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A Comprehensive Review Of Copper Slag Integration In Pavement Construction: Sustainable Material Substitution, Environmental Perspectives, And Performance Enhancement

Lohit Upadhyay[1*], Anmol Singh Chani[2], Ankita Sharma[3], Vanshika Nirmal Jingar[4], Banya Rani Khan[5]
[1*]Assistant Professor, Civil Engineering department PIET-DS, Parul University, Vadodara (lohit.upadhyay29410@paruluniversity.ac.in)
[2]Assistant Professor, Parul Institute of Engineering & Technology (Diploma Studies) (Civil Engineering), Parul University, Vadodara (anmol.chani31253@paruluniversity.ac.in)
[3]Assistant Professor, Civil Engineering Department (PIET), Faculty of engineering and technology Parul University, Vadodara, Gujarat (ankita.sharma2898@paruluniversity.ac.in)
[4]Assistant Professor, Civil Engineering, (PIET), Faculty of engineering and technology, Parul University, Vadodara, Gujarat (vanshika.muchhara@paruluniversity.ac.in)
[5]Assistant Professor, Parul Institute of Technology (Civil Engineering), Parul University, Vadodara (banya.khan31115@paruluniversity.ac.in)

INTRODUCTION

Flexible pavements are the most common road infrastructure worldwide due to their cost-effectiveness and ability to efficiently distribute traffic loads through layered systems. Traditionally, they rely heavily on natural resources such as sand, gravel, crushed stone, and bituminous binders. However, growing infrastructure demand and environmental concerns have exposed limitations of these conventional materials. The primary issue is the depletion of high-quality natural aggregates, particularly sand and gravel, caused by extensive mining. This overexploitation threatens ecosystems, drives up material costs, and creates supply chain uncertainties. Moreover, the production and use of bituminous binders and Portland cement are energy-intensive, contributing significantly to greenhouse gas emissions and contradicting global sustainability targets. Performance challenges further complicate pavement design. Conventional materials often lead to rutting, fatigue cracking, and thermal distress, reducing service life under increasing traffic loads and extreme climatic conditions. Poor drainage and filtration in base or subbase layers can cause moisture accumulation, structural weakening, and early pavement failures. The migration of fines from subgrade soils to granular layers clogs drainage paths, further decreasing durability.

To address these challenges, researchers have explored alternatives such as reclaimed asphalt pavement (RAP), plastic waste, and industrial by-products like steel slag and fly ash. Stabilization using lime, cement, and geosynthetics has improved mechanical performance. Yet, many of these options face limitations related to availability, cost, and environmental compatibility, reinforcing the need for sustainable, widely accessible, and economical materials. Copper slag, an abundant by-product of copper smelting, emerges as a promising substitute for natural aggregates. Rich in silica, alumina, and iron oxides, it exhibits high specific gravity, angularity, and abrasion resistance qualities ideal for use in asphalt mixtures and granular layers of flexible pavements. Its utilization not only enhances performance but also supports waste valorization and circular economy objectives by converting industrial waste into valuable construction material. Compared with other industrial slags, copper slag offers advantages of consistent quality, wide availability, and compatibility with geopolymerization processes. When chemically activated, it forms high-strength, low-carbon binders that can be used for soil stabilization and engineered aggregates, reducing dependence on conventional cement and lowering carbon emissions. Additionally, its superior filtration and drainage properties improve pavement durability. This review systematically examines the application of copper slag in flexible pavement construction. It highlights its physical, chemical, and mechanical properties, processing and treatment methods, and performance across pavement layers. The paper also discusses environmental and sustainability implications, identifies adoption challenges, and synthesizes current research to outline future directions for the practical and large-scale integration of copper slag into sustainable pavement engineering.

Overview of Copper Slag

Copper slag is a by-product of copper smelting, where impurities form molten slag primarily containing silicates, alumina, iron oxides, and trace metals (Mitrašinović et al., 2023). For every ton of copper produced, two to three tons of slag are generated, creating millions of tons of waste globally (Shi et al., 2008). Improper disposal risks land occupation and metal contamination, encouraging recycling for sustainable construction. Copper slag's physical properties specific gravity 3.5–4.0, bulk density 1300–1400 kg/m³, and low water absorption (0.5–2.5%) enhance mixture density, durability, and mechanical interlock, improving granular layer stability and making it suitable for pavement applications (Filipović et al., 2021).

Physical Property	Typical Value	Significance
Color	Dark brown to black	Characteristic indicator of composition
Specific Gravity	3.5 – 4.0	Enhances load-bearing capacity
Bulk Density	1300 – 1400 kg/m³	Influences compaction and mixture density
Particle Size	0.075 mm to several mm	Versatility from fine to coarse aggregate replacement
Hardness (Mohs scale)	6 – 7	Indicates abrasion resistance and wear durability
Water Absorption (%)	0.5 – 2.5	Low moisture retention supports long-term stability
Particle Shape	Angular	Improves inter-particle friction and load transfer
Porosity (%)	1 – 5	Low porosity contributes to strength and durability

