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Comparative Analysis of Sustainable Materials in Road Construction: A Review

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Abstract

The immediate need for sustainable infrastructure has driven research into new materials in road construction to reduce environmental degradation and enhance resource efficiency. This review is a comparative analysis of four innovative technologies involving industrial and natural waste products: recycled aggregates from construction and demolition (C&D) waste, feldspar powder from lithium mining, stabilized dam sediments using eucalyptus ash, and calcium carbide residue (CCR) blended with dredged sludge. All the materials are assessed for their mechanical performance, environmental sustainability, economic viability, and ease of implementation. The findings show that the materials from wastes not only minimize natural resource dependence but also improve mechanical performance, including unconfined compressive strength and California Bearing Ratio, and qualify as potential substitutes for pavement subbase and subgrade layers. The recycled aggregates provide structural stability and economies through thinning of pavement and pressure reduction on the landfill. Feldspar-lateritic clay composites and CCR-stabilized sludge have better strength and durability, whereas dam sediment with eucalyptus ash has exceptional pozzolanic activity, leading to densification and sustainability. From an environmental perspective, the technologies yield lower greenhouse gas emissions, efficient waste disposal, and circular economy compliance. Economically, the use of locally sourced waste saves on material purchasing and construction costs, leading to improved project feasibility. Notwithstanding these benefits, other challenges like variability in quality, absence of standardized guidelines, public mistrust, and regulatory restrictions remain. But developments in stabilization of materials, life cycle assessments technologies, and intelligent monitoring technologies offer potential solutions. The study underscores the transformative potential of integrating sustainable materials in road construction, advocating for field-scale research, optimized blends, and policy support to mainstream green practices in civil infrastructure. This aligns with global sustainability goals and paves the way for resilient, eco-friendly transportation networks.

Keywords: Sustainable Road construction, recycled aggregates, feldspar powder, dam sediment, calcium carbide residue, circular economy, eco-friendly infrastructure

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INTRODUCTION

The construction industry consumes one of the largest shares of natural resources and contributes significantly to global environmental degradation. Road construction, in particular, utilizes natural aggregates, bitumen, and energy-intensive methods, contributing to the depletion of these natural resources, the emission of greenhouse gases, and waste generation. With the acceleration of urbanization and the formation of infrastructure, the demand for sustainable practices has become

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increasingly important. This is one of the most pressing issues regarding the shortage of natural resources, along with increased costs for extraction and transportation. Traditional road construction practices have adverse environmental impacts, which mainly include habitat destruction, air and water pollution, and waste disposal. Thus, it is imperative to innovatively consider road construction. The use of industrial and natural by-products as substitutes for conventional materials opens a dual window of opportunity: resolving waste management bottlenecks and shrinking the environmental footprint of construction operations [1].

In this review of roofing, four green road construction methods use waste substitutes in their standard ingredients. Construction and demolition (C&D) waste, recycled aggregates, and feldspar powder obtained from lithium extraction, dam sediments stabilized with eucalyptus ash, and calcium carbide residue (CCR) with dredged sludge are promising green materials without sacrificing performance. This study balances the feasibility, efficacy, and implications of such methods for a holistic perspective on environmentally friendly approaches to infrastructure development. Thus, by considering these cutting-edge methods, this review provides insights into how the road construction industry can potentially transform and make it more supportive of global sustainability objectives [2].

MATERIAL AND WASTE SOURCES

Recycled Aggregates

Recycled aggregates, obtained from C&D waste products such as concrete, masonry, and rubble, can be used as virgin aggregate substitutes in pavement base courses. This helps minimize the use of natural aggregates, save resources, and decrease landfill pressure. Evaluations of the performance of recycled aggregates, in this case concrete, masonry, and rubble, under climatic conditions have demonstrated suitability for flexible pavement structures using the American Association of State Highway and Transportation Officials (AASHTO) Pavement Design software [3].

Feldspar Powder and Lateritic Clay

Feldspar powder was combined with lateritic clay and stabilized with ordinary Portland cement. This study uses such composite material to address the growing accumulation of feldspar waste in lithium production areas and provides an environmentally friendly alternative for subbase and subgrade applications. This study identified the optimal proportions of materials and highlighted the mechanical advantages of this mix [4].

Dam Sediments and Eucalyptus Ash

Dam sediments are produced through the process of sedimentation, forming deposits in reservoirs, and are solidified with eucalyptus wood ash (EA) and cement. This was applied to further expand the case of biomass waste reuse to sustainable solutions for the disposal of sediments, unlike previous methods that only dealt with land disposal. It follows the ideals of a circular economy, wherein waste streams are integrated into activities that minimize environmental pollution caused by construction [5].

Calcium Carbide Residue and Dredged Sludge

Calcium carbide residue is a byproduct of acetylene manufacturing, which, when combined with dredged sludge, cement, and gypsum, yields improved subgrade materials. This process addresses the dual issues of sludge disposal and CCR waste management: a resource-efficient alternative for road construction. Laboratory and field evaluations verified the effectiveness of this blend in improving the mechanical properties and environmental sustainability [6].

MECHANICAL PERFORMANCE

Recycled Aggregates

These materials possess excellent mechanical stability and require a smaller pavement base layer thickness than virgin aggregates, while exhibiting similar performance behavior. Studies have found reduced rutting and improved fatigue resistance, making these materials suitable for various climatic conditions.

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Feldspar-Lateritic Clay Composite

The composite achieved an unconfined compressive strength (UCS) of 1.6 MPa and a California Bearing Ratio (CBR) of 164.1%, exceeding the requirements for medium-traffic subbases. Compact particle arrangement and cement hydration products contribute to enhanced mechanical performance.

