Analysis of Fixed and Variable Rigid Pavements in Comparison for Longevity, Durability and Cost-effectiveness

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Abstract. Urbanization has increased significantly during the last century, affecting both rural and urban areas. Due to the growing need for improved connectivity and services, roads and other transportation infrastructure are being built quickly. To meet this need, scientists, designers, and builders have been investigating novel and reasonably priced manufactured goods with the goal of streamlining the building process and improving overall robustness. In recent times, concrete pavements have witnessed a surge in popularity in India, driven by the escalating costs associated with bituminous pavement. The main benefit of using stiff pavement is that it is resilient and can hold its form even under harsh weather and traffic situations. Although concrete pavements may have a higher initial cost, they frequently wind up being more economical in the long run since they require less upkeep and have an excellent design life. This study's primary objective is to present a comparative analysis of pavement appropriateness while accounting for longevity, durability, and cost-effectiveness, among other factors. The simulation can be utilised to gain a quantitative understanding of the dynamic strains and deflections present in a rigid pavement and flexible system. It is discovered that the impact of surface roughness on a slab structure's dynamic response is significant for the pavement structure's useable life span and can be taken into consideration during pavement design. The model can be adjusted to determine the k-value needed to assess a pavement's subgrade support as it ages.

Keywords-: Pavement types, Flexible, Rigid, Life-cost analysis, and Durable.

1 Introduction

There are three main types of roadway pavements that are essential to the transportation infrastructure: composite, rigid, and flexible. Generally, compacted soil known as the subgrade supports layers of asphalt concrete that are put atop granular base and subbase layers in flexible pavements. Simpler bituminous surface treatments (BST) or thinner asphalt-surfaced pavements with combined layer thicknesses of less than 15 cm are examples of flexible pavements in some situations. Rigid pavements, on the other hand, are made out of a layer of Portland concrete that is laid directly on top of the subgrade, often combined with an intermediate base layer. Rehabilitating damaged asphalt concrete with Portland concrete or the other way around results in composite pavements [1-3]. The way in which these pavements transfer stress and deflection to the underlying layers is the basis for the terms "flexible" and "rigid". While a stiff layer does the reverse, a flexible layer ideally distributes loads equally and permits nonuniform deflections. However, in actuality, stress and deflection distributions depend on the relative stiffness of these layers compared to the underlying granular layers [4-6]. In general, asphalt concrete is referred to be flexible and Portland concrete as rigid due to its significantly lower stiffness. This basic difference has a big impact on how these pavement kinds are analysed and designed. An example of a flexible pavement cross-section is depicted in this figure. Granular base/subbase layers are layered on top of asphalt concrete layers, which are layered on top of the subgrade. Seal coats could act as a pavement's surface barrier, while tack coats could be used to improve layer adherence. The decision between flexible and rigid pavement types is influenced by a number of variables, such as the construction site's unique characteristics, maintenance requirements, and cost [7-9]. In

order to provide affordable, long-lasting, and effective transportation infrastructure, engineers, designers, and builders must have a thorough awareness of the subtle differences between various pavement types as urbanisation progresses [10-11].

2 Pavement Type

The actual travel surface is made of pavement, which is designed to support and endure the weight of the traffic on it. It increases driver confort by creating friction for automobiles and effectively transfers traffic load from the top surface to the natural soil underneath. Cobblestone paths were widely utilised for human and horse cart transportation in the past, before cars became the norm. Water drainage and environmental considerations are taken into account while designing pavements for both automotive and pedestrian use [12]. Dating back to 4000 BC, the earliest known roads were constructed of timber with stone pavement. In order to distribute applied vehicle loads to the sub-grade, a highway pavement is a structure with multiple layers that is positioned at top of the natural soil sub-grade. The structure of the pavement must guarantee minimal noise pollution, good light refraction, and enough skid resistance and an acceptable riding quality. The major goal is to reduce transmitted stresses from wheel loads to a level that is lower than the bearing capacity of the sub-grade. Road construction in the past involves a lot of stone, gravel, and sand. The surface was levelled and smoothed using water as a binding agent [13]. These days, hard road pavements often fall into two groups.