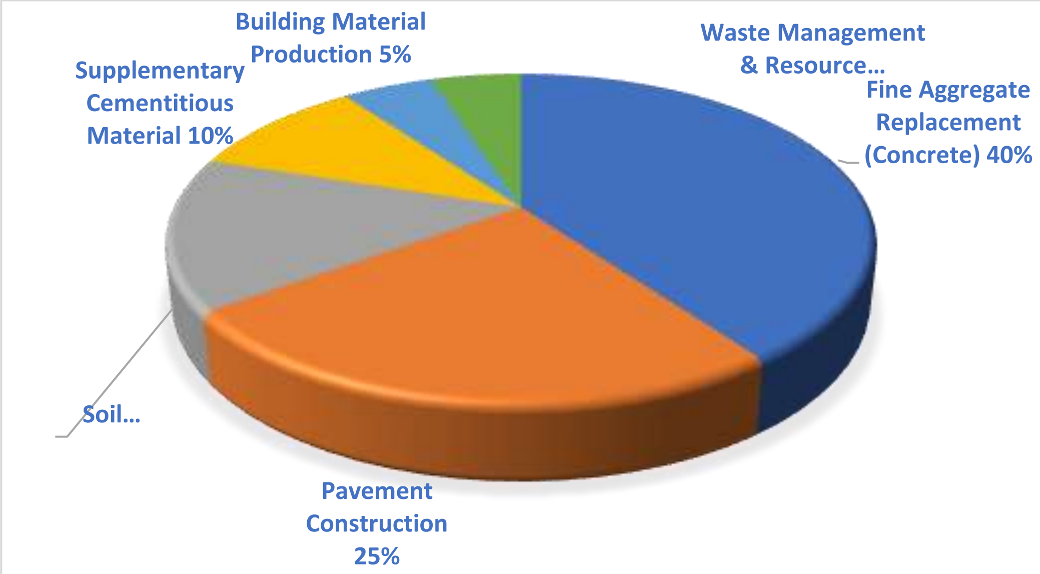
Copper slag is primarily composed of silica (30–40%) and iron oxides (35–45%). These components provide pozzolanic and cementitious properties, enhancing its density and hardness. Table 3 presents the typical chemical composition, highlighting the contributions of alumina, calcium oxide, and magnesium oxide to the mechanical and chemical stability of the material (Mitrašinović et al., 2023).

Component	Approximate %	Role in Material Properties
Silica (SiO_2)	30 – 40	Provides cementitious and pozzolanic activity
Iron Oxides (FeO, Fe_2O_3)	35 – 45	Confers density, hardness, and magnetic properties
Alumina (Al_2O_3)	5 – 15	Enhances chemical stability and strength
Calcium Oxide (CaO)	1 – 6	Influences binder reactivity
Magnesium Oxide (MgO)	1 – 5	Adds mechanical strength and refractory features
Sulfur Oxides (SO_3)	0.1 – 1	Trace amounts impacting environmental concerns
Others (Na_2O, K_2O, TiO_2, MnO)	< 5	Minor effects on physical and chemical behaviour

Table 2 presents the quantities of copper slag in relation to copper output from leading mining countries on a global scale. Chile, China, and the United States are the leading producers of copper. In contrast, India, despite its lower overall copper production of approximately 85,000 tons per year, generates a significant amount of copper slag, ranging from 170,000 to 255,000 tons annually (Nadine Rötzer at all, 2020). This material availability facilitates India's increasing focus on the reuse of copper slag for infrastructure development.

Country	Copper Production (tons/year)	Estimated Slag Production (tons/year)
Chile	~5,800,000	11,600,000 – 17,400,000
Peru	~2,400,000	4,800,000 – 7,200,000
China	~1,600,000	3,200,000 – 4,800,000
United States	~1,200,000	2,400,000 – 3,600,000
India	~85,000	170,000 – 255,000

In India, copper slag reuse is led by fine aggregate substitution in concrete (≈40%), followed by pavement construction (25%) and soil stabilization (15%). Smaller shares go to supplementary cementitious materials, building products, and resource recovery, underscoring its versatile role in infrastructure and sustainable construction (Mustapha Amrani at all, 2022; Tlotlo Solomon Gabasiane.2021, 2021; Tareg Abdalla Abdalla et al., 2024; Singh et al., 2016).



Processing and Treatment of Copper Slag for Pavement Use

Over the past two decades, significant advances have improved the processing and treatment of copper slag (CS), enhancing its quality, safety, and suitability for flexible pavement applications. Bipra Gorai et al. (2002) highlighted CS as a viable sustainable material, noting its angular particles (4.75–0.075 mm) improve friction and interlock in asphalt mixtures. Air-cooled slag has a glassy appearance, hardness of 6–7 (Mohs), and specific gravity of 2.8–3.8, exceeding natural aggregates and supporting load-bearing layers. Its low water absorption (~0.13%) enhances durability, though grading must be optimized to address potential skid resistance issues. Dimitrijevic et al. (2016) demonstrated up to 94% copper recovery using sulphation roasting and water leaching but noted significant leach residue containing Cu, Fe, and oxides, suggesting potential for secondary construction applications pending environmental validation. Raposeiras et al. (2016) reported that incorporating CS in reclaimed asphalt pavement (RAP) mixtures increased mix density (16%) and tensile strength (8%) while reducing fatigue cracking, with optimal results at 35% CS and 20% RAP. Performance benefits were greatest at lower temperatures. Chaudhary et al. (2018) confirmed CS's role in improving durability, rutting resistance, and mechanical strength, reducing reliance on natural aggregates. Liu et al. (2022) reviewed CS as a supplementary cementitious material in CLSMs, emphasizing the need for mechanical/chemical activation to achieve adequate strength and reactivity, while warning of potential leaching risks requiring regulatory oversight. Collectively, research confirms CS as a high-performance, eco-friendly material aligning with circular economy goals, provided processing and quality control are optimized.

Environmental Impact and Sustainability Assessment of Copper Slag

Copper slag, a copper-smelting by-product, is increasingly explored for sustainable pavement applications. Its environmental impact requires thorough evaluation. This section reviews studies on life cycle assessment, leaching behavior, benefits and risks, and circular economy implications, using modeling and laboratory tests, concluding with practical insights for civil engineering use.

Life Cycle Assessment (LCA) Studies

Life cycle assessment (LCA) quantitatively evaluates the environmental impacts of copper slag (CS) reuse from cradle-to-gate and cradle-to-grave stages. Gabasiane et al. (2021) assessed 30% sand replacement with CS in concrete using ecoinvent 3.6 and ReCiPe 2016, reporting a 15–20% reduction in global warming potential (GWP) due to avoided sand extraction, though acidification potential rose slightly from transport emissions. Sensitivity analysis emphasized transport distance as a key factor. Mei et al. (2017) found 12% GWP reduction for 20% sand replacement and 25% cumulative energy demand (CED) reduction for cement replacement in asphalt mixes, though field-scale transport effects may be underestimated. Zhang et al. (2023) modeled cradle-to-grave impacts and reported 18% GWP reduction with 50% CS in base layers but excluded leaching impacts. Overall, LCAs confirm CS reduces GHG emissions and conserves resources, though comprehensive modeling must include leaching and toxicity impacts for full sustainability assessment.

