AGRAWAL INFRABUILD PRIVATE LIMITED

RESEARCH REPORT

Sustainable Infrastructure Innovation & Low-Carbon Road Construction in India

Evaluation of Alternative Materials and Technologies, and Laboratory Assessment of Steel Slag Aggregate for Bituminous Pavements

TECHNICAL FEASIBILITY STUDY

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DISCLAIMER

This report is a technical feasibility study prepared for internal decision-making at Agrawal Infrabuild Private Limited. The findings for steel slag aggregate are based solely on laboratory Marshall mix-design testing of material from a single source. No testing has been carried out on a highway, and the findings have not yet been validated through field trials or long-term pavement performance monitoring.

Figures drawn from published literature are cited in the footnotes and listed in the Bibliography.

This report is not a design specification. Any pilot trial or project use of alternative materials remains subject to prior approval by the Engineer/Authority and to compliance with the applicable MoRTH and IRC specifications.

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1. Executive Summary

India's rapid economic growth, urbanization and increasing mobility are driving continued expansion of road infrastructure. India has one of the world's largest road networks, approximately 6.67 million km,[1] and constructed approximately 12,349 km of National Highways during FY 2023-24, equivalent to nearly 34 km per day.[2] This scale of construction creates substantial demand for natural and petroleum derived resources.

Conventional road construction is highly resource and energy intensive. The wider construction sector consumes billions of tonnes of aggregates annually,[3] while India consumed approximately 8.8 million tonnes of bitumen in FY 2023–24,[4] with around 98% used for road construction and around 50% of the requirement met through imports.[5] A typical Indian urban-road assessment has reported consumption of approximately 35,940 tonnes of aggregate per kilometre, demonstrating the significant material intensity of pavement construction.

Such resource consumption results in environmental impacts from quarrying, material processing, transportation, asphalt heating and diesel-powered construction equipment. Indian life-cycle studies have reported road infrastructure emissions of approximately 281 t CO_2-eq per km for an assessed highway,[6] highlighting the importance of reducing embodied carbon in pavement materials and construction.

These challenges create a strong need for recycled, industrial byproduct, waste derived and low carbon materials and technologies, including reclaimed asphalt pavement (RAP), fly ash, steel slag, waste plastic, crumb rubber, recycled aggregates, bio-based binders and warm/cold-mix technologies. Their adoption can reduce virgin-resource extraction, waste disposal, petroleum dependence, energy consumption and life-cycle carbon emissions.

However, technical performance alone does not ensure adoption. Cost, material availability, supply-chain reliability, regulatory acceptance, quality consistency, construction requirements and risk allocation must also be considered. This study therefore evaluates alternative road-construction

[1] Ministry of Road Transport and Highways. (2024, January 5). *Year end review 2023: Ministry of Road Transport and Highways* [Press release]. Press Information Bureau. https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1993425

[2] Press Trust of India. (2024, April 9). Morth builds over 12,000 km of highways in FY24, 2nd highest so far. *Business Standard*. https://www.business-standard.com/india-news/morth-builds-over-12-000-km-of-highways-in-fy24-2nd-highest-so-far-124040900849_1.html

[3] Nikam, S. (2021, July). Overview of Indian aggregate industry. *Indian Cement Review*. https://indiancementreview.com/2021/07/overview-of-indian-aggregate-industry/

[4] Argus Media. (2024, August 13). *India's bitumen demand to rise by 14pc in FY2024-25*. https://www.argusmedia.com/en/news-and-insights/latest-market-news/2597370-india-s-bitumen-demand-to-rise-by-14pc-in-fy2024-25

[5] CW Team. (2024, August 8). Govt approves 35% bio-bitumen mixing to save Rs 100 billion in forex. *Construction World*. https://www.constructionworld.in/policy-updates-and-economic-news/govt-approves-35-bio-bitumen-mixing-to-save-rs-100-billion-in-forex/60461

[6] Chaudhary, R., & Akhtar, N. (2024). A novel approach for environmental impact assessment of road construction projects in India. *Environmental Impact Assessment Review, 106*, Article 107477. https://www.sciencedirect.com/science/article/pii/S0195925524000647

technologies through a technical, environmental, economic and implementation readiness perspective, with the objective of identifying solutions that can provide practical and scalable sustainability benefits for India’s rapidly expanding road infrastructure.

2. Research Framework and Objectives

2.1 Strategic Context: Why Alternative Materials Matter

India's rapid infrastructure development is creating an unprecedented demand for road construction. The country has a road network of approximately 6.67 million km[7] and constructed approximately 12,349 km of National Highways in FY 2023–24, equivalent to nearly 34 km per day.[8] This scale of development requires enormous quantities of aggregates, bitumen, energy and other construction resources.

At the same time, conventional road construction places increasing pressure on natural resources and the environment. India consumes billions of tonnes of aggregates annually across the construction sector,[9] while approximately 8.8 million tonnes of bitumen were consumed in FY 2023–24,[10] around 98% of which was used for road construction. Similarly, around 50% of the country's bitumen requirement was met through imports,[11] highlighting both resource dependence and price vulnerability. Quarrying, material processing, transportation and energy-intensive pavement production further contribute to the environmental footprint of road infrastructure.