2.1 Flexible pavement

The flexible pavement which are renowned for their capacity to bend under traffic loads are developed using the layered system concept. Because of their plasticity, these pavements can disperse wheel loads and absorb shocks by allowing grain-to-grain contact within the aggregate structure. The pavement, which resembles a flexible sheet, is made up of sand and crushed stone or gravel that has been bound together by a binder made of bitumen. On a naturally compacted subgrade, the composition usually consists of surface course, sub-base course, and subgrade layers (in Fig 1) [14]. Common applications for crushed stone or gravel with asphalt, lime, or cement included base and sub-base courses. Bitumen and aggregate are mixed at high temperatures to create hot-mix asphalt (HMA), which is used to create the flexible pavement's top layer. This mixture solidifies into a strong structure when it cools to room temperature. HMA, commonly known as bitumen, asphalt, asphalt concrete (AC), or tarmac, is a crucial component used in the building of flexible pavements. The three main types of flexible pavements are full-depth asphalt pavement, contained rock asphalt mat (CRAM), and conventionnel layered flexible pavement [15].

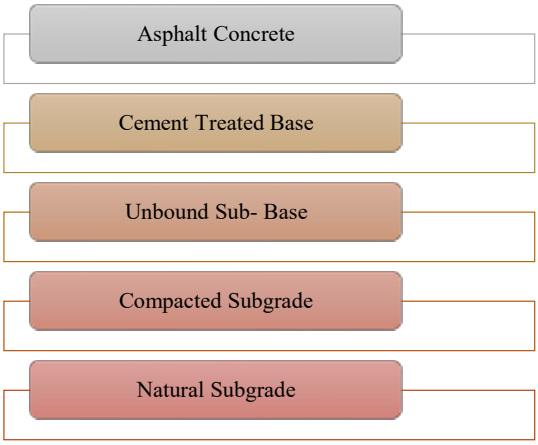

Fig. 1: Flexible pavement

To maximise the performance and guarantee the efficacy of flexible pavements across a range of transportation infrastructure scenarios, it is essential to comprehend the subtleties of these pavements and their varied compositions. Three primary types can be used to broadly classify flexible pavements. Flexible pavements are versatile road structures designed to accommodate varying loads and environmental conditions. They are composed of multiple layers, each contributing to the overall performance and longevity of the pavement. These pavements are categorized based on specific design considerations and material compositions [16]. The primary categories include of Flexible pavements are designed with a focus on the load-distribution characteristics of their component layers, allowing deformation in the subgrade to be transferred to the upper layers. This design principle relies on the flexural strength of the materials, which is comparatively low, necessitating a grain-to-grain contact for load transfer. The completion costs for flexible pavements are lower, but they tend to incur higher repairing costs due to their lower lifespan and higher maintenance requirements [17-19].

Table 1: Comparative flexible vs rigid pavements on the basis of life cycle

Parameter	Flexible Pavement	Rigid Pavement
Initial Cost	Less expensive in regards to initial cost.	Generally, more expensive initially due to the cost of materials like concrete.
Maintenance Cost	Higher long-term maintenance costs due to the need for periodic resurfacing.	Lower maintenance costs; more durable against traffic and environmental conditions.
Durability	Can be strengthened and improved in stages; surfaces can be recycled.	Higher durability and ability to maintain shape under stress.
Design Life	Design life can be extended with proper maintenance and upgrades.	Typically has a longer design life with less frequent need for major repairs.
Suitability	Preferred for areas with less heavy traffic that grows gradually.	Better suited for areas with high traffic volumes and heavy loads.
Material	Uses bituminous (asphalt) materials which are flexible.	Primarily uses concrete materials which are rigid.
Climate Suitability	More adaptable to varying climates due to its flexibility.	Performs well in harsh climates due to its durability but can be susceptible to freeze-thaw cycles.
Foundation	Requires a strong foundation to distribute loads but is more tolerant of minor subgrade movements.	Requires a rigid foundation to prevent cracking and ensure longevity.
Safety Consideration	Offers smooth surfaces that can be milled and recycled.	Provides durable surfaces with long-term performance stability.
Economic Feasibility	Initially more cost-effective but requires careful consideration of long-term maintenance costs.	Higher initial investment but potentially more economical over the life span due to lower maintenance requirements.

The rigid pavements, primarily made of concrete, demand a higher initial investment due to the cost of materials and construction [20]. Despite this, they offer lower maintenance costs over time, showcasing superior durability and the ability to maintain structural integrity under heavy traffic loads and stress. Rigid pavements are known for their longer design life and less frequent need for significant repairs, making them economically feasible in the long run, especially in areas subjected to high traffic volumes and heavy loads as shown in Table 1.