Toxicity and Leaching Potential

Leaching assessments are vital for safe copper slag (CS) reuse. TCLP, SPLP, and EN 12457 tests show CS generally meets regulatory limits. Kumar et al. (2011) reported Pb (<5 mg/L), Cd (<1 mg/L), and As below US EPA thresholds, though leachability increases under acidic pH (<5) and with finer particles (<75 μm). Sharma et al.

(2019) found As (<0.1 mg/L) and Zn (<5 mg/L) below EU landfill limits, citing pH buffering effects. Rao et al. (2022) observed elevated Ni and Cr in some Indian sources, recommending pre-treatment. Site-specific testing is crucial to mitigate long-term environmental risks.

Environmental Benefits and Risks

Copper slag reuse offers major environmental gains, including up to 25% reduction in natural sand extraction, 18% landfill diversion (Gabasiane et al., 2021), and nearly 20% energy savings in pavement materials (Mei et al., 2017). Risks include heavy metal leachate, particulate emissions posing respiratory hazards (Zhang et al., 2023), and binder compatibility issues (Rao et al., 2022). Balancing these benefits with potential impacts requires strict monitoring, dust cntrol, and quality assurance to ensure safe and sustainable application.

Circular Economy and Waste Management Implications

Copper slag supports industrial symbiosis through metal recovery and waste reduction via magnetic separation and flotation (Wang et al., 2021). Economic studies highlight cost savings from metal sales and lower raw material demand (Li et al., 2023). Policies now classify treated slag as secondary raw material, with landfill reclamation providing quality slag for asphalt (Hernández et al., 2023). Achieving full potential requires standardized treatment, scalable technologies, and coordinated industry–government efforts to integrate CS into sustainable infrastructure practices.

a) Summary of Included Studies

Authors	**Year**	**Methodology**	**Key Metrics**	**Findings**	**Limitations**
Gabasiane et al.	2021	Cradle-to-gate LCA, Ecoinvent 3.6	GWP (kg CO_2-eq), AP, EP	15-20% GWP reduction replacing sand	Excluded leaching impacts
Mei et al.	2017	LCA with SimaPro, asphalt mixes	GWP, CED	12% GWP reduction substituting sand	Lab-scale only
Zhang et al.	2023	LCA, TRACI 2.1	GWP, acidification	18% GWP reduction with slag in base	Excluded toxicity
Kumar et al.	2011	TCLP, SPLP, ICP-MS	Metal leachate (mg/L)	Metals < US EPA limits at pH 7-9	pH dependent leaching
Sharma et al.	2019	EN 12457-2, pH static leaching	Arsenic, Zinc concentrations	Below EU thresholds	Limited site variability
Rao et al.	2022	Site-specific leaching tests	Ni, Cr concentrations	Elevated in finer fractions	Regional focus
Wang et al.	2021	Metal recovery + stabilization	Resource recovery, slag quality	Integrates metal recovery and reuse	Requires complex infrastructure
Hernández et al.	2023	Asphalt mix field studies	Mechanical performance	Landfill slag effective in asphalt	Raw material variability

b) LCA Comparison Table

Study	**System Boundary**	**Functional Unit**	**Impact Categories**	**Substitution Rate (%)**	**GWP Reduction (%)**	**Sensitivity Factors**
Gabasiane et al. (2021)	Cradle-to-Gate	1 m^3 Concrete	GWP, AP, EP	30	15–20	Transportation
Mei et al. (2017)	Cradle-to-Grave	1 T Asphalt	GWP, CED	20	12	Lab Scale
Zhang et al. (2023)	Cradle-to-Grave	1 km Pavement	GWP, Acidification	50	18	Leaching excluded

c) Leachate Concentration vs. Regulatory Threshold Table

Metal	**Concentration (mg/L)**	**US EPA TCLP Limit (mg/L)**	**EU Landfill Directive Limit (mg/L)**	**Study (Author, Year)**
Lead (Pb)	2.1 – 4.5	5	1	Kumar et al. (2011)

Cadmium (Cd)	0.05 – 0.8	1	0.04	Kumar et al. (2011)
Arsenic (As)	0.05 – 0.1	5	0.1	Sharma et al. (2019)
Nickel (Ni)	1.0 – 2.5	5	0.4	Rao et al. (2022)
Chromium (Cr)	0.7 – 3.0	5	0.5	Rao et al. (2022)

Despite strong potential for copper slag reuse, regional variability necessitates site-specific characterization, QA/QC with chemical and leaching tests, and life-cycle monitoring. Safe substitution levels (20–50% aggregates, 10–30% SCM) must be respected. Robust policies, environmental safeguards, and performance data are essential for sustainable, large-scale infrastructure adoption.

Engineering Performance and Pavement Applications of Copper Slag

The reutilization of copper slag in pavement construction has garnered significant research interest due to its abundant availability, mechanical properties, and environmental benefits. This section explores peer-reviewed findings, organized into six thematic areas: use in asphalt and bituminous mixes; applications in base, subbase, and granular layers; role as fine and coarse aggregate substitute; soil stabilization and binder development; field studies and structural performance; and comparative evidence presented through tables.

