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Design aspect of flexible pavement and Quality Control Management

Babasaheb B. Labhade [1], Ms. Apeksha Choudhary [2]

[1] Research Scholar, Civil Engineering Department, G H Raisoni University, Amravati, Maharashtra, India
[2] Assistant Professor, Civil Engineering Department, G H Raisoni University, Amravati, Maharashtra, India

Corresponding Author-
Name: Babasaheb B. Labhade
E-Mail Id: babasaheblabhade@gmail.com

Abstract- The present study focuses on the design aspect of flexible pavement and quality control management, incorporating an experimental investigation on the use of natural fibers and waste materials in all layers of flexible pavement, including subgrade, sub-base, base course, and bituminous surface. Natural fibers such as coir fiber, jute fiber, and bamboo fiber were used due to their eco-friendly nature and ability to improve tensile strength and reduce cracking. Waste materials such as fly ash, plastic waste, crumb rubber, and C&D waste were used as partial replacements or additives in different pavement layers. The experimental program involved various laboratory tests such as California Bearing Ratio (CBR) test for subgrade soil, Proctor compaction test, aggregate impact and crushing tests, and Marshall Stability test for bituminous mixes. Different mixes were prepared by varying the percentage of fibers and waste materials to determine the optimum combination. The results showed that the addition of fly ash and coir fiber significantly improved the CBR value of subgrade soil, indicating better load-bearing capacity. Similarly, the use of C&D waste and natural fibers in sub-base and base layers improved aggregate strength and resistance to impact. In bituminous layers, the addition of plastic waste and rubber enhanced Marshall Stability and flexibility, resulting in improved resistance to rutting and cracking. Based on the improved material properties, flexible pavement design was carried out as per Indian Roads Congress guidelines, and it was observed that the thickness of pavement layers can be reduced without compromising strength and performance.

Keywords: Flexible Pavement, Quality Control, CBR Method, Sustainable Materials, Pavement Design, RAP, Waste Plastic, Lifecycle Assessment

I. INTRODUCTION

Transportation is one of the most important factors for the overall development of any country. It plays a key role in economic growth, social connectivity, industrial development, and improvement of living standards. Among all modes of transportation, road transport is the most widely used system in India due to its flexibility, accessibility, and ability to connect even remote areas. Highways and road networks are considered as the backbone of a nation's infrastructure, and their proper design and maintenance are essential for smooth and safe movement of people and goods. Flexible pavement is the most commonly used type of pavement in highway construction due to its cost-effectiveness, ease of construction, and simple maintenance procedures. It consists of multiple layers such as subgrade, sub-base, base course, and bituminous surface, which together help in distributing the traffic load safely to the underlying soil. Unlike rigid pavement, flexible pavement can adjust slightly under load without cracking, which makes it suitable for varying traffic and environmental conditions. However, in recent years, the performance of conventional flexible pavements has been affected due to several challenges such as rapid increase in traffic volume, heavy axle loads, poor drainage conditions, and improper construction practices. These factors lead to common pavement failures such as cracking, rutting, potholes, and surface deformation, which ultimately reduce the service life of roads and increase maintenance costs.

At the same time, there is a growing concern regarding environmental sustainability and resource conservation. Large quantities of waste materials such as plastic waste, fly ash, rubber waste, and construction and demolition (C&D) waste are being generated every year, creating serious environmental and disposal problems. These waste materials, if not properly managed, can lead to pollution of land, water, and air. In this context, the use of waste materials in road construction has emerged as an effective and sustainable solution. These materials can be utilized in different layers of flexible pavement, thereby reducing the dependency on natural resources and minimizing environmental impact. In addition to waste materials, natural fibers such as coir, jute, and bamboo have gained attention due to their eco-friendly nature and ability to improve the mechanical properties of soil and pavement materials. These fibers act as reinforcement and help in improving tensile strength, reducing cracking, and enhancing overall durability. The present study focuses on the design aspect of flexible pavement along with quality control management, incorporating the use of natural fibers and waste materials in all layers of pavement. The study aims to evaluate how these materials influence the engineering properties of pavement layers and how they can be effectively used to improve performance.

