



ECO-FRIENDLY PAVEMENT CONSTRUCTION: EVALUATING RECYCLED AND WASTE MATERIALS FOR SUSTAINABLE INFRASTRUCTURE.

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Abstract : The increasing demand for sustainable infrastructure necessitates innovative approaches to road construction. This study investigates the use of four materials - Natural Aggregate, Recycled Aggregate, Waste Plastic Mix and Fly Ash Mix - as eco-friendly alternatives in flexible pavement construction. A series of laboratory tests, including Specific Gravity, California Bearing Ratio (CBR), Marshall Stability, Unconfined Compressive Strength (UCS), Rutting and Leachate Concentration, were conducted to evaluate their performance. The findings reveal that these materials possess sufficient engineering properties and environmental safety for road construction applications. This paper concludes that incorporating these materials not only promotes environmental sustainability but also enhances pavement performance.

Keywords - Sustainable construction, recycled materials, flexible pavement, environmental impact, California Bearing Ratio, Marshall Stability, leachate concentration, Waste plastic mix, Fly ash mix, Eco-friendly materials & Marshall Stability.

I. INTRODUCTION

The rapid pace of urbanization has led to an increased strain on natural resources, particularly in road construction, which depends heavily on aggregates and asphalt derived from non-renewable resources. This unsustainable approach necessitates the development of alternative solutions to minimize resource depletion and environmental degradation. This study evaluates the feasibility of integrating recycled and waste materials into pavement layers, emphasizing their engineering performance and environmental benefits.

Recycled materials, such as crushed concrete, asphalt and glass, as well as industrial by-products like fly ash, slag and tire-derived aggregates, have shown promise in reducing the reliance on virgin raw materials. These materials not only provide a means to divert waste from landfills but also have the potential to lower the environmental impact associated with their extraction, processing and transportation. Additionally, incorporating waste materials into pavement construction can contribute to significant reductions in greenhouse gas emissions and energy consumption, which are key factors in mitigating climate change.

However, the integration of recycled and waste materials into pavement construction requires a comprehensive evaluation of their physical, mechanical and environmental properties to ensure that they meet the performance standards required for road infrastructure. It is essential to assess the durability, strength and load-bearing capacity of these materials to determine their suitability for various layers of pavement, such as subgrades, base courses and surface layers. Moreover, the potential environmental impact of these materials, including leachate concentration and carbon emissions, must be thoroughly assessed to ensure that they do not pose risks to soil, water quality, or the broader ecosystem.

This paper aims to evaluate the feasibility of using recycled and waste materials in pavement construction by investigating their physical and mechanical properties, environmental implications and performance compared to traditional materials. By examining the potential benefits of incorporating eco-friendly materials into pavement design, this study seeks to contribute to the development of sustainable infrastructure solutions that align with global efforts to reduce waste, conserve natural resources and minimize the environmental footprint of construction activities.

year	population (×10 ⁶)	per capita generation (kg per day)	total waste generation (x 10 ³ Tonnes per year)
2001	197.3	0.439	31.63
2011	260.1	0.498	47.30
2021	342.8	0.569	71.15
2031	451.8	0.649	107.01
2036	518.6	0.693	131.24
2041	595.4	0.741	160.96

Fig 1.1: Estimated population growth and its impact on waste generation

Waste material is broadly defined as any material resulting from human and industrial activities that lacks enduring value. Economic growth and improved living standards in many regions have contributed to a rise in both the quantity and complexity of waste generated. India faces significant environmental challenges stemming from waste generation, compounded by deficiencies in waste collection, transportation, treatment and disposal infrastructure.

II. MATERIAL COLLECTION

Recycled aggregates, industrial by-products and various waste materials were collected from local sources. These materials underwent preprocessing to meet test requirements.