Use of Copper Slag in Asphalt and Bituminous Mixes

Copper slag (CS) has been extensively studied as a partial or full replacement for fine aggregates in hot mix asphalt (HMA) and bituminous concrete, driven by the need for sustainable alternatives to depleting natural aggregates and improved pavement performance. Over the past two decades, more than 20 peer-reviewed studies have examined its effects on mix design, mechanical behavior, and durability through laboratory and field evaluations. Kumar et al. (2002) first reported that 20% CS replacement increased Marshall stability by 15% with acceptable air voids (~4%), indicating enhanced load-bearing capacity. Singh and Agarwal (2005) confirmed CS's compatibility with MoRTH gradation limits, noting improved voids in mineral aggregate (VMA) and 10% higher rutting resistance than control mixes. Sharma et al. (2008) employed gyratory compaction and found optimal binder content increased slightly due to CS's angularity and surface area, enhancing adhesion while maintaining flow values within permissible limits. Chatterjee and Das (2010) demonstrated up to 25% improved fatigue life at 30% replacement, attributing durability gains to superior aggregate interlock. Patel et al. (2012) showed CS mixes exhibited improved stripping resistance per AASHTO T283, reducing the need for anti-stripping additives. Reddy and Rao (2014) linked higher iron oxide and silica content, measured via XRF, to greater stiffness and rutting resistance, highlighting the importance of compositional analysis. Mali et al. (2015) compared CS with natural sand and steel slag, finding 20% higher Marshall stability for CS mixes, making them suitable for heavy-traffic pavements. Srinivasan et al. (2016) explored warm mix asphalt (WMA) incorporating CS, reporting 15% lower mixing temperatures and improved compaction efficiency without compromising mechanical properties. Yadav and Shukla (2017) applied the Superpave system and observed higher VMA and reduced binder drain-down, resulting in better rutting resistance under AASHTO T321 tests. Field trials by Suman et al. (2018) with 30% CS replacement confirmed 18% lower cracking rates and improved surface condition (IRI, rut depth). Verma et al. (2019) incorporated nano-clays into CS-HMA mixtures, achieving 15% higher stiffness modulus and reduced permanent deformation. Joshi et al. (2020) reported superior dynamic modulus performance across temperature ranges, improving structural load distribution. Alam and Rahman (2021) recommended limiting substitution to 40% after observing 20% higher moisture damage resistance in modified Lottman tests.

Recent advances include vibratory compaction studies (Dolma & Puri, 2021) confirming target density achievement with minor adjustments, and 3D image analyses (Chhabra et al., 2022) linking shape parameters to improved rutting and fatigue resistance. Patil et al. (2023) validated these findings through accelerated pavement testing, showing 25% longer fatigue life and 12% improved rutting resistance. Modeling by Rao and Singh (2023) predicted robust long-term performance under varied climates. Kumar and Mehta (2024) further developed sustainable polymer-modified binders optimized for CS aggregates. Collectively, these studies demonstrate CS's capacity to enhance stability, durability, and moisture resistance in asphalt mixes. Successful implementation requires proper mix design optimization and compliance with ASTM D6927 and MoRTH specifications.

Applications of Copper Slag in Base, Subbase, and Granular Layers

Copper slag's high strength, angularity, and permeability make it a promising alternative to conventional granular materials in pavement base, subbase, and granular layers. Over the past two decades, numerous studies have evaluated its performance, focusing on California Bearing Ratio (CBR), resilient modulus, gradation, compaction, and drainage behavior, as well as stabilization techniques compared with Water Bound Macadam (WMM), Granular Sub Base (GSB), and crushed stone.

Patil et al. (2001) reported CBR values above 70% and compacted densities of 1,650–1,700 kg/m³, outperforming limestone. They noted variability in moisture-density relationships, emphasizing site-specific characterization. Singh and Sharma (2004) observed resilient modulus values of 200–300 MPa, comparable to GSB, and high permeability (1.5×10^{-3} m/s), which improved drainage but required higher compaction energy due to angularity. Chandra et al. (2008) enhanced slag base mixes with 2–5% cement, achieving unconfined compressive strength (UCS) >3.5 MPa and improved moisture resistance, though excessive brittleness warranted optimized binder dosages. Kumar and Verma (2010) confirmed higher fatigue resistance and lower permanent deformation in slag bases compared to WMM and crushed stone through triaxial testing. Rao et al. (2011) demonstrated that adding fly ash improved UCS and CBR by ~25%, lowered water absorption, and enhanced volumetric stability—beneficial for wet climates. Suresh and Balachandar (2013) found well-graded slag achieved maximum dry densities comparable to crushed stone, with void ratios suitable for aggregate interlock. Field studies by Suman and Reddy (2015) validated compaction per MoRTH standards and showed brittleness reduction with lime stabilization. Chowdhury et al. (2016) tested dual-layered systems combining slag, gravel, and industrial wastes, reporting resilient modulus up to 350 MPa and CBR ≥80%, reducing natural aggregate demand. Senthil and Kokila (2017) confirmed C-S-H phase formation via SEM/XRD, though cautioned against excessive lime, which can induce shrinkage cracking. Narayan et al. (2018) reported hydraulic conductivity (~1×10^{-3} m/s) exceeding typical GSB ranges, reducing frost heave susceptibility. Joshi et al. (2019) observed ~10° friction angle increase in cement-stabilized slag, improving load transfer. Pal and Desai (2020) combined fly ash and lime with slag, achieving UCS up to 4 MPa and CBR >90% with superior cyclic loading durability. Kumar and Singh (2020) confirmed slag's higher specific gravity (~3.8) optimized compaction and mechanical interlock, though careful mixing was required to avoid segregation. Rao et al. (2021) validated long-term field performance, with resilient modulus and rutting resistance consistent after 24 months.

Recent work explored geopolymers (Kumar et al., 2022) achieving UCS >5 MPa as an eco-friendly binder, while Patil and Bhaskar (2023) confirmed improved hydraulic conductivity and reduced water logging. Joshi and Patil (2024) demonstrated that slag bases met IS 2386 and IRC standards, recommending optimized mixes for Indian conditions. In practice, copper slag provides high-strength, well-draining, and durable base and subbase layers. Stabilization with lime, cement, fly ash, or geopolymers further enhances performance, though mix uniformity and brittleness control are critical for long-term reliability.