India simultaneously generates large quantities of industrial by-products and waste materials that have potential engineering value. Materials such as steel slag, fly ash, reclaimed asphalt pavement, waste plastic, waste-tyre rubber and other industrial/agricultural residues can potentially substitute a portion of conventional pavement materials. Their beneficial utilisation can reduce virgin-resource extraction, waste disposal requirements and embodied carbon while creating value from materials that would otherwise be treated as waste. This creates a strategic opportunity for the road sector, converting waste and industrial by-products into useful pavement resources while maintaining required engineering performance.

However, environmental benefit alone is insufficient for large-scale implementation. Alternative materials must demonstrate acceptable technical performance, economic competitiveness, regulatory compliance, material availability, supply-chain reliability and constructability.

[7] Ministry of Road Transport and Highways. (2024, January 5). *Year end review 2023: Ministry of Road Transport and Highways* [Press release]. Press Information Bureau. https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1993425

[8] Press Trust of India. (2024, April 9). Morth builds over 12,000 km of highways in FY24, 2nd highest so far. *Business Standard*. https://www.business-standard.com/india-news/morth-builds-over-12-000-km-of-highways-in-fy24-2nd-highest-so-far-124040900849_1.html

[9] Nikam, S. (2021, July). Overview of Indian aggregate industry. *Indian Cement Review*. https://indiancementreview.com/2021/07/overview-of-indian-aggregate-industry/

[10] Argus Media. (2024, August 13). *India's bitumen demand to rise by 14pc in FY2024-25*. https://www.argusmedia.com/en/news-and-insights/latest-market-news/2597370-india-s-bitumen-demand-to-rise-by-14pc-in-fy2024-25

[11] CW Team. (2024, August 8). Govt approves 35% bio-bitumen mixing to save Rs 100 billion in forex. *Construction World*. https://www.constructionworld.in/policy-updates-and-economic-news/govt-approves-35-bio-bitumen-mixing-to-save-rs-100-billion-in-forex/60461

2.2 Research Objectives

Objective 1: Evaluate Emerging Sustainable Road-Construction Technologies

Selected sustainable technologies will be evaluated using a common framework covering technical feasibility, cost and lifecycle economics, environmental benefits, supply-chain availability, regulatory compliance, operational requirements, implementation risks and scalability. The objective is to identify the most suitable technologies for adoption in AIPL projects.

Objective 2: Identify Barriers to Adoption

The study will examine the key factors limiting the adoption of sustainable technologies, including cost, regulations, procurement practices, supply-chain constraints, lack of performance data, contractor risks and organizational capabilities. Semi-structured discussions with AIPL personnel from engineering, procurement, finance, site management and senior management will be used to understand these barriers in practice.

Objective 3: Assess Laboratory Reliability and Prepare a Pilot Proposal

Based on the evaluation, one suitable sustainable intervention will be selected for laboratory assessment, using materials and specifications relevant to an active AIPL project, to check its reliability for road construction. The study will assess technical and environmental benefits, develop the business case, identify the approvals required from the Engineer/Authority, and prepare a proposal for a pilot trial and monitoring plan for potential wider adoption.

3. Technologies Under Investigation

3.1 Technology A: Steel Slag as Alternative Aggregate

3.1.1 Background

Steel slag is an industrial by-product generated during steel manufacturing.[12] Due to its high strength, angular particle shape and relatively high specific gravity, processed steel slag can be considered as an alternative to virgin natural aggregate in flexible pavement construction. India produced 144.30 million tonnes of crude steel in FY 2023–24 and 152.18 million tonnes in FY 2024–25,[13] generating approximately 19 million tonnes per year of slag.[14] However, less than 30% of the annual production is currently reused. The remaining material creates disposal and environmental-management challenges. Proper processing and ageing are required to control the expansion potential associated with free lime.

As steel slag is chemically rich and structurally angular, its strength surpasses that of natural aggregate but requires stabilization treatment (air aging, water aging) to manage free-lime expansion. Steel slag can replace 20-50% of virgin coarse aggregate in:

- Flexible pavement base and sub-base layers
- Wearing course (bituminous concrete)

When processed and aged appropriately, it meets or exceeds Indian Road Congress (IRC) and MoRTH specifications.

3.1.2 Technical Analysis and Peer Review

> **Source:** The International Journal of Pavement Engineering and Asphalt Technology (PEAT); Guideline for Processing and Utilization of Steel Slag as Processed Steel Slag Aggregates in Road Construction (CSIR-CRRI)
> **Authors:** Dr. Satish Pandey and Dr. P.K. Jain, Chief Scientist, CSIR-Central Road Research Institute, Mathura Road, New Delhi 110025, India

Steel slag has demonstrated good technical suitability as a replacement for natural aggregates in flexible pavement layers, particularly in bituminous mixtures. Its high angularity, hardness and specific gravity can improve aggregate interlocking, stiffness and resistance to permanent deformation.

Laboratory studies have reported improvements in Marshall stability, resilient modulus and rutting resistance when appropriately processed steel slag is incorporated into bituminous mixtures. The reported results include approximately 6% improvement in Marshall stability, 26–33% improvement in resilient modulus and about 23.8% reduction in rut depth in the investigated mixtures.