II. METHODOLOGY

STUDY AREA: The study is based on highway conditions similar to the Kondhali–Talegaon section of NH-53, where traffic load and environmental conditions are considered for pavement design.

MATERIALS USED:
The materials used in this study are divided into conventional materials, natural fibers, and waste materials.
Conventional Materials:

- Soil (Subgrade)
- Aggregates (Sub-base and Base)
- Bitumen (Surface Layer)

Natural Fibers:

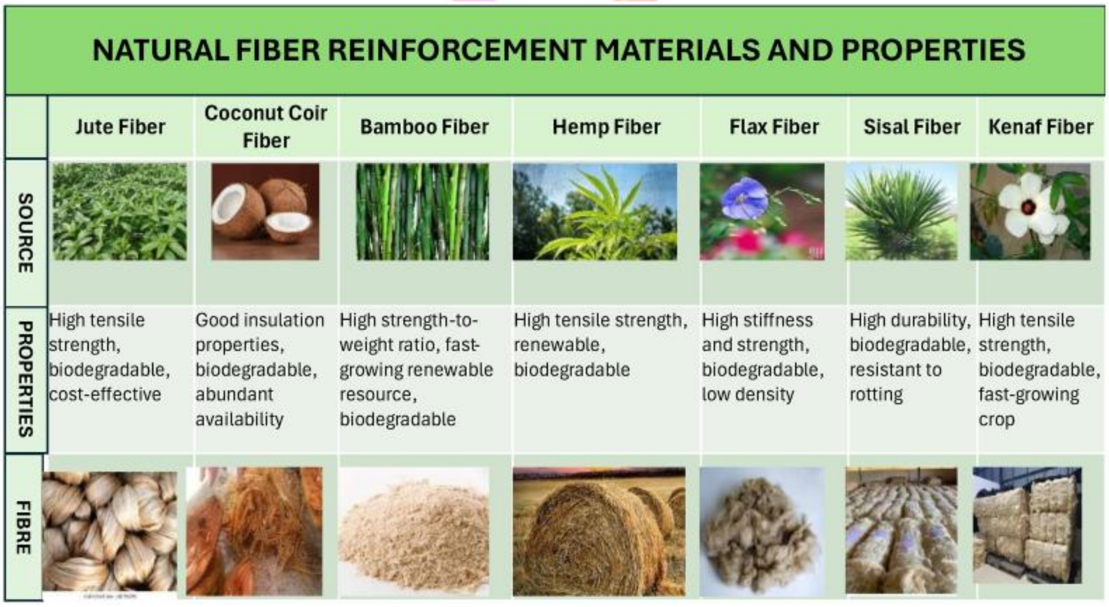

Fig. 3.2: Natural Fibers Used

1. Coir Fiber
2. Jute Fiber
3. Bamboo Fiber

Waste Materials:

Fig. 3.3: Waste Materials Used

1. Plastic Waste
2. Fly Ash
3. Rubber (Crumb Rubber)
4. C&D Waste

LAYER-WISE MATERIAL UTILIZATION:

In the present study, a systematic approach has been adopted for the utilization of natural fibers and waste materials in different layers of flexible pavement. Each layer of the pavement structure performs a specific function, and therefore, suitable materials are selected and incorporated based on their engineering properties and performance requirements. The objective of this layer-wise material utilization is to enhance the strength, durability, and overall performance of the pavement while promoting sustainable construction practices. In the subgrade layer, which acts as the foundation of the pavement, natural soil is modified by adding fly ash and coir fiber. Fly ash improves the soil properties through pozzolanic reaction, resulting in increased strength and reduced plasticity. Coir fiber, being a natural reinforcing material, enhances the tensile strength of soil and helps in reducing shrinkage and swelling behavior. This combination leads to an increase in the California Bearing Ratio (CBR) value of the subgrade, thereby improving its load-bearing capacity and stability. In the sub-base layer, aggregates are partially replaced with construction and demolition (C&D) waste, along with the addition of jute fiber. The use of C&D waste helps in conserving natural aggregates and provides an economical alternative material. Jute fiber improves the bonding between particles and reduces deformation under load. This modified sub-base layer shows better load distribution characteristics and improved drainage properties, which are essential for the long-term performance of pavement. In the base course, which is the main structural layer responsible for carrying heavy traffic loads, aggregates are combined with fly ash and bamboo fiber. Fly ash acts as a filler material and enhances the binding properties of aggregates, while bamboo fiber increases stiffness and resistance to deformation. This results in a stronger and more stable base layer with improved load-carrying capacity and resistance to fatigue failure. In the bituminous surface layer, bitumen is modified by adding plastic waste and crumb rubber. Plastic waste improves the binding properties of bitumen and increases resistance to water penetration, while rubber enhances flexibility and reduces cracking due to temperature variations. The modified bituminous mix exhibits higher Marshall Stability and better performance under traffic loads, resulting in improved durability and reduced maintenance requirements. Thus, the layer-wise utilization of natural fibers and waste materials ensures that each layer of the flexible pavement contributes effectively to the overall strength and performance of the pavement system. This approach not only improves engineering properties but also provides an eco-friendly and cost-effective solution for modern highway construction.

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Subgrade Layer
- Soil + Fly ash + Coir fiber
- Purpose: Improve CBR and reduce swelling

Sub-base Layer
- Aggregates + C&D waste + Jute fiber
- Purpose: Improve load distribution and drainage

Base Course
- Aggregates + Fly ash + Bamboo fiber
- Purpose: Increase strength and stiffness

Bituminous Surface
- Bitumen + Plastic waste + Rubber
- Purpose: Improve flexibility and durability

III. RESULTS AND DISCUSSION

SUBGRADE SOIL RESULTS (CBR TEST):

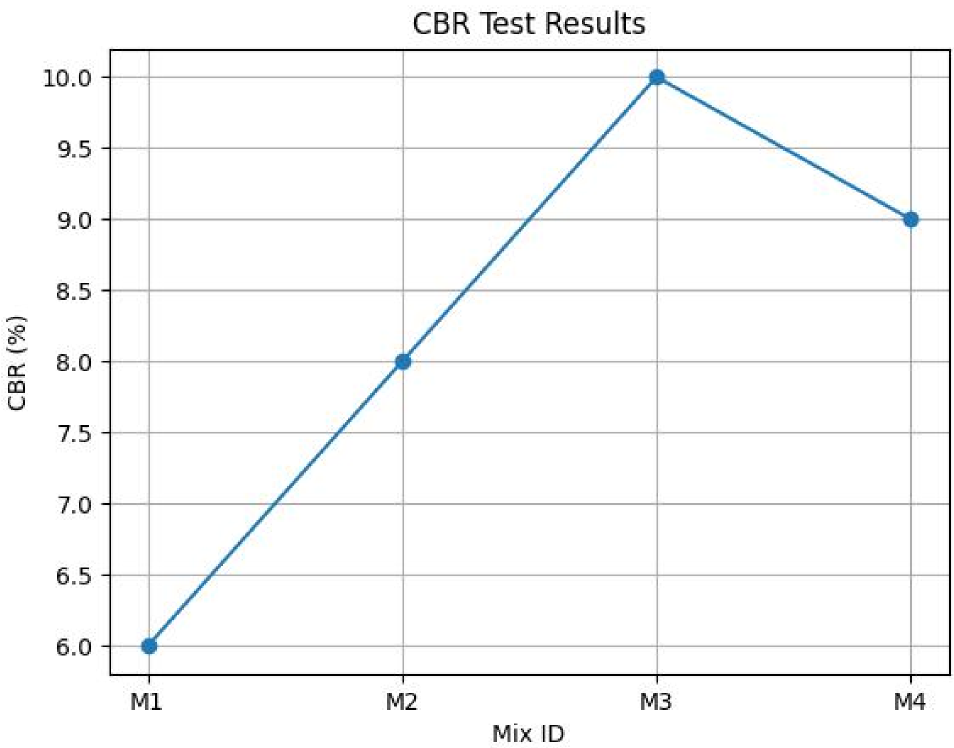
The California Bearing Ratio (CBR) test is one of the most important laboratory tests used in pavement design to evaluate the strength and load-bearing capacity of subgrade soil. In the present study, the CBR test was conducted on both conventional soil and modified soil by incorporating fly ash and coir fiber in different proportions. The objective of this test is to analyze how the addition of waste material (fly ash) and natural fiber (coir fiber) influences the engineering properties of subgrade soil.

