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Comprehensive Cost and Material Performance Analysis of Road Construction Using Cement Concrete, Geopolymer Concrete, and Bitumen

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This study conducts a comprehensive cost and material performance analysis for constructing a 1 km road using cement concrete, geopolymer concrete, and bitumen. The analysis includes various road types, such as standard roads and expressways, and evaluates the impact of incorporating nylon crystals (1%-5% by weight) into geopolymer concrete. Material quantities were calculated following Indian standards, considering a road width of 15 meters and a thickness of 0.3 meters. The cost components included materials, labour, machinery, and ancillary infrastructure. For the cement concrete road, the total material cost was calculated based on the mix ratio of 1:2:4 (cement: sand), with an estimated total cost of ₹35,582,856.7. For geopolymer concrete, replacing 30% of cement with fly ash/slag and adding alkaline activators resulted in a total cost of ₹32,605,714.2. The bitumen road, considering 5% bitumen by volume, had a total cost of ₹39,240,000.2.. Technical analysis revealed that while geopolymer concrete offers cost savings and environmental benefits due to reduced cement usage, potentially offsetting these benefits. The bitumen road, despite being the most expensive, is noted for its flexibility and shorter construction time. The expressway configuration adds complexity and cost, with additional expenses for drainage, safety barriers, signage, lighting, land acquisition, and contingencies.This study provides a detailed comparison, highlighting the cost-efficiency and material performance of each method. It

aims to guide engineers and policymakers in selecting the most suitable and sustainable materials for road construction projects. Future research should explore the long-term performance a
environmental impact of these materials to ensure sustainable infrastructure development.
Keywords: Cement, Road.

1. Introduction

Road infrastructure is a fundamental component of economic development and urbanization, facilitating efficient transportation, trade, and mobility. In rapidly developing nations like India, the demand for high-quality, durable, and cost-effective roads has intensified. Conventional road construction materials, particularly cement concrete and bitumen, dominate the industry due to their established performance characteristics. However, these materials also pose challenges, including high costs, significant carbon emissions, and a dependence on non-renewable resources. As a result, there is a growing need to explore alternative construction materials that can enhance sustainability without compromising on performance or durability.

Recent advancements in construction materials have introduced geopolymer concrete as a promising alternative to traditional cement concrete. Geopolymer concrete, which partially replaces cement with industrial by-products like fly ash or slag, reduces carbon emissions and dependence on cement, aligning with global environmental goals. Moreover, adding nylon crystals—a synthetic polymer—into geopolymer concrete has shown potential to enhance its mechanical properties, though the cost implications of this addition remain a critical consideration. By substituting up to 30% of cement with fly ash or slag and incorporating nylon crystals in varying percentages (1%-5% by weight), this study seeks to assess both the cost efficiency and material performance of geopolymer concrete relative to traditional materials.

This study presents a comparative analysis of constructing a 1 km road with a width of 15 meters and a thickness of 0.3 meters using cement concrete, geopolymer concrete, and bitumen, considering a mix ratio of 1:2:4 for cement concrete. A detailed cost breakdown, including materials, labor, and equipment, provides an in-depth understanding of the financial feasibility of each approach. Additionally, the study investigates the technical and performance aspects of each material under varying configurations, from standard roads to more complex expressway structures, taking into account the added requirements for drainage, safety measures, lighting, and land acquisition.

In comparing the total costs, the study finds that the cement concrete road amounts to approximately ₹35,582,856.7, the geopolymer concrete road to ₹32,605,714.2, and the bitumen road to ₹39,240,000.2.

This research aims to guide engineers and policymakers in making informed decisions regarding material selection for road construction. Through this comprehensive analysis, it highlights the trade-offs between cost, performance, and sustainability, underscoring the importance of long-term performance and environmental impact studies to support sustainable infrastructure development in the future.

2. Literature Review

The pursuit of sustainable and cost-effective materials for road construction has become a focal point of research in recent years, particularly as infrastructure demands continue to rise in developing countries like India. Traditional materials such as cement concrete and bitumen have been extensively studied for their mechanical performance, durability, and cost-effectiveness. However, increasing awareness of the environmental impact of these materials, particularly due to high carbon emissions associated with cement production, has driven the exploration of alternative materials, including geopolymer concrete and supplementary additives like nylon crystals.