2.2 Rigid Pavement

This type of pavement is more rigid than asphalt pavement due to the materials significant stiffness. By applying flexural strength to transfer wheel loads to the subsurface layer, it functions as a rigid plate and reinforcement in the form of steel rod or mesh are the ingredients of rigid pavement [21]. Three layers should be employed while building a rigid pavement, according to information supplied by [22]. A prepared subgrade, a sub-base or base, and a concrete slab (in Fig 2). They are typically used in the construction of major highways and airports, particularly those in the highway system that can support the weight of large automobile.

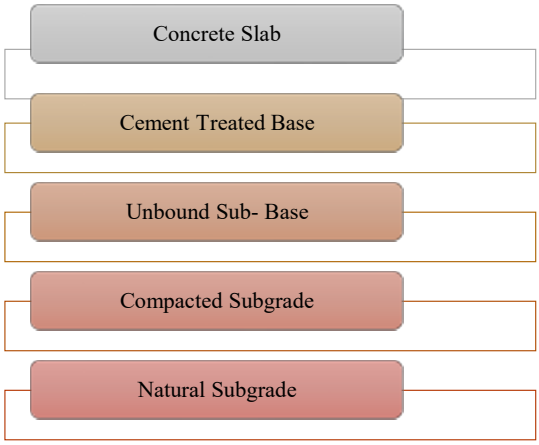

Fig. 2: Rigid pavement

According to [23], the four primary types of concrete pavements that are frequently utilized are pre-stressed concrete pavement (PCP), jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP). Portland cement concrete (PCC), sometimes known as cement or concrete, is the most widely used material for making strong pavement slabs. PCC stands apart because to its production and design methods [24]. The first PCC pavement was constructed in 1889 due to its accessibility and economy, which were primarily developed in the 19th century.

Table 2: Comparative flexible vs rigid pavements on the basis of construction

Feature	Flexible Pavement	Rigid Pavement
Deformation in Subgrade	Transferred to upper layers	Not transferred to subsequent layers
Design Basis	Load distributing characteristics of component layers	Flexural strength or slab action
Flexural Strength	Low	High
Load Transfer	Grain to grain contact	No grain-to-grain load transfer exists
Cost (Completion/Repairing)	Low completion cost, high repairing cost	High completion cost, low repairing cost
Life Span	Low (High maintenance cost)	High (Low maintenance cost)
Subgrade Surfacing	Sub base required, surfacing cannot be laid directly on subgrade	Directly laid on subgrade
Thermal Stresses	None (ability to contract and expand freely)	More vulnerable to induction (limited ability to contract and expand)
Expansion Joints	Not needed	Needed
Strength Dependency on Subgrade	High	Less
Surfacing Rolling	Required	Not needed
Traffic Accessibility (After Construction)	Within 24 hours	Cannot be used until 14 days of curing
Force of Friction	Less	High
Vulnerability to Damage	Damaged by oils and certain chemicals	No damage by oils and greases

The Flexible pavements are designed with a focus on the load-distribution characteristics of their component layers, allowing deformation in the subgrade to be transferred to the upper layers. This design principale relies on the flexural strength of the materials, which is comparatively low, necessitating a grain-to-grain contact for load transfer. The completion costs for flexible pavements are lower, but they tend to incur higher repairing costs due to their lower lifespan and higher maintenance requirements. They require a sub base since surfacing cannot be laid directly on the subgrade, and they exhibit a high dependency on the strength of the subgrade. Flexible pavements can adapt to thermal stresses without the need for expansion joints and can be opened to traffic within 24 hours after construction as shown in Table 2.

3 Categories of Pavements

3.1 Category of Flexible Pavement

There are three categories of flexible pavement mentioned in this study as depicted in Fig. 3. Conventional layered flexible pavement is a widely used method for road construction, combining layers for durability and performance. Full-depth asphalt pavement is a streamlined design, primarily based on asphalt concrete, and is suitable for low to moderate traffic volumes and specific soil conditions [22]. Contained rock asphalt mats enhance the structural integrity of the pavement, demonstrating the adaptability of flexible pavement solutions for specific engineering and performance requirements.