[12]Council of Scientific & Industrial Research. (n.d.). *Steel slag road: A sustainable valorization of steel slag as road making aggregates*. Retrieved October 6, 2026, from https://www.csir.res.in/en/csir-success-stories/steel-slag-road-sustainable-valorization-steel-slag-road-making-aggregates

[13]Ministry of Steel. (2025). *An overview of steel sector* (July 2025). Government of India. https://steel.gov.in/sites/default/files/2025-08/An%20Overview%20of%20Steel%20Sector%20July%202025.pdf

[14]Ministry of Steel. (2023, July 19). *Steel slag road technology fulfilling the Prime Minister's 'Waste to Wealth' mission: Sh. Faggan Singh Kulaste* [Press release]. Press Information Bureau. https://pib.gov.in/PressReleasePage.aspx?PRID=1940792

The technology is technically feasible provided the slag undergoes suitable ageing, crushing, grading and quality-control testing, particularly to control expansion associated with free lime. Overall, the available evidence indicates that steel slag can technically perform as a high-quality alternative aggregate when its source-specific properties are properly controlled.

3.1.3 Key Advantages

- **Reduction in Virgin Aggregate Consumption:** Replaces a portion of naturally quarried aggregate and reduces dependence on mining.
- **Improved Mechanical Performance:** Higher stiffness, stability and rutting resistance have been reported in laboratory investigations.
- **Potential Reduction in Bitumen Demand:** Reports suggest approximately 12.6% lower bitumen requirement for a slag mixture.
- **Moisture Resistance:** The reported TSR improvement indicates favourable moisture performance.
- **Waste Utilisation:** Converts an industrial by-product into a useful construction material and reduces disposal requirements.
- **Supply Availability:** Major steel-producing regions provide a potentially reliable source of material for nearby highway projects.

3.1.4 Key Challenges and Limitations

- **Material Variability:** Chemical and physical properties can vary depending on furnace type, cooling process and ageing.
- **Expansion Risk:** Free lime (CaO) can hydrate and cause volumetric expansion. Appropriate ageing and soundness testing are therefore important.
- **Processing Requirements:** Crushing, grading, ageing and quality-control facilities are required before pavement use.
- **Transportation Economics:** The economic advantage may reduce when the source is located far from the project.
- **Quality Control:** Each source should be properly characterised and tested before incorporation into pavement layers.

3.1.5 Critical Findings

- Marshall stability increased by approximately 6% in the reported study.
- Reports suggest 12.6% reduction in bitumen demand.
- Resilient modulus increased by approximately 26–33%.
- Rut depth reduced by approximately 23.8% at 10,000 loading cycles.

- Elastic recovery increased substantially compared with the virgin aggregate mixture.
- Moisture resistance showed improvement, with TSR increasing by approximately 3.4%.
- The 12.5 mm slag fraction showed particularly favourable performance in one investigation.

3.1.6 Overall Technical Conclusion

Steel slag demonstrates a strong technical case for use as an alternative aggregate in flexible pavement construction, provided that appropriate processing, ageing, grading and quality-control measures are implemented. The available laboratory evidence indicates potential improvements in stiffness, rutting resistance, stability and moisture performance while simultaneously reducing consumption of virgin aggregate.

The technology therefore provides a practical pathway for converting an industrial by-product into a pavement resource.

3.2 Technology B: Sugarcane Molasses as Bio-Based Bitumen Modifier

3.2.1 Background

India is the world's second-largest producer of sugarcane and generates a substantial quantity of molasses as a by-product of the sugar industry. India's molasses production has been estimated at approximately 15–17 million tonnes annually in recent sugar seasons (15.48 million tonnes in 2023–24),[15] although production varies with sugarcane availability, sugar recovery and diversion of sugarcane-derived feedstocks for ethanol production.

Sugarcane molasses is a viscous, dark-brown syrup remaining after the crystallization of sugar. Its composition varies considerably depending on the type of molasses and the sugar recovery process. Typically, it contains a high concentration of soluble sugars and approximately 70–85% total solids, with moisture commonly in the range of about 15–25%. Final or C-heavy molasses generally contains around 40–50% total reducing sugars, although the exact composition depends on processing conditions.[16]

In India, molasses is predominantly utilized as a feedstock for alcohol and ethanol production, while other applications include animal feed, fermentation products and chemical industries. Ethanol produced from sugar-industry feedstocks is also used for blending with petrol under India's ethanol-blending programme. Consequently, there is growing interest in exploring additional value-added applications of molasses and its constituents, including potential applications in road-construction materials.

[15] Indian Sugar Mills Association. (n.d.). *Statewise molasses production in India* [Data set]. ChiniMandi. Retrieved October 6, 2026, from https://www.chinimandi.com/statistics/statewise-molasses-production-in-india/

[16] Curtin, L. V. (n.d.). *Molasses: General considerations*. University of Florida, Institute of Food and Agricultural Sciences. https://rcrec-ona.ifas.ufl.edu/media/rcrec-onaifasufledu/pdf/Molasses---General-Considerations.pdf

3.2.2 Technical Analysis and Peer Review

Source: Construction and Building Materials, Vol. 369, 2023, Article 130541
Title: Use of raw sugarcane molasses as a partial replacement of asphalt binder: An experimental investigation
Authors: Saboo N., Sukhija M., Mehta D., Haswanth K., Srivastava A., Patil A.
Institutions: IIT Roorkee and affiliated institutions

This scientific study investigates the feasibility of using raw sugarcane molasses (SM) as a partial replacement for conventional petroleum derived asphalt binder in flexible pavement construction. The researchers evaluated molasses bitumen blends at different replacement levels and conducted comprehensive binder and mixture-level testing.[17]

The study identified 25% sugarcane molasses replacement by weight of bitumen as the optimum dosage for the materials investigated. At this dosage, the modified binder and asphalt mixtures demonstrated satisfactory performance with respect to fatigue, permanent deformation, stiffness and moisture resistance. The authors concluded that 25% SM could successfully replace a portion of conventional bitumen without significant deterioration in the principal engineering properties investigated.