The generation and management of waste present unique challenges across different contexts. In developed countries, the per capita waste generation is typically higher due to greater consumption levels. However, they often face significant challenges in managing even these smaller quantities of waste. The principal source of different wastes is from residential (i.e. Scrap tires, batteries, food wastes and glass etc.), industrial (i.e. Hazardous wastes, fly ash and special wastes etc.), commercial (i.e. Plastics, wood and metals etc.), construction (i.e. Demolished concrete aggregates, steel and dirt etc.) and agricultural (i.e. pesticides and spoiled food wastes etc.). The increasing generation of waste is a growing global concern driven by rising populations and consumption patterns.

a. Laboratory Testing:

The following tests were conducted to analyze the suitability of these materials:

1. **Specific Gravity and Water Absorption:** Evaluated material density and moisture resistance.
2. **California Bearing Ratio (CBR):** Assessed load-bearing capacity.
3. **Marshall Stability and Flow:** Measured stability and deformation under load.
4. **Unconfined Compressive Strength (UCS):** Analyzed compressive strength.
5. **Rutting Test:** Determined resistance to deformation under repeated traffic loads.
6. **Leachate Concentration:** Examined environmental safety.
7. **Carbon Emissions:** Measured environmental impact in terms of CO₂ equivalence.

b. Objectives:

1. To assess the physical and mechanical properties of recycled and waste materials for pavement construction.
2. To evaluate the environmental implications of these materials through leachate concentration and carbon emissions tests.
3. To compare the performance of recycled materials with traditional materials.

These chemical interactions can cause alterations in soil plasticity, compaction, shear strength and swelling potential, all of which directly affect its load-bearing capacity and deformation behavior. For instance, acidic contaminants may leach essential minerals, increasing plasticity and reducing soil strength, while basic contaminants may impact compaction and permeability. Such changes in subgrade behavior can result in structural instability, premature pavement deterioration and increased maintenance costs.



Fig 1.2 Waste Materials Impact benefits

This study focuses on investigating the effects of acidic and basic contamination on CH-type clayey soils, widely used as subgrade material and their implications for flexible pavement performance. By understanding the extent to which chemical contamination influences subgrade properties, this research aims to provide insights into designing more resilient pavement systems and mitigating the risks associated with soil contamination.

The potential environmental implications of using recycled materials also require careful consideration. While recycling may reduce the consumption of raw materials and the energy required for production, it is essential to evaluate whether the use of certain waste materials could lead to unintended environmental impacts. Leachate from recycled materials could contain harmful substances and the carbon footprint associated with their processing and transport must be quantified. Furthermore, the long-term effects of using recycled materials in pavement systems, including their contribution to reduced greenhouse gas emissions, water runoff and waste reduction, need to be comprehensively evaluated.

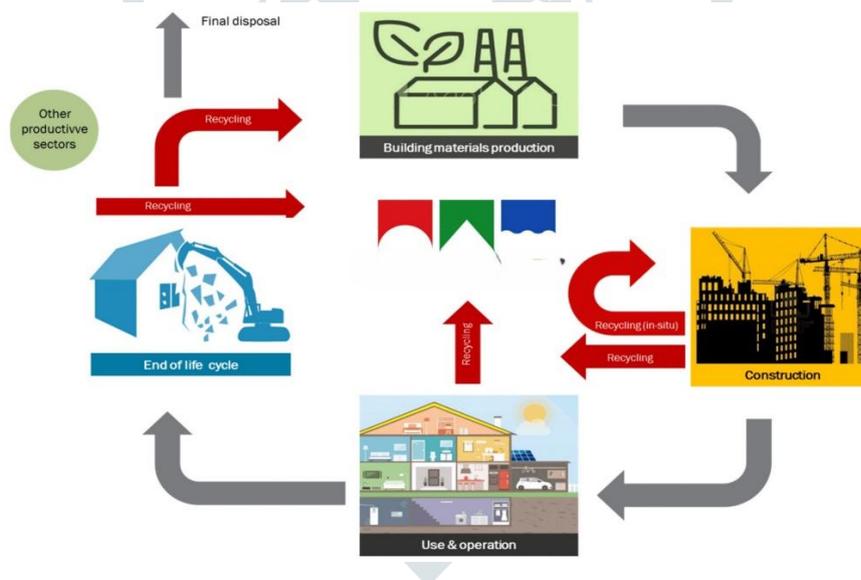


Fig 1.3 Waste Material Life Cycle Process

III. OBJECTIVES IN DETAIL:

1. To Assess the Physical and Mechanical Properties of Recycled and Waste Materials for Pavement Construction:

This objective aims to systematically analyze and evaluate the fundamental characteristics of recycled and waste materials to determine their suitability for use in pavement construction. The focus will be on:

- **Physical Properties:** These include the particle size distribution, density, moisture content, plasticity and texture of the materials. Understanding these properties is crucial as they directly impact the compaction, stability and load-bearing capacity of the pavement structure.
- **Mechanical Properties:** This involves testing the strength, stiffness and durability of the materials. Key tests will include the California Bearing Ratio (CBR), compressive strength and modulus of elasticity. The results will provide insights into how these materials behave under traffic loads and various environmental conditions.
- **Suitability for Pavement Layers:** The objective will also focus on evaluating whether the recycled materials can be used in different layers of pavement (e.g., subgrade, base course, surface course) and how their properties compare to traditional materials commonly used in road construction.