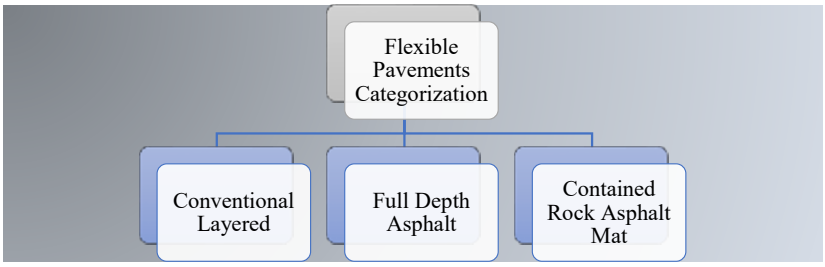

Fig. 3: Categories of flexible pavement

Conventional Layered Flexible Pavement: This layout contains multiple layers, every serving a specific purpose. The foundation lies within the subgrade, providing important help to the subsequent layers. Above it, the subbase, composed of granular substances, enhances load distribution and drainage. The base path further fortifies the structure, and the

topmost layer, asphalt concrete, forms a clean, wear-resistant riding surface [23]. This conventional technique gives adaptability to diverse subgrade situations and heavy traffic situations. Whilst it has validated to be powerful and durable over time, it does require periodic upkeep to deal with wear and tear. Generally, the Conventional Layered Flexible Pavement is still a dependable option for street production, providing a stability among cost-effectiveness and lengthy-time period performance..

Full-Depth Asphalt Pavement: This represents a simple design method in road construction, where the entire road structure is made of asphalt concrete, without the thinner layers of substructure and base coarse. This configuration simplifies development engineering, eliminating the need for additional layers while preserving structural integrity. Pavement strength and load potential generally result from a thicker asphalt layer [24]. This design is especially suitable for roads with little traffic and special terrain conditions. Its simplicity allows for cost-effective construction and protection. Although not as common as Conventional Layered Flexible Pavement, full surface asphalt pavements offer advantages in positive applications and demonstrate adaptability and effectiveness when a simplified structure meets the job requirement**s.**

Contained Rock Asphalt Mat: Within the flexible pavement system the rock asphalt mat serves numerous crucial functions. Firstly, it complements the structural integrity of the asphalt layers, providing resistance to deformation. The use of a rock asphalt carpet highlights the adaptability of flexible pavement solutions to specific technical and performance needs. This innovative approach is consistent with ongoing efforts in pavement engineering to optimize materials and design for durability, safety, and cost-effectiveness [25]. The integration of stone asphalt slabs into flexible pavements demonstrates the continued search for durable and resilient infrastructure solutions as technologies and methods continue to evolve.

3.2 Categories of Rigid Pavement

Concrete pavements are crafted from a variety of materials, inclusive of asphalt, dense or open-grain aggregates, and concrete pavements, as shown in Fig. 4. Plain concrete pavements use speedy-decrease joints, while Reinforced Concrete Pavements (JRCP) combine strength and flexibility through strategic placement and reinforcement of joints [26]. Continous reinforced concrete (CRCP) uses steel reinforcing bars to control cracks, reduce and improve sustainability of the road. The prestressed concrete helps in the enhancemnt of the durability and load capability which is achieved by increasing the compressive stresses on concrete, making it appropriate for bridges, roads and airports.