Dam Sediment with EA

The stabilized dam sediments demonstrated a UCS improvement of 770%, with a peak CBR value of 55%, surpassing the subbase material standards. The pozzolanic properties of EA significantly enhance interparticle bonding and sediment densification.

CCR-Stabilized Sludge

The UCS of CCR-stabilized sludge reached 215.4 kPa, meeting the secondary road subgrade requirements. This blend also reduces the moisture content to 32%, thereby improving stability and long-term performance [7].

ENVIRONMENTAL IMPACTS

Recycled Aggregates

The adoption of recycled aggregates reduced CO_2 emissions by 22–65% compared to those of virgin aggregates. This reduction highlights their role in mitigating the environmental impact of aggregate mining and production.

Feldspar Powder Utilization

By repurposing feldspar powder, this approach mitigates the waste accumulation from lithium extraction processes and reduces the environmental footprint of road construction.

Dam Sediments with EA

The combination of dam sediments and biomass ash minimizes reliance on virgin materials, reduces landfill use, and promotes sustainable waste management.

CCR with Dredged Sludge

CCR-based stabilization addresses sludge disposal challenges while reducing reliance on natural materials and enhancing sustainability through waste valorization [8].

COST EFFICIENCY

Recycled Aggregates

Significant cost savings were achieved through reduced material extraction and thinner pavement layers when using recycled aggregates derived from C&D waste. These aggregates, which include reclaimed concrete, bricks, and masonry, serve as effective substitutes for natural aggregates in pavement bases and subbase layers. Their recyclability not only reduces the need for virgin materials and hence raw material purchase costs, but also significantly lowers the environmental and economic costs of landfill disposal. Moreover, because of their good compaction properties and mechanical stability, recycled aggregates tend to have reduced pavement structure thickness to provide comparable or better performance than traditional materials. This translates into additional savings in transportation, labor, and equipment costs.

Feldspar Powder

Using feldspar powder for road building presents a cost-effective and eco-friendly alternative through the reuse of a readily available industrial byproduct produced from lithium extraction operations. This technology presents the double benefits of mitigating waste generation and increasing material procurement expenses. When combined with lateritic clay and stabilized with ordinary Portland cement, feldspar powder is a composite material with improved mechanical properties that is applicable for use in subbase and subgrade layers. The use of this waste product not only minimizes the demand for virgin

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earth and other traditional materials but also lowers the cost of mining, processing, and shipping typical aggregates [9].

Dam Sediments with EA

The application of Eucalyptus ash-stabilized dam sediments showed a significant 6.6-fold decrease in construction expenses, highlighting the large economic potential for the utilization of natural waste materials. Such sediments, normally stored in reservoirs and usually considered to be disposal issues, are efficiently converted into useful construction materials using stabilization with EA, a byproduct biomass. This novel combination not only enhanced the material's mechanical strength to be acceptable for use as a subbase but also negated the use of expensive virgin aggregates and elaborate waste management methods [10].

CCR-Stabilized Sludge

Using CCR blended with dredged sludge and reducing the use of traditional cement, this process presents a cost-efficient and environmentally friendly approach to road subgrade construction. CCR itself is a byproduct of acetylene gas production and would otherwise be regarded as an industrial waste with disposal issues. However, when properly mixed with dredged sludge and trace amounts of cement and gypsum, the mechanical durability and stability of the final product were greatly enhanced. This lowers reliance on expensive cement, resulting in cost savings in material purchases.

CHALLENGES AND INNOVATIONS

Challenges

Material Consistency

Standardizing the quality and consistency of recycled materials is a significant hurdle. Variability in source materials, processing methods, and regional differences complicate their adoption at the scale.

Durability and Longevity

Long-term durability under varying climatic and traffic conditions requires a comprehensive investigation. To better document the freeze-thaw cycles, moisture susceptibility, and other mechanical wear factors need to be studied further.

Public Perception and Acceptance

The acceptance of alternative materials must be strengthened in the public and industry. Misconceptions regarding the reliability and safety of recycled materials can hinder their widespread adoption.

Regulatory and Policy Barriers

The unavailability of a standardized set of guidelines and supporting regulations could indeed act as a major barrier to the adoption of these new materials in mainstream construction practices [11].

Innovations

Circular Economy Integration

Modifying the waste management sector according to circular economy principles shifts waste materials to valuable resources and enhances sustainable material loops.

Advanced Stabilization Techniques

The development of mechanical properties for alternative materials is significantly higher than that of pozzolanic materials and chemical binders. Notable improvements can be observed by mixing biomass ash with cement or by activating industrial waste products with chemicals.

Comprehensive Life Cycle Assessments

Life cycle assessments have provided more detailed insight into the environmental and economic implications of using these materials to help concerned parties make informed decisions.

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Smart Materials and Monitoring

New and emerging technologies, such as intelligent materials embedded with sensors, enable real-time monitoring of road performance, provide early warnings of problems, and improve maintenance strategies.

Localized Solutions

Encouragement to resort to, where possible, waste materials that are regionally available creates an alternative that incurs lower transportation costs and carbon emissions and provides context-specific solutions for inadequacies present in the region [12].

CONCLUSION

The methods discussed highlight the revolutionary potential regarding the application of industrial and natural waste materials for road construction. All these techniques have enormous environmental, economic, and mechanical advantages that promise sustainable infrastructure development. Such promising approaches include recycled aggregates, feldspar powder composites, stabilized dam sediments, and CCR-based blends, which promise traditional material alternatives and can be used in global sustainable development initiatives. Future research should focus on field-scale applications, optimization of material blends, and the development of standard guidelines for fast and wide adoption. Sustainability can bring relief to most environmental burdens while meeting the challenges of resource scarcity and waste management in industry.

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