The subgrade layer plays a critical role in supporting the entire pavement structure, and therefore, improving its strength directly contributes to enhanced pavement performance. Modified soil samples were prepared carefully by mixing the required percentage of fly ash and coir fiber uniformly with soil, and then tested under standard conditions.

CBR Test Results:

Table 4.1: CBR Test Results

Mix ID	Fly Ash (%)	Coir Fiber (%)	CBR (%)
M1	0	0	6
M2	5	0.5	8
M3	10	1.0	10
M4	15	1.5	9



Graph 4.1: Variation of CBR Value with Waste Material

Observations:

- The CBR value of subgrade soil increases significantly with the addition of fly ash and coir fiber.
- The conventional soil (M1) shows a CBR value of 6%, which is relatively low.
- With the addition of 5% fly ash and 0.5% coir fiber (M2), the CBR increases to 8%, indicating improvement in soil strength.
- Maximum CBR value of 10% is obtained for mix M3 (10% fly ash + 1% coir fiber), which indicates optimum performance.
- Further increase in fly ash and fiber content (M4) results in a slight decrease in CBR value to 9%, due to poor bonding and excess material content.

Discussion:

The improvement in CBR value is mainly due to the pozzolanic reaction of fly ash, which forms cementitious compounds that enhance soil strength. Coir fiber acts as a reinforcing material that increases tensile strength and reduces cracking. The combined effect results in improved load-bearing capacity. However, excessive addition leads to non-uniform mixing and reduced bonding, which decreases strength. Hence, an optimum proportion is necessary.

SUB-BASE AND BASE COURSE RESULTS:

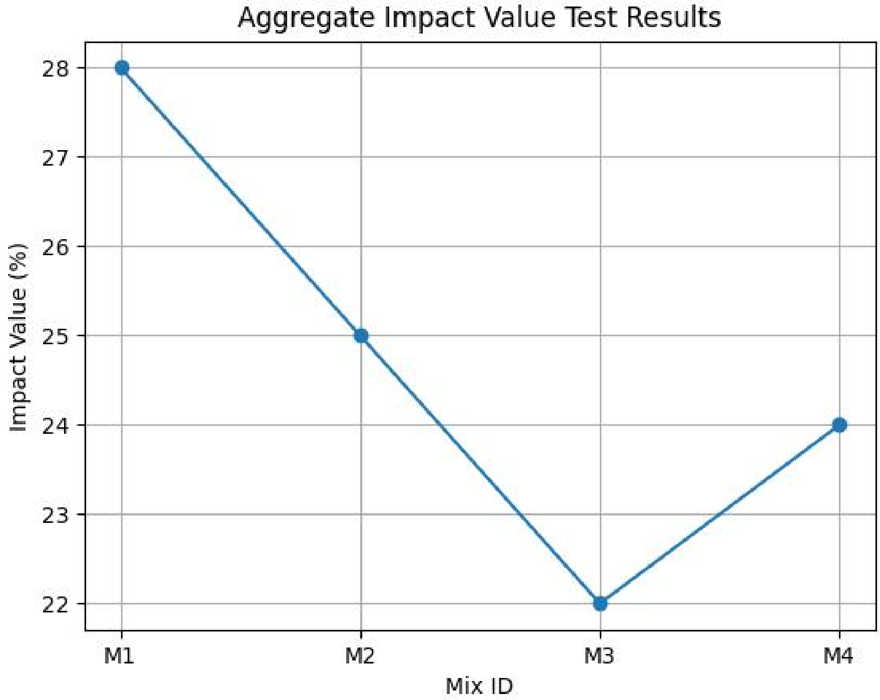
The sub-base and base layers are responsible for distributing loads and providing structural support. In this study, aggregates were partially replaced with C&D waste, and natural fibers were added to improve performance.