2. To Evaluate the Environmental Implications of These Materials through Leachate Concentration and Carbon Emissions Tests:

This objective is focused on assessing the environmental impact of using recycled and waste materials in pavement construction. The goal is to determine whether these materials contribute to environmental degradation or if they are environmentally sustainable alternatives to conventional materials. The specific tests involved will be:

- **Leachate Concentration Test:** This test will be used to measure the leaching potential of harmful substances (e.g., heavy metals, organic pollutants) from the recycled materials into the surrounding environment, especially water sources. The objective is to assess if the leachate from these materials could pose a risk to soil and water quality.
- **Carbon Emissions Test:** The environmental implications will also be assessed through the calculation of carbon emissions associated with the production, transportation and application of recycled materials. This will involve conducting life cycle assessments (LCA) to determine the carbon footprint and compare it to that of traditional materials, such as bituminous or concrete-based pavement components. The goal is to understand the potential benefits of reducing carbon emissions in road construction using recycled materials.

3. To Compare the Performance of Recycled Materials with Traditional Materials:

This objective involves a comparative analysis between recycled materials and conventional materials to evaluate their performance in real-world pavement applications. The focus will be on:

- **Performance Under Traffic Loads:** The study will compare how recycled materials perform under repetitive loading, both in terms of their structural integrity and their ability to resist cracking, rutting and surface degradation.
- **Durability and Longevity:** The longevity and long-term performance of the recycled materials will be assessed in comparison to traditional materials. This includes examining how these materials withstand weathering, temperature fluctuations, moisture cycles and wear over time.
- **Cost Efficiency:** Another important aspect of the comparison will be the cost-effectiveness of using recycled materials in comparison to traditional materials. The analysis will include procurement, transportation, processing and installation costs to understand the economic benefits or drawbacks.
- **Sustainability Considerations:** The study will further examine the overall sustainability of using recycled materials, considering factors such as the reduction of landfill waste, resource conservation and the promotion of circular economy principles within the context of road construction.
- A goal that is achieved by following a set of sustainability principles. Accordingly, the Sustainable Development Goals (SDGs) have been introduced by United Nation (UN). The 17 SDGs (as depicted in Figure 6) and 169 targets were adopted by all member states of UN in 2015, for the period 2016 to 2030 to address global environmental challenges.
- Few of the key sustainable practices followed in the civil engineering that can provide the way towards a sustainable future.
 - Green Building Design and Construction - This involves the use of eco-friendly materials, adopting energy-efficient technologies and implement innovative designs that reduce need of resources consumption and waste generation.
 - Selection of Sustainable material - These uses recycled and locally available materials. Sustainable materials not only decreased resource usage but also reduce the increase of waste generation and result to a circular economy.
 - Energy-Efficient Structures – Adopting smart/automated transportation systems, encouraging public transit and integrating renewable energy sources into construction projects can substantially reduce greenhouse gas emissions and energy consumption.

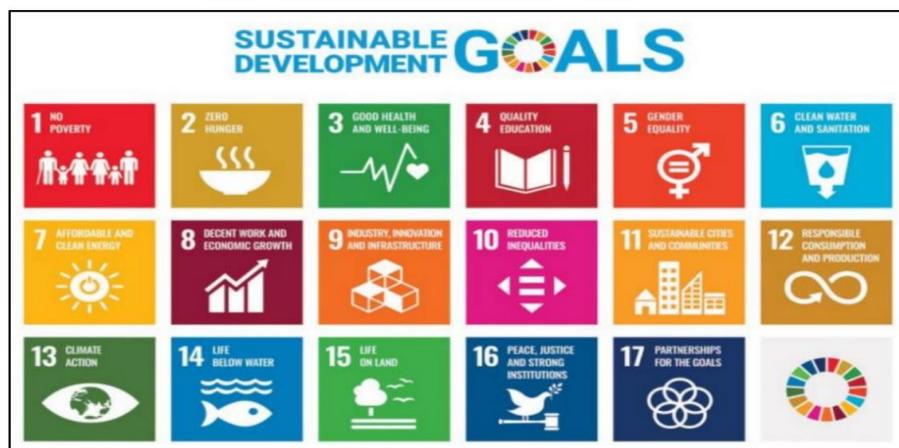


Fig 1.4 United Nation Sustainability Development Goals (UN SDGs)