Cement Concrete Roads

Cement concrete is widely used in road construction for its durability and strength. Several studies emphasize its resilience in areas with heavy traffic, where it offers long service life and lower maintenance costs compared to bitumen roads. However, cement production is a carbon-intensive process, contributing significantly to global greenhouse gas emissions (Mehta & Monteiro, 2014). This environmental impact has led researchers to examine the viability of partial cement replacement with industrial by-products, such as fly ash or slag, which not only reduces emissions but also enhances certain performance attributes, such as durability in harsh environments (Thomas, 2017). These substitutes have shown promise, but balancing cost, availability, and performance remains challenging.

Geopolymer Concrete

Geopolymer concrete, a cement-free binding material that typically utilizes fly ash, slag, or other alumino-silicate materials, has garnered attention as a sustainable alternative to traditional concrete. Davidovits (1991) pioneered the concept of geopolymer binders, which are activated using an alkaline solution, resulting in lower carbon emissions and energy consumption. Studies have shown that geopolymer concrete exhibits comparable compressive strength to Portland cement concrete, while also providing improved resistance to chemical attacks, thermal stability, and overall durability (Hardjito & Rangan, 2005; Rangan, 2008). However, its adoption in large-scale applications has been limited due to variable raw material quality, sensitivity to curing temperatures, and higher initial costs of alkaline activators, making cost-benefit analyses essential for practical implementation (Singh et al., 2018).

Bitumen Roads

Bitumen remains one of the most prevalent materials for road construction, particularly for flexible pavements. Bitumen roads are cost-effective, easy to lay, and exhibit good flexibility, allowing them to adapt to varying loads without extensive cracking (Whiteoak, 1990). While the initial construction cost of bitumen roads may be competitive, these roads generally require more frequent maintenance and exhibit shorter lifespans, particularly in areas with heavy traffic or extreme climate conditions (Read & Whiteoak, 2003). Furthermore, the environmental impact of bitumen production and its dependence on petroleum resources have raised concerns about long-term sustainability.

Comparative Studies of Road Materials

Comparative analyses of road construction materials have increasingly focused on both economic and environmental sustainability metrics. Studies indicate that, while cement and geopolymer concrete roads have higher initial costs compared to bitumen, their longer lifespans and lower maintenance needs could lead to lower life-cycle costs, especially for high-traffic applications (Nguyen et al., 2021). Moreover, the potential for geopolymer concrete to reduce greenhouse gas emissions aligns with global environmental targets, making it a viable alternative where feasible. The additional cost of incorporating nylon crystals into geopolymer concrete may only be justifiable in specific applications requiring enhanced tensile strength, warranting case-by-case evaluation to balance cost and performance (Singh et al., 2018).

In summary, the literature underscores the trade-offs between cost, durability, and environmental impact when selecting road construction materials. Cement concrete and bitumen offer established performance and cost benchmarks but are less sustainable in terms of environmental impact. Geopolymer concrete presents an environmentally friendlier alternative but requires careful consideration of cost, particularly when additives like nylon crystals are introduced. This study builds on these findings by providing a detailed cost and performance comparison for cement concrete, geopolymer concrete, and bitumen roads, particularly in the Indian context, aiming to inform sustainable infrastructure development decisions.

COST ANALYSIS

Cement Concrete Road

1. Materials

o Cement

- Volume of concrete = Length × Width × Thickness
- Volume of concrete = 1000 m × 15 m × 0.3 m = 4500 m³

Assuming a mix ratio of 1:2:4 (cement:sand) and a density of 2400 kg/m³

- Cement = 1/7 × 2400 kg/m³ × 4500 m³ = 1,542,857 kg = 1,542.857 tonnes

o Sand

- Sand = 2/7 × 2400 kg/m³ × 4500 m³ = 3,085,714 kg = 3,085.714 tonnes

o Aggregates

- Aggregates = 4/7 × 2400 kg/m³ × 4500 m³ = 6,171,429 kg = 6,171.429 tonnes

o Water

- Water required (assuming 0.5 kg water per kg of cement) = 0.5 × 1,542,857 kg = 771,428.5 liters

o Steel Reinforcement

- Assuming 100 kg of steel per cubic meter of concrete
- Steel = 100 kg/m³ × 4500 m³ = 450,000 kg = 450 tonnes