Aggregate Impact Value Test:

Table 4.2: Aggregate Impact Value Test Results

Mix ID	C&D Waste (%)	Fiber (%)	Impact Value (%)
M1	0	0	28
M2	5	0.5	25

M3	10	1.0	22
M4	15	1.5	24



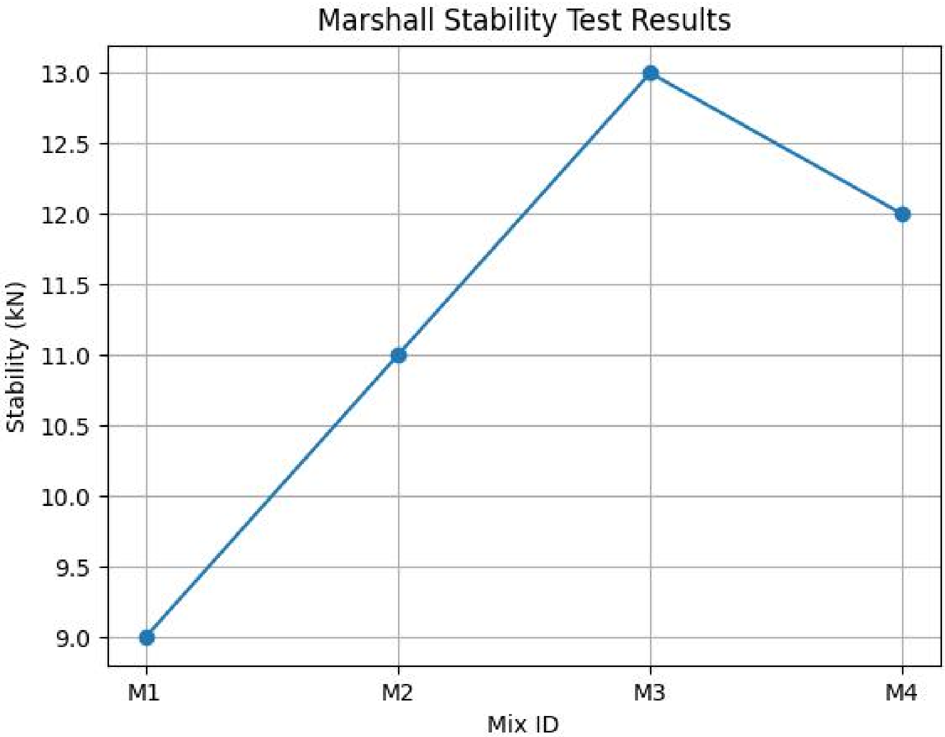
Graph 4.2: Impact Value Variation

BITUMINOUS MIX RESULTS (MARSHALL STABILITY):
Marshall Stability test is conducted to evaluate the strength and performance of bituminous mixes.