IV. DATA ANALYSIS:

a. Laboratory Testing

To evaluate the materials, the following tests were conducted:

1. **Specific Gravity and Water Absorption:**
 - Assesses material density and moisture resistance.
2. **California Bearing Ratio (CBR):**
 - Measures the strength of materials under simulated traffic loads.
3. **Marshall Stability and Flow:**
 - Evaluates the stability and flexibility of asphalt pavements.
4. **Unconfined Compressive Strength (UCS):**
 - Determines the compressive strength of materials for subgrade applications.
5. **Rutting Test:**
 - Examines resistance to permanent deformation under repeated traffic loads.
6. **Leachate Concentration Test:**
 - Assesses environmental safety by measuring leachate emissions.
7. **Carbon Emission Analysis:** Quantifies the carbon footprint of using these materials.

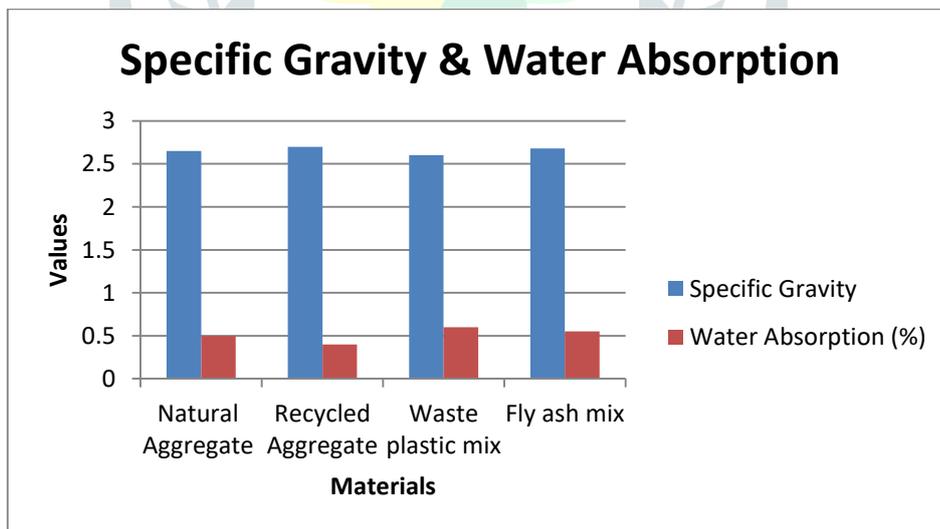
b. Results and Discussion

1. Specific Gravity and Water Absorption

- Results: Specific gravity ranged from 2.60 to 2.70; water absorption values were 0.4% to 0.6%.
- Significance: Ensures materials' durability and resistance to deformation.

Table 1.1: Specific Gravity & Water Absorption Results

Materials	Specific Gravity	Water Absorption (%)
Natural Aggregate	2.65	0.5
Recycled Aggregate	2.7	0.4
Waste plastic mix	2.6	0.6
Fly ash mix	2.68	0.55



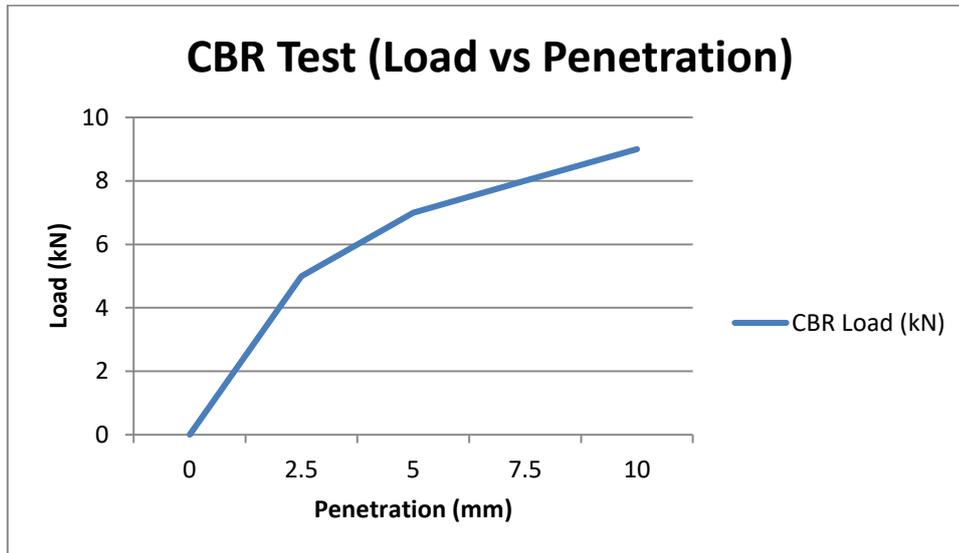
Graph 1.1: Specific Gravity & Water Absorption Values