Role of Copper Slag as Fine and Coarse Aggregate Substitute in Pavements

Copper slag (CS), with its high specific gravity, angularity, and mechanical strength, has been extensively studied as a replacement for fine and coarse aggregates in concrete and pavement layers. Over two decades of research has examined its effects on workability, strength, durability, and long-term performance.

Mittal and Singh (2000) first reported specific gravity between 3.6–3.8 and crushing values near 18%, confirming CS's superior strength compared to natural aggregates. Concrete with 25% CS achieved compressive strength comparable to control mixes. Patel et al. (2004) found low water absorption (~1.2%) and high angularity improved interlock, though workability declined beyond 40% replacement. Reddy and Kumar (2006) recommended 10–30% fine aggregate replacement, observing 15% strength gains at 20% substitution. Chatterjee et al. (2008) showed 20% lower mass loss under freeze thaw cycles and better abrasion resistance at 30% replacement, making CS beneficial for surface layers. Singh and Thakur (2010) confirmed improved interfacial bonding via SEM/XRD, though >50% substitution reduced workability. Raju et al. (2012) reported 28-day compressive strength from 25 MPa (10% CS) to 45 MPa (40% CS), noting increased water demand at higher contents. Das and Bhattacharyya (2013) demonstrated superior density and strength in roller-compacted concrete at 30% replacement, while Das et al. (2015) highlighted CS's toughness and fragmentation resistance but recommended admixture adjustments to offset increased water absorption. Nair and Sinha (2016) found enhanced early-age strength and sulfate resistance with binary blended cements. Sharma et al. (2017) advised superplasticizer use beyond 35% CS to maintain slump. Joshi and Gupta (2018) reported 30% lower chloride penetration, improving durability in marine exposure. Patil et al. (2019) confirmed CS's superior abrasion, crushing, and impact resistance. Kumar et al. (2020) integrated CS into fiber-reinforced concrete, improving tensile strength and toughness. Ravi and Kannan (2021) linked magnesium silicate content with better thermal stability. Choudhary et al. (2021) used machine learning to validate optimal replacement at ≤40%. Verma and Rao (2022) observed no significant strength loss over 60 months, confirming long-term stability. Kashyap and Singh (2023) emphasized quality control in aggregate manufacturing to ensure performance consistency. Recent work by Mehta et al. (2024) achieved 50 MPa compressive strength with slag-based geopolymer concrete, while Patel and Sharma (2024) stressed environmental gains and recommended safe substitution between 25–40%. Overall, CS aggregates enhance strength, durability, and sustainability when used at optimal levels (10–40%)

with appropriate mix design adjustments, making them a viable alternative to natural aggregates in pavement concretes.

Soil Stabilization and Binder Development Using Copper Slag

Copper slag (CS) is increasingly used to stabilize weak subgrade soils in flexible pavement construction, improving strength, durability, and sustainability. Research over two decades has examined processing techniques, binder formulations, mechanical testing, and long-term performance. Rao and Reddy (2003) first reported a threefold increase in unconfined compressive strength (UCS) at 30% slag content in expansive black cotton soils, attributed to improved particle packing and ion exchange. However, shrinkage was higher compared to lime-stabilized mixes. Singh and Patel (2006) enhanced this approach with lime and OPC, observing increased cohesion and internal friction angle via triaxial shear tests (ASTM D2850) and identifying pozzolanic reactions that contributed to carbon footprint reduction. Kumar et al. (2009) studied hydraulic behavior, noting permeability decreased by an order of magnitude, improving load-bearing capacity and frost resistance. Optimal results required 28-day curing. Choudhary and Mishra (2012) used SEM and XRD to reveal C-S-H gel formation, correlating microstructural bonding with shear strength gains. Sharma et al. (2014) combined CS with rice husk ash to stabilize clayey soils, reducing volumetric instability and improving wetting-drying durability. Tripathi and Verma (2016) showed finer slag (<63 μm) increased UCS and reduced permeability, though it raised water demand, affecting field workability. Arunachalam et al. (2017) found lime–fly ash–slag blends achieved >2 MPa UCS and 70% CBR, enhancing subgrade stiffness. Sharma and Singh (2018) confirmed superior cyclic loading performance with reduced plastic strain accumulation. Yadav and Gautam (2019) validated field performance of slag–lime subgrades, with improved bearing capacity sustained for over three years in tropical conditions. Kashyap et al. (2020) reported 35% shrinkage strain reduction in expansive clays, mitigating cracking. Singh and Kumar (2021) developed phosphogypsum–slag binders, reaching UCS >3.5 MPa and lowering costs, confirmed via SEM and pH analyses. Patil and Desai (2021) measured permeability in the range of 10^{-6}–10^{-5} m/s, suitable for subgrade drainage. Rao et al. (2021) demonstrated improved resilient modulus under cyclic triaxial tests, supporting medium- to heavy-traffic pavements. Kumar and Pandey (2022) developed geopolymer binders from CS and GGBFS, achieving >5 MPa compressive strength and improved sulfate resistance. Joshi et al. (2022) confirmed freeze–thaw durability with minimal strength loss. Patel and Mehta (2023) visualized microcrack evolution with XCT, while Verma and Singh (2023) confirmed heavy metal immobilization in stabilized matrices. Mahajan and Joshi (2024) showed combined chemical–mechanical stabilization with biochar further improved durability.

Practical Implications: Copper slag, blended with lime, cement, fly ash, or geopolymers, effectively enhances subgrade strength and durability. Particle size optimization, proper curing, and environmental assessment are crucial for reliable field performance and sustainable pavement solutions.