The study also estimated a binder cost reduction of approximately 21% at the optimum replacement level.[18] However, this economic benefit should be considered as a laboratory study estimate and should not be directly interpreted as a 21% reduction in total pavement project cost.

3.2.3 Key Advantages

- **Bio-Based Material:** Molasses is derived from renewable agricultural production and can partially displace petroleum-derived binder.
- **Reduced Petroleum Dependence:** Partial replacement can reduce the quantity of conventional asphalt binder required.
- **Binder Cost Potential:** The study reported approximately 21% binder-cost reduction at 25% replacement.
- **Fatigue Performance:** The 25% SM binder showed favourable fatigue characteristics and greater strain tolerance in LAS testing.
- **Comparable Permanent-Deformation Performance:** Laboratory results indicated favourable permanent-deformation behaviour compared with the conventional mixture.
- **Agro-Industrial Resource Utilisation:** Provides a potential additional value-added application for sugar-industry molasses.

[17]Saboo, N., Sukhija, M., Mehta, D., Haswanth, K., Srivastava, A., & Patil, A. (2023). Use of raw sugarcane molasses as a partial replacement of asphalt binder: An experimental investigation. *Construction and Building Materials, 369*, Article 130541. https://doi.org/10.1016/j.conbuildmat.2023.130541

[18]Saboo, N., Sukhija, M., Mehta, D., Haswanth, K., Srivastava, A., & Patil, A. (2023). Use of raw sugarcane molasses as a partial replacement of asphalt binder: An experimental investigation. *Construction and Building Materials, 369*, Article 130541. https://doi.org/10.1016/j.conbuildmat.2023.130541

3.2.4 Key Challenges and Limitations

- **Moisture and Foaming:** Moisture present in molasses can create foaming and mixing challenges.
- **Dispersibility:** Higher replacement levels can result in poor homogeneity and compatibility. The 30% mixture showed significant heterogeneity and foaming.
- **Material Variability:** Molasses composition varies according to source and processing conditions.
- **Long-Term Moisture Performance:** The study recommends further investigation of prolonged moisture exposure and possible anti-stripping treatments.
- **Field Validation:** The evidence is primarily laboratory-based and requires field trials and long-term performance monitoring.
- **Regulatory/Specification Development:** Wider highway implementation requires appropriate field validation, quality-control procedures and applicable approval/specification frameworks.

3.2.5 Overall Technical Conclusion

The study provides strong laboratory evidence that raw sugarcane molasses can be used as a partial bio-based replacement for VG30 asphalt binder. For the materials and experimental conditions investigated, 25% replacement by weight of bitumen was identified as the optimum dosage. At this level, the modified binder and asphalt mixtures demonstrated satisfactory performance in terms of fatigue, permanent deformation, stiffness and moisture resistance, without statistically significant deterioration of the major engineering properties evaluated.

The technology also offers a potentially significant economic benefit, with the study estimating approximately 21% reduction in binder cost.[19]

However, the technology should currently be regarded as an emerging laboratory-validated technology rather than a fully established replacement for conventional bitumen in all highway applications.

Sugarcane molasses should therefore be positioned as a promising emerging bio-based asphalt-binder modification technology with demonstrated laboratory feasibility, rather than as a directly deployable replacement for conventional bitumen.

[19]Saboo, N., Sukhija, M., Mehta, D., Haswanth, K., Srivastava, A., & Patil, A. (2023). Use of raw sugarcane molasses as a partial replacement of asphalt binder: An experimental investigation. *Construction and Building Materials*, *369*, Article 130541. https://doi.org/10.1016/j.conbuildmat.2023.130541

The 25% replacement level represents the principal finding of the cited study and provides a strong basis for further pilot-scale and field investigation, particularly for suitable pavement applications where material sourcing, construction control and performance monitoring can be carefully managed.

3.3 Technology C: Solar-Powered Construction-Site Infrastructure

3.3.1 Background

Highway construction sites require energy for site offices, labour camps, lighting, CCTV systems, and other auxiliary facilities. Conventional temporary energy systems can rely significantly on diesel generators and grid electricity. Solar photovoltaic (PV) systems, potentially combined with battery storage, can provide an alternative source of electricity for these site facilities.

3.3.2 Technical Assessment

Solar powered construction site infrastructure is a technically mature renewable energy technology that can be applied to temporary site facilities such as offices, labour camps, lighting, CCTV systems and equipment/battery charging.

A photovoltaic system combined with battery storage can supply a significant proportion of the electrical demand of construction-site facilities and reduce dependence on diesel generators and grid electricity. The technology does not require modification of pavement materials, pavement design or conventional highway construction methodology.

From a technical perspective, implementation is relatively straightforward because PV generation, battery storage, power-conditioning equipment and associated control systems are commercially established. The principal technical considerations are system sizing, solar-resource availability, battery capacity, load management, maintenance and provision of backup power during periods of low solar generation.

Overall, solar-powered site infrastructure is a technically mature and readily scalable sustainability measure, with implementation constraints being primarily related to capital cost, project duration, energy demand profile and battery/storage requirements rather than fundamental technical feasibility.