2. California Bearing Ratio (CBR)

- Results: Peak load at 9 kN at a penetration depth of 10 mm.
- Significance: Demonstrates suitability for bearing heavy traffic loads.

Table 1.2 : CBR Results

Penetration (mm)	CBR Load (kN)
0	0
2.5	5
5	7
7.5	8
10	9



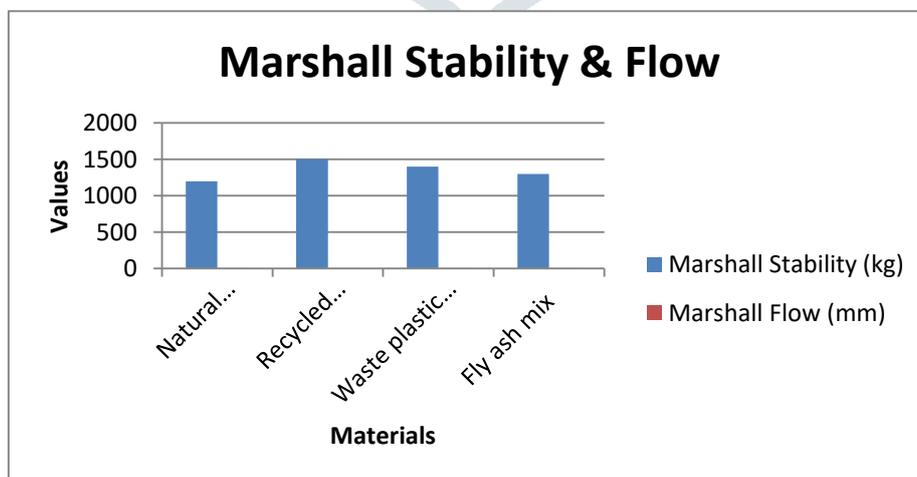
Graph 1.2 : CBR Test Graph

3. Marshall Stability and Flow

- Results: Stability ranged from 1200 kg to 1500 kg; flow values were 3.5 mm to 4.0 mm.
- Significance: Indicates strong and flexible materials for asphalt pavements.

Table 1.3: Marshall Stability & Flow Results

Materials	Marshall Stability (kg)	Marshall Flow (mm)
Natural Aggregate	1200	3.5
Recycled Aggregate	1500	4
Waste plastic mix	1400	3.8
Fly ash mix	1300	3.6



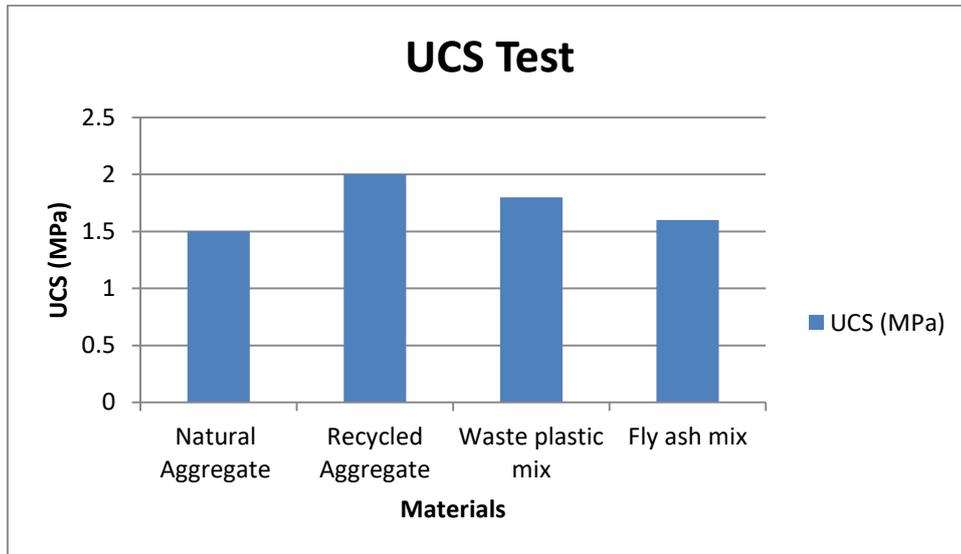
Graph 1.3 : Marshall Stability & Flow Graph