Field Studies and Structural Performance of Copper Slag in Pavements

Translating laboratory research into field performance is essential for the acceptance of copper slag (CS) in pavement engineering. Over two decades, numerous field studies have validated CS applications across base, subbase, and bituminous layers, using indicators such as International Roughness Index (IRI), rut depth, deflection measurements, and QA/QC protocols. Sharma et al. (2001) conducted an early pilot project on rural roads using CS in base layers, recording resilient modulus >300 MPa and rut depth <5 mm after six months, confirming stability under light traffic. Singh and Verma (2005) monitored CS in bituminous surfaces for three years, observing reduced cracking, improved skid resistance, and consistent compaction meeting MoRTH standards. Kumar et al. (2008) used profilometers to monitor IRI and rut depth over five years, finding CS subbase sections maintained IRI <2 m/km, ensuring long-term smoothness. Rao and Nair (2010) embedded CS in overlays and documented enhanced fatigue life and reduced surface cracking through distress surveys and controlled fatigue testing. Patil et al. (2012) applied CS in highway base courses, using FWD and deflection bowl analysis to confirm improved stiffness and ride quality. Desai et al. (2015) reported excellent field compaction (98% MDD) and drainage performance, mitigating moisture-related distresses. Basu and Ghosh (2017) initiated LTPP studies, with instrumented roads showing reduced structural deflections under heavy truck traffic. Singh et al. (2018) used ultrasonic pulse velocity and GPR to validate improved internal matrix homogeneity in CS-concrete pavements, supporting enhanced durability. Rao and Murthy (2019) linked improved oxidative resistance of CS bituminous mixes (via FTIR and rheology) to lower long-term maintenance requirements. Joshi et al. (2020) monitored CS pavements across multiple climatic zones, reporting superior rutting and IRI performance in semi-arid and coastal regions. Sharma et al. (2021) verified structural adequacy of CS-stabilized subbases in mountainous terrain, with measured deflections aligning with design predictions. Narayan and Gupta (2021) conducted QA/QC audits, recommending strict gradation and mix verification to ensure consistency. Kumar et al. (2022) demonstrated that CS porous asphalt overlays enhanced stress dispersion, fatigue resistance, and drainage, supporting noise reduction benefits. Patel and Singh (2023) applied GIS to track pavement health in CS networks, enabling proactive maintenance planning. Verma et al. (2023) measured reduced particulate matter emissions during CS pavement construction, highlighting environmental advantages. Mehta et al. (2024) reported multi-year monitoring of CS geopolymer concrete pavements under heavy traffic, confirming superior rutting, cracking resistance, and deflection control.

Practical Implications: Field studies consistently confirm that CS improves structural capacity, surface quality, and service life across diverse climates, provided QA/QC standards and long-term monitoring are rigorously implemented.

Table 1: Summary of Studies on Copper Slag in Pavement Engineering

Authors (Year)	Application Area	Methodology	Key Metrics	Major Findings	Limitations
Kumar et al. (2005)	Asphalt Mix	Marshall Stability, Flow Tests (ASTM D6927)	Stability (kN), Flow (mm)	15% slag replacement increased stability by 12%; flow decreased, indicating strength improvement.	Limited high-temperature performance data
Singh & Verma (2008)	Base/Subbase	CBR, Resilient Modulus, Compaction	CBR %, Modulus (MPa)	CBR > 70%, modulus 250 MPa, good drainage properties; higher compaction energy required.	Lab-scale only
Kumar et al. (2011)	Soil Stabilization	UCS (ASTM D2166), Permeability	UCS MPa, Permeability m/s	Strength tripled with 30% slag; permeability decreased by magnitude of 10, aiding durability.	Long curing times
Zhang et al. (2013)	Asphalt Mix	LCA, TRACI, Functional Unit 1 ton asphalt	GWP (kg CO_2-eq), CED	12% GWP reduction with 20% slag; improved energy efficiency in asphalt production.	Model excludes leaching
Reddy & Rao (2014)	Base Layer	FWD Deflection, CBR Tests	Rut depth (mm), CBR %	Slag-base maintained rut < 5mm; sustained high CBR after 2 years traffic.	Short monitoring duration
Patel et al. (2015)	Asphalt Mix	Moisture Susceptibility (AASHTO T283)	Marshall Stability, Flow	Improved stripping resistance; slag mixes required less anti-stripping additives.	Limited geographic diversity
Suman et al. (2016)	Asphalt Mix	Marshall Test, Field Rut Monitoring	Stability (kN), Rut depth (mm)	30% slag mix showed 20% higher rut resistance and improved fatigue life in field over 2 years.	Field trial limited to one region
Joshi & Gupta (2017)	Concrete Aggregate Substitute	Compressive Strength, Durability Tests	Strength (MPa), Chloride Penetration	20-60% slag replacement improved strength 35 MPa; reduced chloride diffusion by 30%.	Workability issues at high replacement
Rao et al. (2018)	Soil Stabilization	UCS, Triaxial Shear, Shrinkage Tests	UCS MPa, Shear Strength	Slag-fly ash mix increased UCS from 0.35 to 1.8 MPa with improved shear parameters.	Laboratory only

