	4.50
S	0.10
TiO_2	0.66
K_2O	0.14

B. Physical Properties

1) Gradation

The sieve size analysis results for slag, crushed aggregates and moorum samples are presented in table 2 and the graph of sieve size and mean percentage passing is shown in the fig. 3.

Table 2
Sieve size analysis of the slag, crushed aggregates and moorum samples

Sieve Size (in mm)	Mean %age passing					
	SLAG	A40	A20	A10	A6	Moorum
53.00	100.00	100.00	100.00	100.00	100.00	100
26.50	78.19	15.45	99.67	100.00	100.00	92.74
9.50	47.34	0.17	1.78	75.69	100.00	65.88
4.75	34.96	0.16	0.41	2.96	94.05	41.39
2.36	25.90	0.16	0.38	1.55	54.92	25.04
0.43	8.87	0.14	0.34	1.14	31.87	15.10
0.075	1.00	0.06	0.13	0.30	11.85	10.73

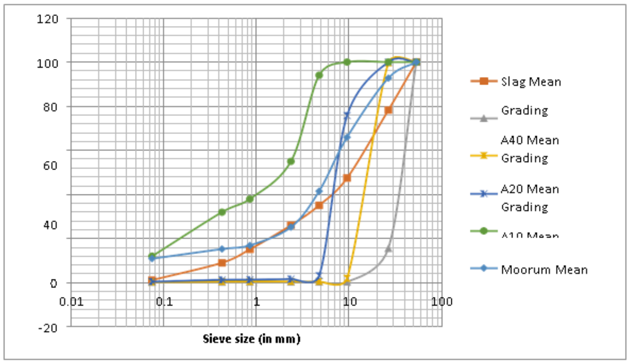

Fig. 3. Graph of sieve size ~ mean % age passing of the slag, crushed aggregates and moorum

2) Blending

a. Blending of Slag and Crushed Aggregates

Blending of slag and crushed aggregates was done to meet the requirements of GSB grading II (to be used in filter layer of GSB) and GSB grading IV (to be used in drainage layer of GSB) as per MoRTH specifications. After so many trials, the final proportions of the aggregates were found and are given in table 3.

Table 3
Blending of the slag and crushed aggregates to meet the desired gradation for GSB Grading II

Grading II Limits			Blending
Sieve Size	%passing (L)	%passing (U)	Slag=76%+A6=24%
53	100	100	100.00
26.5	70	100	83.42
9.5	50	80	59.98
4.75	40	65	49.14
2.36	30	50	32.87
0.425	10	15	14.39
0.075	0	5	3.60

Table 4
Blending of the slag and crushed aggregates to meet the desired gradation for GSB Grading IV

Grading IV Limits			Blending
Sieve Size	%Passing (L)	%Passing (U)	Slag=80%+A40=20%
53	100	100	100.00
26.5	50	80	65.64
4.75	15	35	28.00
0.075	0	5	0.81

The UCS value of the combination of moorum and crushed aggregates was found to be more as compared to that of the combination of crushed aggregates only for particular cement content. The equivalent UCS values of the cylinder specimens were found to be more as compared to those of the cube specimens. The 7 days UCS values for cement bound materials should be between 4.5 to 7 MPa for use in the base and between 1.5 to 3 MPa for use in sub-base (drainage or filter layer) as per IRC SP: 89(2010). So, depending on the required UCS value for construction of a particular layer the corresponding cement content can be taken to satisfy the requirements.

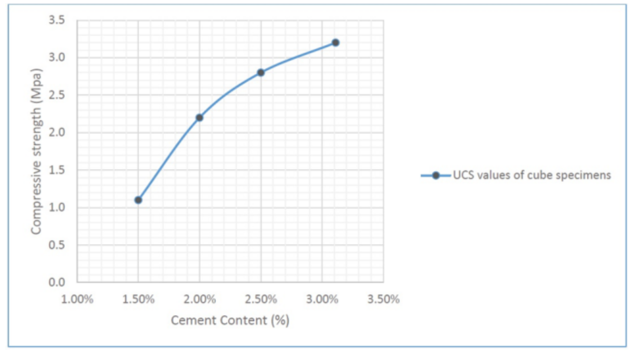

Fig. 4. UCS values of cube specimens for use in the drainage layer of cement treated sub- base [A40=35% +A10=50% +A6 =15%]