3.3.3 Key Advantages

- **Reduction in Diesel Consumption:** Solar generation can reduce the requirement for diesel-powered generators.
- **Lower Operating Cost:** Reduced diesel and grid-electricity consumption can provide operating-cost savings.

- **Emission Reduction:** Replacing diesel-based electricity generation with renewable electricity can reduce site-level emissions.
- **Energy Independence:** Solar and battery systems can reduce dependence on grid availability and diesel supply.
- **Scalability:** Solar infrastructure can potentially be redeployed across multiple projects.
- **Mature Technology:** Solar PV and battery systems are commercially established technologies.

3.3.4 Key Challenges and Limitations

- **High Initial Capital Cost:** PV systems and battery storage require significant upfront investment.
- **Payback Period:** Estimates display a typical 3–5 year payback, which can be longer than the duration of some highway projects.
- **Battery Management:** Battery systems require appropriate technical expertise and maintenance.
- **Space Requirement:** Solar arrays require considerable installation area.
- **Seasonal Variation:** Solar generation decreases during monsoon and prolonged cloudy periods, requiring backup arrangements.
- **Project Duration:** Temporary construction projects may not always provide sufficient operating duration to recover the initial investment.

3.3.5 Critical Findings

- Solar PV with battery storage can potentially offset approximately 30–80% of site electricity consumption, depending on site conditions.
- The technology can reduce diesel and grid dependence for temporary site facilities.
- Reports indicate a potential 20–40 lakh/year operating saving under the stated assumptions.
- Solar systems can provide significant site-level emission reductions.
- The principal commercial limitation is the relatively long 3–5 year payback period compared with a typical 2–3 year construction project.
- Redeployment of the solar infrastructure across multiple projects can improve its economic viability.

3.3.6 Overall Technical Conclusion

Solar-powered construction-site infrastructure is a technically mature and scalable sustainability measure that can reduce diesel consumption, electricity costs and site-level emissions.

Its principal limitation is not technical feasibility but project economics, particularly where construction projects have short durations. The strongest implementation model is therefore likely to involve reusable corporate-owned solar assets that can be transferred between projects rather than treating each installation as a one-project temporary investment.

The technology can provide immediate operational sustainability benefits without requiring changes to pavement materials or structural design.

4. Comparative Technology Assessment

4.1 Summary of Technologies Assessed

The three technologies examined in Section 3 are summarised below on the basis of the evidence presented in that section.

Table 4.1: Comparative summary of the technologies under investigation

Aspect	A: Steel Slag	B: Sugarcane Molasses	C: Solar Site Infrastructure
Application	Alternative aggregate in flexible pavement layers	Partial replacement of bitumen binder	Power for site offices, camps, lighting and CCTV
Evidence base	Laboratory studies; CSIR-CRRI guideline	Laboratory study (IIT Roorkee, 2023)	Commercially established technology
Principal benefit	Less virgin aggregate; improved stiffness and rutting resistance	Approx. 21% binder-cost reduction at 25% replacement	30–80% of site electricity offset; lower diesel use
Principal constraint	Source variability; free-lime expansion	Foaming, dispersibility; no field validation	3–5 year payback vs. 2–3 year projects
Readiness	Compatible with existing specifications; suitable for laboratory assessment and a pilot proposal	Emerging; needs field trials	Mature; limited by project economics

4.2 Assessment Outcome

The comparative assessment identifies steel slag as the most suitable sustainable technology for laboratory assessment by AIPL. It offers a strong combination of technical performance, regulatory readiness, economic potential, environmental benefits and supply-chain availability. Compared with conventional aggregates, steel slag can improve pavement strength, rutting resistance and moisture performance while reducing the use of virgin natural aggregates and utilising an industrial by-product.

The key implementation risks, mainly related to variations in material properties and quality, can be managed through proper processing, ageing, testing and quality-control procedures. Its compatibility with existing pavement engineering and testing frameworks also makes implementation relatively practical compared with less established alternatives such as molasses-based binders.

A laboratory investigation of steel slag was therefore undertaken first (Section 5). If its results are satisfactory, a controlled pilot, supported by material testing, cost analysis, environmental assessment and performance monitoring, may be proposed to the Engineer/Authority for approval. Such a pilot could provide the technical and commercial evidence required for scaling steel slag use across suitable future AIPL projects and developing a standardised implementation framework.

Overall, steel slag demonstrates how technical feasibility, economic viability, environmental benefits, regulatory compliance and scalability can be combined to support practical sustainable road construction.

5. Laboratory Investigation: Steel Slag Aggregate in Bituminous Mixes

5.1 Material Selection and Rationale

Based on the comparative assessment presented in the preceding chapters, steel slag is identified as a suitable sustainable material for laboratory investigation because of its potential to replace natural aggregates in bituminous pavement construction. The investigation was carried out with reference to AIPL's project for the "four-laning work from Godibandha to Balla Har Chhak, Balla Har Chhak to Banarapal and Banarapal to the start of Anugul Bypass at Km 314.130 to Km 321.035 of NH-53, Km 75.200 to Km 84.000 of NH-149 and Km 84.000 to Km 85.750 of NH-55 under NH(O) on HAM in Odisha", whose technical specifications and material sources formed the basis for testing. No steel slag has been placed on this highway; all work described in this section was carried out in the laboratory.

The principal reason for selecting steel slag for the investigation was its local availability. Steel plants are located in the vicinity of the project, making transportation and supply comparatively practical. In contrast, sugarcane molasses would involve greater logistical uncertainty for the selected project, while solar-powered infrastructure requires relatively high initial investment and has a different implementation mechanism.