Marshall Stability Results:

Table 4.3: Marshall Stability Test Results

Mix ID	Plastic (%)	Rubber (%)	Stability (kN)
M1	0	0	9
M2	5	2	11
M3	10	4	13
M4	15	6	12



Graph 4.3: Marshall Stability Variation

DENSITY AND COMPACTION RESULTS:

Compaction characteristics of soil and pavement materials play a very important role in determining the strength, stability, and durability of flexible pavement. Proper compaction ensures that the pavement layers achieve maximum density, which helps in reducing voids, increasing load-bearing capacity, and improving resistance to deformation under traffic loads. In the present study, compaction tests were conducted to evaluate the effect of natural fibers and waste materials on the compaction properties of soil.

The Standard Proctor Compaction Test was performed on both conventional soil and modified soil samples to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). The modified soil samples were prepared by incorporating fly ash and coir fiber in suitable proportions, and their compaction characteristics were compared with those of natural soil.

Results:

Table 4.4: Compaction Test Results

Mix	OMC (%)	MDD (g/cc)
M1	12	1.85
M3	10	1.92

COMPARATIVE ANALYSIS:

Strength Comparison:

Table 4.5: Strength Comparison

Parameter	Conventional	Modified
CBR	6%	10%
Impact Value	28%	22%
Stability	9 kN	13 kN

Cost Comparison:

Table 4.6: Cost Comparison

Parameter	Conventional	Modified
Material Cost	High	Reduced
Maintenance Cost	High	Low

PAVEMENT DESIGN RESULTS:

The pavement design results are one of the most important outcomes of this study, as they reflect the practical applicability of using natural fibers and waste materials in flexible pavement construction. Based on the improved engineering properties obtained from laboratory tests such as CBR, Aggregate Impact Value, and Marshall Stability, the pavement thickness was designed and compared with conventional pavement design.

The design of flexible pavement was carried out using the guidelines of the Indian Roads Congress (IRC:37), considering parameters such as traffic load, subgrade strength (CBR value), and material properties. Two sets of pavement designs were prepared: one for conventional materials and the other for modified materials incorporating natural fibers and waste materials.

The results indicate that due to the improvement in strength characteristics of subgrade, sub-base, base, and bituminous layers, it is possible to reduce the thickness of certain pavement layers without affecting the overall performance and durability of the pavement.

Pavement Thickness:

Table 4.7: Pavement Thickness Comparison

Layer	Conventional	Modified
Bituminous Layer	40 mm	40 mm
DBM	80 mm	70 mm
Base	150 mm	130 mm
Sub-base	200 mm	180 mm

CONCLUSION

Based on the experimental study on design of flexible pavement using natural fibers and waste materials in all layers, the following conclusions are drawn:

1. The use of natural fibers such as coir, jute, and bamboo significantly improves the engineering properties of pavement materials, especially tensile strength and resistance to cracking.
2. The incorporation of waste materials such as fly ash, plastic waste, rubber, and C&D waste enhances the strength, durability, and performance of flexible pavement.
3. The CBR value of subgrade soil increases with the addition of fly ash and coir fiber, which improves the load-bearing capacity of the pavement.
4. The use of C&D waste in sub-base and base layers improves aggregate interlocking and reduces impact value, resulting in stronger and more stable layers.
5. The addition of plastic waste and rubber in bituminous mixes increases Marshall Stability and improves flexibility, thereby reducing the chances of cracking and rutting.
6. The experimental results indicate that there is an optimum percentage of waste materials and fibers, beyond which the strength starts decreasing due to poor bonding and workability issues.
7. The modified pavement structure shows better performance compared to conventional pavement, in terms of strength, durability, and resistance to deformation.
8. Due to improved material properties, the thickness of pavement layers can be reduced, leading to saving in construction materials.
9. The use of waste materials helps in reducing environmental pollution and supports proper waste management.
10. The overall study proves that sustainable materials can be effectively used in flexible pavement design without compromising performance.
11. Proper quality control during construction plays a major role in achieving desired results and ensuring long service life of pavement.

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