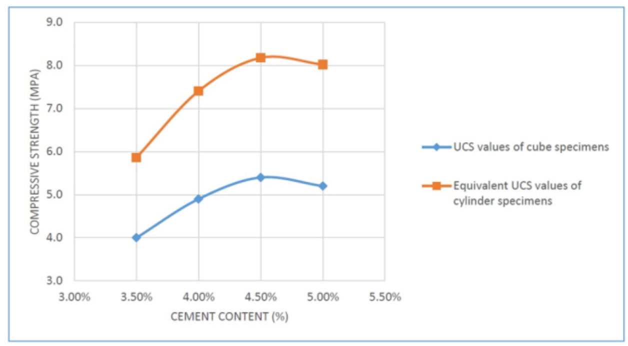

Fig. 5. Comparison of the UCS values of cube specimens with the equivalent UCS values of cylinder specimens for use in the cement treated base [Moorum=50%+ A10=15%+A6=35%]

6. Conclusion and Future Scope

A. General

From the experiments conducted on the slag samples and locally available hard moorum, and from the analysis of results, the conclusions drawn are summarized below.

1) Characterization of Slag

- The slag sample used in this work contains about 30% by weight of CaO, SiO2 and 20% by weight of FeO and some amount of Al2O3 and MgO, confirms the slag as steel slag.
- The phases present in the slag are in carbonate, hydroxide or silicate form rather than oxide form making it suitable for construction purposes.
- The heavy and toxic metals present in the slag and its leachate water are either zero or negligible. Hence, the potential for environmental hazards is very low.

2) Physical Properties

- The slag samples are well graded which require less amount of crushed (conventional) aggregates for blending to meet the desired grading for use in different layers of sub-base. For filter layer a maximum up to 76% slag and for drainage layer a maximum up to 80% slag can be used to satisfy the

Table 5
(B) Physical properties of the combination of the slag and crushed aggregates, a combination of crushed aggregates only, and combination of moorum and crushed aggregates for use in different table title comes here

Property	Granular Sub-base Filter Layer (GSB II)	Granular Sub-base Drainage layer (GSB IV)	Cement Treated Sub-base Drainage Layer (GSB IV) 2% cement	Cement Treated Base (GSB II) 4% Cement	Cement Treated Sub-base Filter Layer (GSB II) 2.5% Cement	Remarks with ref. to
	slag=76% + A6=24%	**slag=80% + A40=20%**	**A40=35% +A10=50% +A6 =15%**	**Moorum=50% + A10=15% +A6=35%**	**Moorum=50% + A10=15% +A6=35%**	**MOTRH /IRC**
Liquid Limit (LL)	24.50	30.00	17.6	21.00	21.00	<45
Plastic Limit (PL)	-	-	-	-	-	-
Plasticity Index (PI)	NP	NP	NP	NP	NP	<20
Combined Flakiness Index	17.59	28.89	73.28	66.94	66.94	-
Impact Value	14.72	14.77	18.84	23.01	23.01	<40
Wet Impact Value	-	-	-	31.45	31.45	<40
Optimum Moisture Content (%)	9.56	9.15	4.92	7.04	6.35	-
Max. Dry Density (g/cc)	2.34	2.43	2.32	2.38	2.35	-
CBR (%)	78.90	215.30	-	-	-	>30

Table 6
Unconfined compressive strength results of cube specimens (7 Days)