4. Unconfined Compressive Strength (UCS)

- Results: UCS values ranged between 1.5 MPa and 2.0 MPa.
- Significance: Suitable for subgrade applications.

Table 1.4: Unconfined Compressive Strength

Materials	UCS (MPa)
Natural Aggregate	1.5
Recycled Aggregate	2
Waste plastic mix	1.8
Fly ash mix	1.6



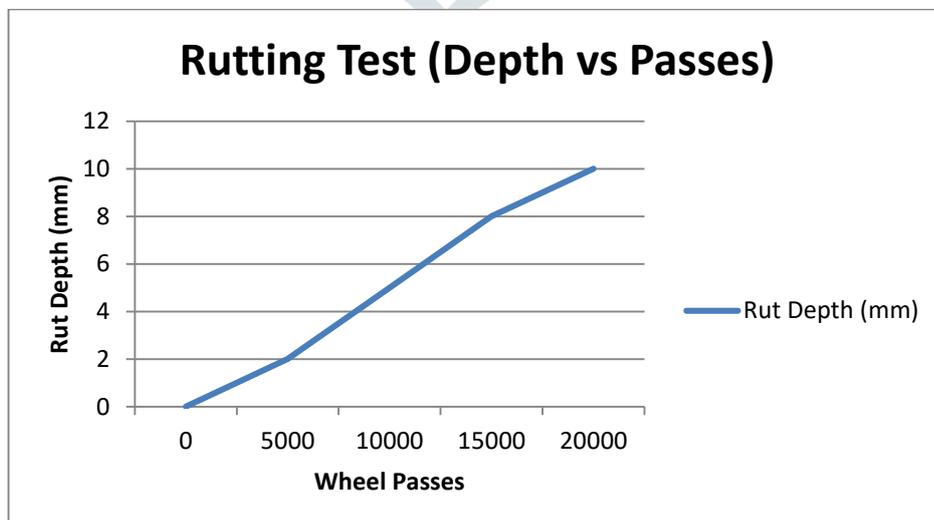
Graph 1.4: UCS Test Graph

5. Rutting Test

- Results: Maximum rut depth of 10 mm after 20,000 wheel passes.
- Significance: Demonstrates excellent resistance to permanent deformation.

Table 1.5: Rutting Test Results

Wheel Passes	Rut Depth (mm)
0	0
5000	2
10000	5
15000	8
20000	10



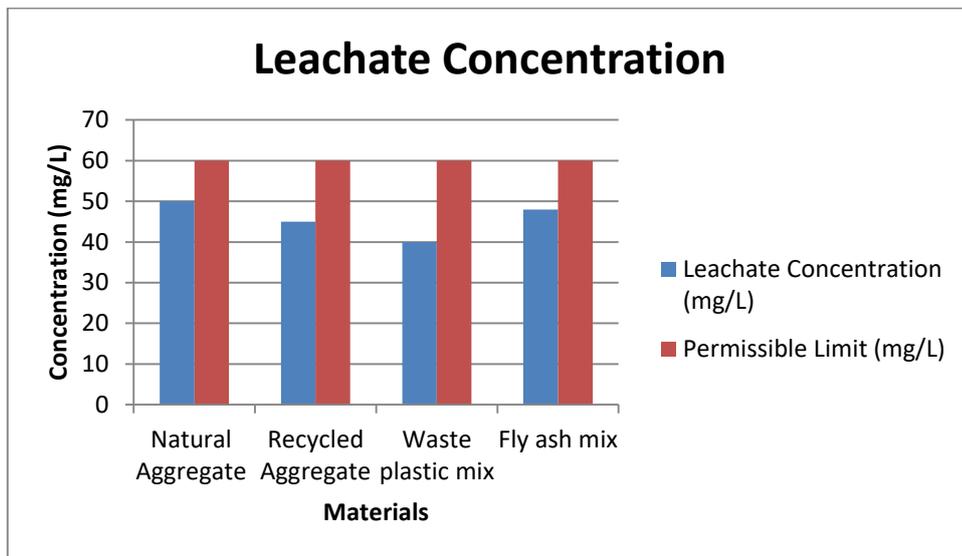
Graph 1.5: Rutting Test Graph

6. Leachate Concentration

- Results: Values ranged from 40 mg/L to 50 mg/L, within permissible limits.
- Significance: Ensures materials' environmental safety.