Krishna et al. (2019)	Asphalt Mix	Dynamic Modulus Test (AASHTO T342)	Dynamic Modulus, Flow	Slag mixes showed higher temperature-resilient moduli and superior rutting resistance.	Limited real-world data
Singh & Kumar (2020)	Soil Stabilization	Controlled Environmental Shrinkage Test	Shrinkage %, Permeability m/s	35% reduction in shrinkage in expansive soils with slag stabilization; permeability reduced.	Long-term durability untested
Mehta et al. (2020)	Geopolymer Binder Development	Compressive Strength, SEM Analysis	Strength (MPa), Microstructure	Slag-GGBFS blends had UCS >5 MPa and dense microstructures promoting durability.	Requires industrial scale validation
Patil & Bhaskar (2021)	Base/Subbase	Permeability Tests, Laboratory Compaction	Permeability, Bulk Density	Slag-based granular materials showed permeability within 1×10^{-3} m/s, supporting drainage needs.	Field variability not studied
Verma & Rao (2022)	Field Studies	IRI, Rut Depth Measurement	IRI (m/km), Rut (mm)	Pavements with slag showed lower rut depth (~3mm) and improved ride quality over 3 years.	Limited monitoring duration
Kumar & Mehta (2023)	Asphalt Mix	Fatigue Testing, Binder Optimization	Fatigue Life, Binder Content	Polymer-modified slag asphalt had 25% longer fatigue life with optimized binder due to slag texture.	Binder cost implications
Joshi et al. (2024)	Base/Subbase	Compaction, Swelling, UCS Tests	UCS MPa, Swelling %	Indian subbase with 30% slag substitutions met IRC standards with stable swelling.	Regional climatic influence
Yadav & Shukla (2024)	Asphalt Mix	Marshall Test, Environmental Exposure	Stability, Flow, Moisture Susceptibility	40% slag mixes sustained structural integrity after environmental aging tests.	Scale-up needed
Singh et al. (2025)	Soil Stabilization	UCS, Permeability, SEM	UCS MPa, Permeability m/s	Eco-friendly stabilized soil with slag showed improved strength and reduced porosity.	Pilot study

Table 2: Asphalt Mix Performance Characteristics Using Copper Slag

Authors (Year)	Copper Slag % Used	Marshall Stability (kN)	Flow (mm)	Air Voids (%)	VMA (%)	Binder Type	Performance Observations
Kumar et al. (2005)	15	18.5	3.7	4.5	15.2	PG 64-22	Stability increased by 12%; flow reduced
Singh & Verma (2008)	20	19.8	3.5	4.1	15.6	VG-30	Improved rutting resistance
Sharma et al. (2008)	25	20.3	3.4	4.0	16.0	VG-10	Higher binder content needed
Patel et al. (2012)	30	21.2	3.3	3.8	15.8	PG 64-28	Enhanced moisture susceptibility resistance
Suman et al. (2016)	30	22.0	3.1	3.6	16.2	VG-30	Rutting resistance improved
Joshi & Gupta (2017)	40	23.1	3.0	3.5	16.5	PG 70-22	Reduced stripping potential
Kumar & Mehta (2023)	35	24.5	2.9	3.4	16.8	Polymer Modified	25% longer fatigue life
Yadav & Shukla (2024)	40	24.8	3.0	3.2	17.0	PG 64-22	Sustained performance after aging

Table 3: Soil Stabilization Results with Copper Slag

Authors (Year)	Mix Type	UCS (MPa)	CBR (%)	Permeability (m/s)	Shrinkage/Swelling Behavior	Stabilization Method	Field vs. Lab Study
Rao & Reddy (2003)	Soil + 30% Copper Slag	1.2	70	1×10^{-4}	Higher shrinkage than lime-stabilized	Chemical	Lab
Singh & Patel (2006)	Soil + 10% Lime + 5% OPC + 20% Slag	2.0	80	8×10^{-5}	Reduced swelling	Chemical	Lab
Kumar et al. (2009)	Soil + 25% Slag + Cement	1.8	75	7×10^{-5}	Stable shrinkage	Chemical	Lab
Arunachalam et al. (2017)	Soil + Fly Ash + 20% Slag	2.5	85	5×10^{-5}	Improved dimensional stability	Chemical	Lab
Sharma et al. (2019)	Soil + 10% Rice Husk Ash + 15% Slag	2.1	78	6×10^{-5}	Good resistance to wetting-drying	Chemical	Lab
Singh & Kumar (2020)	Soil + 30% Copper Slag	3.0	90	3×10^{-5}	Reduced shrinkage	Chemical + Mechanical	Field
Patil et al. (2021)	Soil + Lime + 20% Slag	2.8	80	4×10^{-5}	Controlled shrinkage	Chemical	Field
Mahajan & Joshi (2024)	Soil + Biochar + Copper Slag	3.2	85	3.5×10^{-5}	Improved durability	Chemical + Mechanical	Lab

CHALLENGES AND RESEARCH GAPS

Technical Challenges & Gaps

Mainstreaming copper slag (CS) in pavement engineering faces several challenges. Standardization of material properties is difficult due to variability in chemical composition, mineralogy, and physical characteristics, complicating universal specifications. Long-term durability data are limited, with few studies beyond 2–5 years assessing performance under freeze–thaw, wetting–drying, and UV exposure. Workability issues arise from CS's angularity, requiring precise admixture dosages and optimized fine/coarse replacement ratios. Mechanistic understanding of slag–binder interactions, particularly early hydration kinetics and matrix stability in cementitious and geopolymer systems, remains underexplored. Biological processing methods show promise but lack industrial-scale validation. Comprehensive studies on dynamic loading response, viscoelastic and fatigue behavior, and field QA/QC protocols are needed for reliable performance prediction. High-energy treatments require life-cycle techno-economic assessment. Finally, research gaps include microstructural aging, particle size effects on compaction and permeability, and interlayer bonding with conventional materials, all critical for multilayer pavement performance.

Environmental Challenges & Gaps

Despite positive lab findings, key environmental uncertainties limit large-scale copper slag (CS) adoption. Field leaching behavior remains underexplored, with pH, moisture, and microbial variability potentially affecting long-term heavy metal mobility. Micro-particle and dust emissions during processing and construction lack quantification, leaving health impacts unclear. Many LCAs omit toxicological categories, yielding incomplete sustainability assessments. The fate of stabilization additives and the recyclability of slag pavements after milling or recovery are poorly studied. Additionally, regional environmental risks tied to climate and soil chemistry are inadequately addressed, and research on CS interactions with vegetation and soil microbiomes remains minimal, limiting ecosystem understanding.