Cement treated Sub-base Drainage layer(GSB IV) 2% cement		**Cement treated Base(GSB II) 4% cement**		**Cement treated Sub-base Filter layer (GSB II) 2.5% cement**	
A40=35% +A10=50% +A6 =15%		Moorum=50%+ A10=15% +A6=35%		Moorum=50%+ A10=15% +A6=35%	
OMC=4.92% MDD=2.321 g/cc		OMC=7.04% MDD=2.378 g/cc		OMC=6.35% MDD=2.351 g/cc	
Cementcontent (%)	**UCS value(MPa)**	**Cementcontent (%)**	**UCS value(MPa)**	**Cement content (%)**	**UCS value(MPa)**
1.50%	1.1	3.50%	4.0	2.00%	2.8
2.00%	2.2	4.00%	4.9	2.50%	3.1
2.50%	2.8	4.50%	5.4	3.00%	3.3
3.00%	3.2	5.00%	5.2	3.50%	3.5

Table 7
Unconfined compressive strength results of cylindrical specimens (7 Days)

Cement Treated Base			**Cement Treated Filter layer of Sub-base**		
OMC=7.04% MDD=2.378 g/cc			**OMC=6.35% MDD=2.351 g/cc**		
Cement Content (%)	**UCS Value (MPa)**	**Equivalent Cube Strength (MPa)**	**Cement Content (%)**	**UCS value (MPa)**	**Equivalent Cube Strength (MPa)**
3.50%	4.7	5.9	2.00%	2.7	3.4
4.00%	5.9	7.4	2.50%	3.3	4.2
4.50%	6.5	8.2	3.00%	3.7	4.6
5%	6.4	8.0	3.50%	3.9	4.9

desired grading (GSB grading II and grading IV respectively as per the MoRTH specifications).

- The finer material content in the moorum used for this work is very high. Hence, the amount of moorum that can be used for base and sub-base is limited to 50% in the total aggregate blend.
- The impact values of the slag, crushed aggregates and wet impact value of moorum are within the maximum limits for road base or sub-base applications.
- The specific gravity of the slag aggregates is much higher than that of the crushed aggregates. Hence, the MDD and CBR values of the slag and aggregate blends are very high.
- The specific gravity of moorum is comparatively more than that of the crushed aggregates. Hence, the MDD values are also higher in the moorum aggregate blend.
- Cement is used as a binder for stabilization of moorum because of its high plasticity (PI= 20). The UCS values of the combination of moorum and crushed aggregates specimens satisfy the desired lower limits for use in the cement treated base or sub-base layers.
- The UCS value of cement treated moorum-crushed aggregates blend is more as compared to that of crushed aggregates blend for particular cement content.

B. Conclusion

This study evaluates the potential of steel slag and locally available hard moorum as eco-friendly alternatives to conventional aggregates in road base and sub-base construction. Slag sourced from the Bhilai Steel Plant was found to be well-graded, possessing excellent physical properties that make it suitable for use in both filter and drainage layers, comprising up to 80% of the total aggregate mix. It not only meets the required strength and durability standards but also poses minimal environmental risk. Similarly, hard moorum, with its high fines content and local availability, demonstrated satisfactory engineering properties for dense-graded base or sub-base layers. When stabilized with small quantities of cement, moorum achieved enhanced strength often outperforming conventional aggregates. The combined use of these materials offers a sustainable, cost-effective solution that aligns with environmental objectives and technical performance criteria. Thus, the findings support the practical application of slag and moorum as viable substitutes for natural aggregates in promoting greener and more resource-efficient road construction practices.

C. Future Scope of Work

The present study has successfully demonstrated the viability of using steel slag and locally available hard moorum as sustainable substitutes for conventional aggregates in road base and sub-base layers. However, to further strengthen the applicability and practical implementation of these eco-friendly materials in road construction, additional research is recommended in the following areas:

- Dynamic Load Performance and Resilient Modulus: While the current investigation focused on static strength parameters such as California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), future work should include repeated load triaxial tests to simulate real-life traffic loading. This will help determine the resilient modulus of slag- and moorum-based layers, providing a more accurate understanding of their long-term behavior under dynamic loading conditions.
- Permeability Evaluation: Given the role of drainage in sub-base performance, it is important to assess the permeability characteristics of slag and crushed aggregate mixtures, especially in the drainage layer. Further testing will help verify their effectiveness in moisture management and assess any potential impact on the structural integrity and durability of the pavement.

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