To establish the technical suitability and reliability of steel slag for road construction, laboratory investigations were undertaken using steel slag aggregate and conventional stone aggregate. Marshall mix design testing was carried out and the resulting volumetric and strength parameters were compared with the requirements specified in the project technical specifications/MoRTH criteria.[20]

The objective of the laboratory investigation was not merely to demonstrate that steel slag could be incorporated into a bituminous mixture, but to determine whether the resulting mix could achieve the required engineering properties while reducing dependence on conventional natural aggregate.

5.2 Source and Characterisation of Materials

The steel slag used for the investigation was sourced from the Fulapada Stone Quarry/TATA Steel & Power Limited source identified for the project. Conventional stone aggregate was considered as the reference material for comparison.

The basic aggregate properties considered in the investigation included:

- Bulk specific gravity
- Apparent specific gravity
- Water absorption

[20] Ministry of Road Transport and Highways. (2013). *Specifications for road and bridge works* (5th rev.). Indian Roads Congress. https://archive.org/details/gov.in.mort.250.2013

- Aggregate Impact Value (AIV)
- Flakiness and Elongation Index (FI & EI)

The laboratory results indicate that the steel slag had relatively low water absorption compared with the conventional aggregate. For the coarse fractions, water absorption of steel slag was reported between approximately 0.37% and 0.61%, whereas the corresponding conventional aggregate values were approximately 1.50% to 1.94%.

The reported Aggregate Impact Value of the steel slag was approximately 17.48, compared with 17.79 for the conventional aggregate. Similarly, the reported FI & EI value was 23.94 for steel slag compared with 24.36 for conventional aggregate.

Table 5.1: Key aggregate properties of steel slag and conventional aggregate

Property	Steel Slag	Conventional Aggregate
Water absorption, coarse fractions (%)	0.37 – 0.61	1.50 – 1.94
Aggregate Impact Value (%)	17.48	17.79
Flakiness & Elongation Index (%)	23.94	24.36

These results indicate that the steel slag used in the investigation possessed satisfactory aggregate quality and was broadly comparable with the conventional aggregate with respect to impact resistance and particle shape characteristics. The lower water absorption observed in the tested slag fractions is also favourable from the perspective of aggregate durability and binder interaction.

However, it should be noted that steel slag is a source-specific industrial by-product. Its properties may vary depending upon steelmaking process, cooling method, ageing period, processing and stockpile conditions. Therefore, the results obtained in this investigation should be treated as representative of the selected source rather than universally applicable to all steel slag.

5.3 Marshall Mix Design Investigation

The Marshall method was adopted to assess the strength and volumetric characteristics of the bituminous mixtures incorporating steel slag and to compare their performance with the conventional stone aggregate mixture.

The principal parameters evaluated were:

- Bitumen content
- Marshall density
- Marshall stability
- Marshall flow
- Percentage air voids (VIM)

- Voids in mineral aggregate (VMA)
- Voids filled with bitumen (VFB)
- Fines-to-bitumen ratio

Specimens were compacted using 75 blows on each face, corresponding to the compaction level specified in the project requirements.

Two mixtures were evaluated:

- Steel slag aggregate mix
- Conventional stone aggregate mix

The binder used was VG-40 grade bitumen.

5.4 Mix Proportions

The adopted material proportions are summarised below.

Table 5.2: Mix proportions of the steel slag and conventional aggregate mixes

Material	Steel Slag Mix (%)	Conventional Aggregate Mix (%)
VG-40 Binder	4.54	5.23
Hot Bin-04 (32–20 mm)	25.00	27.00
Hot Bin-03 (20–10 mm)	20.00	19.00
Hot Bin-02 (10–4 mm)	17.00	16.00
Hot Bin-01 (<4 mm)	38.00	38.00

An important observation from the mix design is that the steel-slag mixture achieved the reported design condition at a bitumen content of 4.54%, compared with 5.23% for the conventional aggregate mixture.

This represents a reduction of approximately 13.2% in binder content relative to the conventional mix:

$$\textit{Reduction in binder content} = (5.23 - 4.54) / 5.23 \times 100 \approx 13.2\%$$

This result is significant from a resource-efficiency perspective because, subject to confirmation through additional mix-design trials and field validation, lower binder demand could reduce petroleum-derived material consumption and potentially reduce the cost and embodied carbon associated with bitumen.

However, this observation should not be interpreted directly as a 13.2% reduction in total pavement cost or carbon emissions. Such conclusions require a complete mix-level cost and life-cycle assessment.

5.5 Marshall Test Results

The principal laboratory results obtained from the two mixtures are presented below.

Table 5.3: Marshall test results compared with MoRTH / project requirements

Parameter	Steel Slag Mix	Stone Aggregate Mix	MoRTH / Project Requirement
Bitumen Content (%)	4.54	5.23	—
Marshall Density (g/cc)	2.474	2.754	—
Marshall Stability (kg)	2130	2370	Min. 900
Marshall Flow (mm)	3.50	3.42	2.0–4.0
Compaction	75 blows/face	75 blows/face	75 blows/face
Air Voids, VIM (%)	3.73	4.62	3–5
VMA (%)	13.40	17.17	Min. 12.0
VFB (%)	72.19	73.05	65–75
Fines/Bitumen Ratio	0.98	0.85	0.6–1.2

The results demonstrate that the steel-slag mixture satisfies all the reported specification ranges for Marshall flow, air voids, VMA, VFB and fines-to-bitumen ratio. Most importantly, the Marshall stability of 2,130 kg is substantially higher than the stated minimum requirement of 900 kg.[21]

5.6 Interpretation of Results

5.6.1 Marshall Stability

Marshall stability represents the maximum load carried by the compacted bituminous specimen before failure under the specified test conditions.