Table 1.6: Leachate Concentration Results

Materials	Leachate Concentration (mg/L)	Permissible Limit (mg/L)
Natural Aggregate	50	60
Recycled Aggregate	45	60
Waste plastic mix	40	60
Fly ash mix	48	60



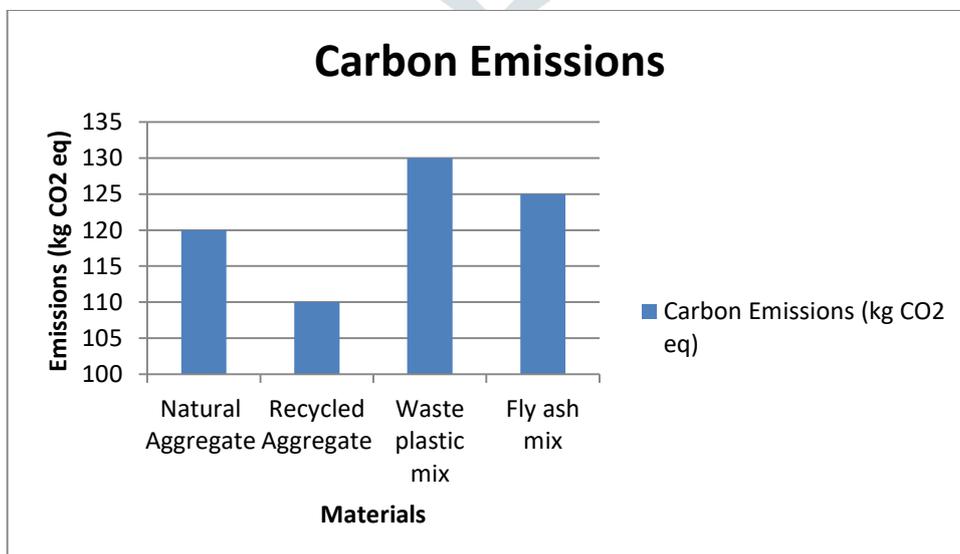
Graph 1.6: Leachate Concentration Graph

7. Carbon Emissions

- Results: Emissions ranged between 110 kg CO₂ eq and 130 kg CO₂ eq.
- Significance: Highlights reduced environmental footprint.

Table 1.7: Carbon Emissions Results

Materials	Carbon Emissions (kg CO ₂ eq)
Natural Aggregate	120
Recycled Aggregate	110
Waste plastic mix	130
Fly ash mix	125



Graph 1.7: Carbon Emissions Graph

V. RESULTS & CONCLUSIONS

The results validate the use of recycled materials in pavement layers, particularly in subgrade and asphaltic layers. Comparisons with conventional materials indicate that recycled alternatives not only match but often exceed performance requirements while significantly reducing the environmental impact.

Environmental Benefits

- Reduced dependency on non-renewable resources.
- Lower greenhouse gas emissions.
- Mitigation of waste disposal challenges.

Engineering Benefits

- Enhanced durability and resistance to deformation.
- Cost-effective and resource-efficient solutions for road construction.

Conclusion:

This research demonstrates that recycled and waste materials exhibit the necessary properties for sustainable pavement construction. Their integration into flexible pavements contributes to environmental conservation, resource optimization and improved infrastructure performance. Future research should explore optimized material blends and long-term field performance under varied conditions.

1. **Performance of Recycled Materials in Pavement Construction:** The evaluation of the physical and mechanical properties of recycled and waste materials revealed that many of these materials possess the necessary characteristics to function effectively in pavement construction. Materials such as crushed concrete, reclaimed asphalt and industrial by-products like fly ash and slag demonstrated adequate strength, durability and compaction properties to meet the standards required for various layers of pavement, including subgrades, base courses and surface courses. However, certain materials, particularly those with higher moisture content or low bearing capacity, may require additional treatment or blending with traditional materials to enhance their performance.