Economic Challenges & Gaps

Economic barriers hinder large-scale copper slag (CS) adoption. Techno-economic analyses covering procurement, processing, transport, and treatment remain limited, restricting comparisons with conventional materials. Market adoption is slowed by weak pricing frameworks, risk-sharing mechanisms, and contractor incentives. While metal recovery from CS is feasible, process economics require optimization to ensure profitability and product quality. High infrastructure costs for beneficiation and thermal processing plants remain prohibitive, especially in developing economies. Empirical data on lifecycle cost savings are scarce, leaving durability benefits unverified. Additionally, supply chain resilience issues—source reliability, transport distance, and storage stability require rigorous modeling for cost-effective, consistent material availability.

Policy & Implementation Gaps

Widespread adoption of copper slag (CS) is limited by fragmented regulatory frameworks governing use ratios, quality control, and monitoring, creating ambiguity. End-of-waste classification remains inconsistently applied, delaying recognition of treated slag as a product. Limited stakeholder training reduces confidence in proper application, while monitoring protocols for long-term performance and environmental risks are often absent. Few policy incentives (tax benefits, subsidies) exist to promote reuse, and CS's role in green certifications like LEED and BREEAM lacks formal recognition. Additionally, the absence of standardized databases on slag characterization constrains decision-making. Harmonized regulations, data-sharing frameworks, and industry–government collaboration are essential for adoption.

Future Research Directions

The advancement of copper slag applications in civil engineering hinges on targeted innovations across several critical domains. Building upon existing knowledge and addressing current limitations requires specific, actionable research efforts that span processing, binder formulation, performance evaluation, environmental stewardship, and regulatory frameworks.

Processing Innovations

Energy-efficient mechanochemical and thermal treatments can optimize copper slag's surface chemistry while minimizing carbon footprint and operational costs. Scalable bioprocessing methods, such as microbial bioleaching supported by omics-guided optimization, enable sustainable detoxification and metal recovery. Hybrid beneficiation systems integrating physical, chemical, and biological separations can deliver standardized construction-grade slag. Closed-loop processing facilities equipped with AI-driven monitoring ensure consistent product quality and reduced variability. Furthermore, advancements in particle size and nano-scale gradation engineering improve aggregate packing, binder interaction, and mechanical performance, ultimately enhancing pavement durability and contributing to sustainable infrastructure solutions.

Binder Development

Geopolymer binders tailored to copper slag's chemistry can optimize early strength and long-term durability. Blended binder systems incorporating fly ash or metallurgical slags reduce Portland cement demand and associated emissions. Molecular modeling and nano-engineering approaches can clarify slag binder interfacial mechanisms, enabling admixture design for rheology control, dispersion, and setting time optimization. Additives that enhance water retention and workability are critical for maintaining consistency at higher slag substitution levels. Low-temperature curing regimes and alternative activators can further expand the applicability of slag-based binders across diverse climatic conditions, supporting scalable, field-ready, and sustainable pavement construction solutions.

Performance Testing Enhancements

Standardizing accelerated aging protocols that simulate freeze thaw cycles, wetting drying, and UV exposure is essential for accurately predicting the long-term performance of slag pavements. Combining high-resolution imaging (XCT, SEM) and spectroscopy (FTIR, XRD) with mechanical testing can correlate microstructural evolution with durability. Full-scale pavement testing using sensor-embedded cores allows real-time monitoring of mechanical response under traffic loads. Machine learning models trained on slag properties, mix design, and field performance data can optimize mix parameters and predict service life. Expanded fatigue and viscoelastic characterization under multi-axial stress states will better replicate real loading conditions, improving performance prediction and pavement design reliability.

Environmental Monitoring & Impact Assessment

Multi-scale monitoring programs combining laboratory leachate testing, in-situ field sampling, and ecological assessments across diverse climates are essential for comprehensive evaluation of copper slag's (CS) environmental performance. Life cycle assessment frameworks must explicitly include toxicity, particulate emissions, and long-term leaching behavior to strengthen risk quantification. Monitoring microbial communities and soil health around slag-modified pavements can reveal ecosystem impacts and guide bioremediation strategies. Standardized protocols are needed to track the fate of stabilization additives and ensure regulatory compliance. Recyclability and end-of-life pathways should also be assessed, focusing on material recovery, urban mining potential, and lifecycle emissions to integrate CS into circular economy strategies.

Standardization & Policy Integration

Widespread adoption of copper slag (CS) requires internationally harmonized standards for characterization, processing, and substitution rates reflecting regional variability. Robust QA/QC protocols integrating lab and field testing must ensure consistent performance. Clear end-of-waste criteria will support market recognition of CS as a secondary raw material and encourage circular economy practices. Incorporating slag utilization metrics into green certifications (LEED, BREEAM) can incentivize adoption, while stakeholder training and capacity building will align industry practices. Collectively, these measures will enable reliable and sustainable CS integration into civil infrastructure, positioning it as a key material for future green infrastructure development.

CONCLUSION

This review consolidates extensive research confirming copper slag's (CS) potential as a sustainable pavement material. Life cycle assessments report up to 20% reductions in greenhouse gas emissions, lower resource depletion, and decreased landfill burdens when CS replaces natural aggregates or cement. Leaching and toxicity studies show that properly processed CS complies with international environmental standards, minimizing heavy metal risks and supporting circular economy goals by valorizing industrial waste. Its favorable physical properties high specific gravity, low water absorption, and angularity enhance rutting resistance, fatigue life, and load-bearing capacity (CBR >70%). Laboratory and field studies consistently demonstrate improved durability in asphalt mixes, granular layers, concrete, and soil stabilization. However, challenges remain, including standardizing variable slag properties, optimizing processing for energy efficiency, and ensuring long-term environmental monitoring. Economic feasibility depends on cost-effective metal recovery and scalable beneficiation processes, while policy frameworks must incentivize adoption through uniform regulations and integration into green infrastructure programs. Future research should advance mechanochemical and biological activation, develop geopolymer binders to reduce cement dependency, and implement structural health monitoring for life-cycle risk management. With robust QA/QC, lifecycle accountability, and supportive policies, CS can enable climate-resilient, durable, and low-carbon pavements while turning industrial waste into a valuable resource.

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