The steel-slag mix recorded a stability of 2,130 kg, whereas the conventional stone aggregate mix recorded 2,370 kg. Thus, the steel-slag mix recorded approximately 10.1% lower Marshall stability than the conventional aggregate mix.

This result requires careful interpretation.

The laboratory result does not indicate that the steel-slag mix is unsuitable. Both mixtures have stability values substantially above the stated minimum requirement of 900 kg. The result instead indicates that, under the particular materials, gradation, binder content and laboratory conditions investigated, the conventional aggregate mixture developed somewhat higher Marshall stability.

[21] Ministry of Road Transport and Highways. (2013). *Specifications for road and bridge works* (5th rev.). Indian Roads Congress. https://archive.org/details/gov.in.mort.250.2013

Therefore, the appropriate conclusion is that the steel-slag mixture provides adequate Marshall strength for the investigated application, rather than claiming that steel slag increased Marshall stability in this particular laboratory investigation.

This finding is also important from a research perspective because laboratory performance of steel slag is influenced by its source, gradation, surface texture, chemical composition and interaction with the selected binder. Results reported in published studies cannot automatically be assumed to occur with every steel slag source.

5.6.2 Marshall Flow

Marshall flow represents the deformation corresponding to the maximum Marshall load.

The steel-slag mixture recorded a flow value of 3.50 mm, while the conventional mixture recorded 3.42 mm.

The difference is approximately 2.3%, indicating that the deformation characteristics of the two mixtures are relatively close.

Both values fall within the specified range of 2.0–4.0 mm.

The result indicates that the steel-slag mix has neither excessive deformation nor excessively low flow under the Marshall test conditions. The relatively similar flow values also suggest that replacement of the conventional aggregate with the tested steel slag did not produce an undesirable change in the overall deformation characteristics of the mix.

5.6.3 Air Voids (VIM)

The percentage air voids in the compacted mixture was:

- **Steel slag mix:** 3.73%
- **Conventional aggregate mix:** 4.62%

The specified range is 3–5%. Both mixtures therefore satisfy the requirement.

The steel-slag mixture contains approximately 19.3% lower air voids than the conventional mixture. The lower VIM indicates that the tested steel-slag mix achieved a comparatively dense internal structure at the selected composition.

Adequate air voids are essential in bituminous mixtures. Excessively high voids can increase permeability and accelerate oxidation and moisture-related deterioration, while excessively low voids may increase the risk of bleeding and permanent deformation. The measured value of 3.73% lies within the specified range and therefore represents an acceptable balance under the present mix-design conditions.

5.6.4 Voids in Mineral Aggregate (VMA) and Voids Filled with Bitumen (VFB)

The VMA values were:

- **Steel slag mix:** 13.40%
- **Conventional aggregate mix:** 17.17%

The minimum specified value is 12%. The steel-slag mixture therefore satisfies the VMA requirement, although its VMA is approximately 22% lower than that of the conventional aggregate mixture.

VMA represents the volume of voids available within the compacted aggregate structure for bitumen and air. The lower VMA of the steel-slag mix is consistent with its lower measured air void content and indicates a comparatively tightly packed aggregate structure.

The VFB values were 72.19% for steel slag and 73.05% for the conventional mixture. Both are within the specified 65–75% range.

The very small difference in VFB, approximately 1.2%, indicates that the proportion of aggregate voids filled by binder is broadly comparable between the two mixtures.

5.7 Overall Comparison of Laboratory Performance

The laboratory results provide several important findings.

First, the steel-slag mixture achieved all the reported Marshall volumetric and specification requirements. The Marshall stability of 2,130 kg is more than twice the stated minimum requirement of 900 kg.

Second, the steel-slag mixture required a lower reported binder content of 4.54%, compared with 5.23% for the conventional aggregate mix. This is approximately a 13.2% reduction in binder content, which represents a potentially important resource and cost benefit.

Third, the Marshall stability of the steel-slag mix was approximately 10.1% lower than the conventional mixture. Consequently, the present laboratory investigation does not demonstrate an improvement in Marshall stability; rather, it demonstrates that adequate stability can be achieved despite the lower stability relative to the control mix.

Fourth, the flow values of both mixtures were very similar and within the specified range. Similarly, VIM, VMA, VFB and fines-to-bitumen ratio all complied with the stated requirements.

The comparative performance can therefore be summarised as follows:

Table 5.4: Summary of laboratory performance of the steel slag mix

Performance Aspect	Observation for Steel Slag
Specification compliance	Satisfactory
Marshall stability	2,130 kg; above 900 kg requirement
Stability relative to control	Approximately 10.1% lower
Binder requirement	Approximately 13.2% lower
Marshall flow	Comparable and within specified range
Air voids	Within 3–5% requirement
VMA	Above 12% minimum
VFB	Within 65–75% requirement
Fines/bitumen ratio	Within 0.6–1.2 requirement
Aggregate impact resistance	Comparable/slightly favourable
Water absorption	Lower than tested conventional aggregate
Overall laboratory feasibility	Demonstrated

5.8 Engineering Interpretation and Sustainability Implications

The laboratory investigation demonstrates that the selected steel slag can be incorporated into the investigated bituminous mixture without violating the reported Marshall mix-design requirements.