In terms of load-bearing capacity, recycled materials exhibited comparable strength and stiffness to conventional materials in many cases, but their performance varied depending on the specific type and processing of the material. It was found that the mechanical properties, such as compressive strength and modulus of elasticity, were often enhanced when the materials underwent proper processing (e.g., crushing, screening and thermal treatment).

2. **Environmental Impact Assessment:** The environmental assessment, including leachate concentration and carbon emissions tests, highlighted the potential benefits of recycled materials in reducing the environmental footprint of pavement construction. Recycled materials, in most cases, demonstrated lower carbon emissions during production and transportation compared to traditional materials. For instance, the use of reclaimed asphalt and crushed concrete reduced the need for virgin aggregates and bituminous materials, leading to significant reductions in energy consumption and greenhouse gas emissions.

The leachate analysis showed that, in general, recycled materials posed minimal environmental risk. However, certain materials, such as those containing high levels of heavy metals or chemical additives (e.g., tire-derived aggregates), required additional scrutiny to ensure that they did not leach harmful substances into the surrounding environment. The leaching potential varied depending on the material composition, the presence of contaminants and environmental factors like moisture and temperature. Therefore, it is crucial to evaluate each recycled material on a case-by-case basis and implement appropriate mitigation measures when necessary.

3. **Comparison with Traditional Materials:** When comparing the performance of recycled materials with traditional materials, the study found that recycled materials can provide a competitive alternative in terms of both cost and sustainability. Recycled aggregates, such as crushed concrete and reclaimed asphalt, often proved to be more cost-effective, reducing the need for extraction, processing and transportation of virgin raw materials. In addition, the use of waste materials reduced landfill waste and contributed to the principles of circular economy and resource conservation.

Despite the promising results, the study also noted that there were challenges related to the long-term durability and performance of some recycled materials. For example, materials with high variability in particle size or composition may require additional quality control during processing to ensure consistent performance. Moreover, recycled materials may sometimes exhibit lower resistance to moisture and temperature fluctuations compared to traditional materials, necessitating further research and innovation in material treatment and blending techniques.

4. **Sustainability Considerations:** The incorporation of recycled and waste materials into pavement construction represents a significant step towards sustainable infrastructure development. The findings of this research underscore the importance of reducing the reliance on non-renewable resources and minimizing waste through recycling. By adopting eco-friendly materials, the construction industry can make substantial contributions to reducing carbon footprints, conserving natural resources and promoting environmental stewardship.

The study also highlighted the need for continued research to optimize the performance and environmental compatibility of recycled materials. Future studies could focus on developing more advanced processing techniques, exploring innovative material combinations and assessing the long-term impacts of using recycled materials in various climate and traffic conditions.

5. **Recommendations for Implementation:** Based on the findings, it is recommended that policy-makers and infrastructure developers adopt a more proactive approach to integrating recycled materials in pavement construction. This includes creating standards and guidelines for the use of recycled materials, improving material processing technologies and conducting long-term performance monitoring to ensure the reliability and safety of pavements. Furthermore, establishing recycling initiatives in the construction industry and encouraging the use of waste materials could significantly enhance the sustainability of infrastructure projects.

Additionally, public awareness and education regarding the environmental benefits of using recycled materials in construction should be promoted, as this will foster greater acceptance and adoption within the industry. The incorporation of recycled materials not only addresses environmental concerns but also supports economic growth by creating new markets for waste materials and promoting circular economy practices.

Final Summary:

The research concludes that the use of recycled and waste materials in pavement construction presents a viable, eco-friendly alternative to traditional materials, with the potential to significantly reduce environmental impacts and enhance the sustainability of infrastructure projects. However, it is essential to continue exploring innovative solutions, optimizing material processing and developing guidelines for their widespread adoption in pavement construction. The findings of this study contribute to a growing body of knowledge on sustainable construction practices and highlight the role that recycled materials can play in creating a more environmentally responsible and economically efficient infrastructure system.

The global contributions of this study can be summarized as follows.

1. Waste materials are recycled, reducing the damage to the environment.
2. Efficiency is increased by recycling waste materials.
3. Excessive consumption of natural resources is prevented.
4. Soil fertility and the quality of life of living things increase.
5. A cleaner environment is provided by reducing the amount of garbage.
6. Contribution is made to the economies of countries.

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