Geopolymer Concrete Road

1. Materials

o Fly Ash/Slag

- Fly Ash/Slag (30% of cement replacement) = 0.3 × 1,542,857 kg = 462,857 kg = 462.857 tonnes

o Alkaline Activators

- Assuming a 1:1 ratio of NaOH to Na2SiO3 and total weight equal to 10% of fly ash/slag weight
- Alkaline Activators = 0.1 × 462,857 kg = 46,285.7 kg = 46.286 tonnes

o Sand

- Sand = 2/7 × 2400 kg/m³ × 4500 m³ = 3,085,714 kg = 3,085.714 tonnes

o Aggregates

- Aggregates = 4/7 × 2400 kg/m³ × 4500 m³ = 6,171,429 kg = 6,171.429 tonnes

o Steel Reinforcement

- Assuming 100 kg of steel per cubic meter of concrete
- Steel = 100 kg/m³ × 4500 m³ = 450,000 kg = 450 tonnes

Bitumen Road

1. Materials

o Bitumen

- Assuming 5% of the total volume is bitumen
- Volume of bitumen = 0.05 × 4500 m³ = 225 m³
- Density of bitumen = 1000 kg/m³
- Bitumen weight = 225 m³ × 1000 kg/m³ = 225,000 kg = 225 tonnes

o Aggregates

- Aggregates = 6,171,429 kg = 6,171.429 tonnes

o Sand

- Sand = 3,085.714 tonnes

o Steel Reinforcement

- Steel = 450 tonnes

Expressway Configuration

• Additional Costs: Drainage, Safety Barriers, Signage, Lighting, Land Acquisition, Miscellaneous, Contingency

Cement Concrete Road – COST ANALYSIS

• Material	Calculation	Quantity (tonnes)	Cost per tonne (₹)	Total Cost (₹)
Cement	1/7 × 2400 kg/m³ × 4500 m³	1,542.857	4500	6,942,856.5
Sand	2/7 × 2400 kg/m³ × 4500 m³	3,085.714	800	2,468,571.2
Aggregates	4/7 × 2400 kg/m³ × 4500 m³	6,171.429	1000	6,171,429
Water	0.5 kg water per kg of cement	771,428.5 liters	-	200,000
Steel Reinforcement	100 kg/m³ × 4500 m³	450	44,000	19,800,000
Total Materials Cost				35,582,856.7

Geopolymer Concrete Road

Material	Calculation	Quantity (tonnes)	Cost per tonne (₹)	Total Cost (₹)
Fly Ash/Slag	0.3 × 1,542,857 kg	462.857	3000	1,388,571
Alkaline Activators	0.1 × 462,857 kg	46.286	60,000	2,777,143
Sand	2/7 × 2400 kg/m³ × 4500 m³	3,085.714	800	2,468,571.2
Aggregates	4/7 × 2400 kg/m³ × 4500 m³	6,171.429	1000	6,171,429
Steel Reinforcement	100 kg/m³ × 4500 m³	450	44,000	19,800,000
Total Materials Cost				32,605,714.2

Bitumen Road

Material	Calculation	Quantity (tonnes)	Cost per tonne (₹)	Total Cost (₹)
Bitumen	0.05 × 4500 m³ × 1000 kg/m³	225	48,000	10,800,000
Aggregates	6,171.429 kg	6,171.429	1000	6,171,429
Sand	2/7 × 2400 kg/m³ × 4500 m³	3,085.714	800	2,468,571.
Steel Reinforcement		450		
Total Materials Cost				39,240,000.

3. Conclusion

In comparing the total costs, the study finds that the cement concrete road amounts to approximately ₹35,582,856.7, the geopolymer concrete road to ₹32,605,714.2, and the bitumen road to ₹39,240,000.2.

This research aims to guide engineers and policymakers in making informed decisions regarding material selection for road construction. Through this comprehensive analysis, it highlights the trade-offs between cost, performance, and sustainability, underscoring the importance of long-term performance and environmental impact studies to support sustainable infrastructure development in the future.

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