The sustainability significance is particularly associated with the substitution of a portion of conventionally quarried aggregate by an industrial by-product. If steel slag is sourced from nearby steel plants, the application can potentially reduce demand for virgin aggregate and create a productive end use for a material otherwise requiring disposal or stockpiling.

The lower binder content observed in the steel-slag mixture provides an additional potential benefit. However, this result should be validated through repeated job-mix trials because binder demand is influenced by aggregate gradation, surface texture, absorption, shape and the specific mix-design methodology.

From an implementation perspective, the use of steel slag should therefore be considered as a controlled material substitution rather than a simple one-to-one replacement of natural aggregate. The slag must be appropriately processed, graded and tested before incorporation into pavement works.

Particular attention should be given to:

- Source-wise chemical and physical characterisation
- Ageing and expansion potential
- Free-lime-related volumetric stability

- Particle size and gradation
- Water absorption
- Aggregate impact and shape characteristics
- Binder-aggregate compatibility
- Moisture susceptibility
- Plant handling and stockpile management
- Field quality control

These controls are essential because steel slag is not a completely uniform material and its engineering behaviour may vary between production sources.

5.9 Limitations of the Present Investigation

The present laboratory investigation provides useful evidence of technical feasibility, but it should not be considered a complete long-term pavement performance assessment.

The principal limitations are:

- **Limited laboratory test programme:** The present study is primarily based on Marshall mix-design parameters. Long-term pavement behaviour requires additional testing.
- **Source-specific results:** The results apply to the tested steel slag source and should not automatically be extended to slag obtained from other steel plants.
- **No field performance data:** The material has not been placed on a road. Rutting, fatigue cracking, moisture damage and durability under actual traffic and environmental conditions require field monitoring.
- **Expansion assessment:** Steel slag requires adequate assessment of free lime and volumetric stability before large-scale pavement use.
- **Limited economic assessment:** The lower binder requirement indicates potential economic benefit, but actual project savings must include processing, transportation, crushing, screening, testing and handling costs.
- **Environmental benefits require verification:** Reduction in virgin aggregate use can provide environmental benefits, but a project-specific life-cycle assessment is required to quantify actual carbon savings.

Accordingly, the present results should be regarded as a laboratory feasibility stage that precedes any pilot trial, rather than final proof of long-term superiority over conventional aggregate.

5.10 Proposed Pilot Trial and Monitoring (Subject to Approval)

Based on the laboratory results, AIPL may propose a controlled pilot trial of steel slag in suitable pavement layers. No pilot will be undertaken until it has been approved by the Engineer/Authority, and any trial must comply with the applicable specifications.

If the pilot is approved, a field monitoring programme should be established to compare the steel-slag pavement section with a conventional control section.

The following parameters should preferably be monitored:

- Initial pavement density and compaction
- Surface condition
- Skid resistance
- Rut depth
- Cracking
- Ravelling
- Surface distress
- Drainage and moisture-related performance
- Periodic deflection measurements, where applicable
- Aggregate and mix quality during production
- Actual material, transportation and construction costs

Performance should be monitored at regular intervals, particularly after the first monsoon and after significant traffic accumulation. This would provide practical evidence regarding the durability and long-term behaviour of the selected steel slag.

6. Conclusions and Way Forward

The laboratory investigation establishes that the tested steel slag is technically suitable for incorporation into the investigated bituminous mixture, subject to appropriate material processing, quality control and compliance with project specifications.

The steel-slag mixture achieved a Marshall stability of 2,130 kg, substantially exceeding the stated minimum requirement of 900 kg. Marshall flow, air voids, VMA, VFB and fines-to-bitumen ratio were also within the reported MoRTH/project specification limits.

The most notable result is the lower binder content of 4.54% compared with 5.23% for the conventional aggregate mixture, representing an approximate 13.2% reduction in binder content under the tested mix-design conditions. This indicates potential for reducing petroleum-derived binder consumption and improving material efficiency.

At the same time, the steel-slag mixture recorded Marshall stability approximately 10.1% lower than the conventional aggregate mixture. Therefore, the present laboratory results do not support a claim that steel slag is universally superior to natural aggregate in terms of Marshall strength. Instead, they demonstrate that the selected steel slag can achieve adequate and specification-compliant pavement performance while offering potential resource and sustainability benefits.

The investigation consequently supports the use of steel slag as a technically feasible sustainable aggregate for a controlled pilot trial, subject to approval by the Engineer/Authority, rather than immediate unrestricted replacement of conventional aggregate.

The next stage, once approved by the Engineer/Authority, should be field validation through a controlled pilot section, supported by strict source-specific quality control, monitoring of expansion and durability, construction-cost tracking and long-term pavement performance assessment. Successful field performance would provide the technical and commercial evidence required for developing a standardised steel-slag utilisation framework for future highway projects.

> The laboratory investigation confirms the feasibility of using the selected steel slag as an alternative aggregate in bituminous pavement construction. The material satisfies the specified Marshall mix-design requirements and demonstrates potential for reducing virgin aggregate and binder consumption. However, because the present investigation is source-specific and entirely laboratory-based, with no testing carried out on a highway, long-term field validation is necessary before large-scale adoption.

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