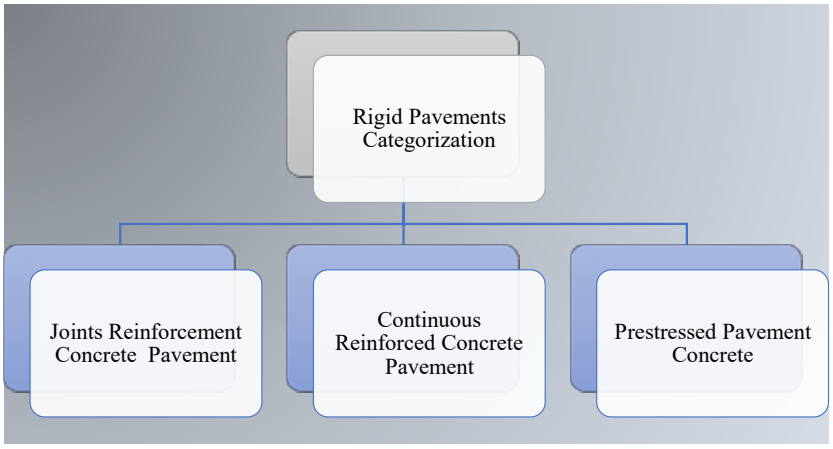

Fig. 4: Categories of rigid pavement

Jointed Reinforced Concrete Pavement (JRCP): Pavement design utilized in road construction, which combines the strength of concrete with the flexibility provided by strategic joint placement and reinforcement. This construction technique involves embedding steel reinforcement bars (rebar) within the concrete pavement to enhance its load-carrying capacity and control cracking. The presence of the steel reinforcement within these slabs enables to distribute masses across the pavement, lessen the formation of cracks, and extend the pavement's universal lifespan. The joints in JRCP are intentionally created to avoid the expansion and contraction of the concrete because of temperature changes and to alleviate strain without inflicting harm to the pavement. Those joints are spaced similarly apart than in different forms of jointed concrete pavements, making an allowance for large slabs of concrete [27]. The long-term durability and high traffic loads call for JRCP pavemnets. It has been found from the studies that JRCP, has the capability to balance the rigid strength of concrete by making use of joints and reinforcement, that in return makes it more durable and reliable pavement solution.

Continuous Reinforced Concrete Pavement (CRCP): This type of pavement is suited for which involves heavy traffic and regular vehicle flows as pavements are made from continuous reinforced concrete (CRCP) which are mostly long-lasting and effective construction method. It has been found that when compared with standard concrete pavements these

pavements rely on joints intended to control cracking, CRCP method uses continuous steel reinforcement bars which are placed throughout its length, where there are transverse joints, however creation and expansion joints are an exception. This type of continuous reinforcement has the benefit of allowing the concrete to fracture in an increasingly controlled manner, as in this pavements cracks are being held tightly and collectively with the help of steel bars [28]. The continuous reinforcement type pavements reacts to temperature variations and load pressure, that result in allowing for even load distribution as well as avoiding the pavement from deteriorating significantly over time.

Pre-stressed Pavement Concrete: The road surfaces are found to have better durability and load bearing capacity when the pavements are created from prestressed concrete that is a type of modern construction approach. This technique involves pre-tensioning or post-tensioning steel tendons within the concrete before it sets, applying a compressive stress that counteracts the tensile stresses exerted by traffic loads and environmental factors [29]. Prestressing the concrete in this manner allows the pavement to handle greater loads and resist cracking more effectively than traditional concrete surfaces. The prestressed concrete pavement is designed to maintain its integrity under the stress of heavy and continuous traffic, making it particularly suitable for bridges, highways, and airfields where long-term performance and minimal maintenance are crucial.

Table 4 : Comparaison of categories of rigid pavement on the basis of their features

Feature	JRCP	CRCP	Pre-stressed Concrete Pavement
Design Concept	Combines concrete strength with flexibility through strategic joint placement and reinforcement	Uses continuous steel reinforcement without transverse joints, except for expansion and construction joints	Applies pre-tensioning or post-tensioning steel tendons within the concrete
Primary Use	Road construction suitable for areas with heavy traffic loads	Designed for heavy and continuous traffic loads, ideal for major roadways	Suitable for bridges, highways, and airfields with heavy and continuous traffic
Crack Control	Steel rebar embedded within the pavement controls cracking, with deliberately placed joints for expansion	Continuous reinforcement allows for controlled cracking, with cracks held tightly together by steel bars	Pre-stressing counteracts tensile stresses, enhancing crack resistance
Joint Spacing	Wider joint spacing, allowing for larger concrete slabs	No transverse joints except for necessary construction and expansion joints	Not applicable (focus on tensioning steel tendons)
Load Distribution	Steel reinforcement helps distribute loads evenly, reducing crack formation	Even load distribution prevents severe deterioration, enhancing durability	Compressive stress from prestressing allows for greater load-bearing capacity
Maintenance	Low-maintenance due to reduced crack formation and extended lifespan	Reduced maintenance needs due to minimized wide crack occurrence	Minimal maintenance required due to enhanced durability and resistance to cracking
Durability and Longevity	High, particularly in heavy traffic areas	Very high, designed to accommodate continuous heavy loads	Exceptionally high, designed for long-term performance under heavy traffic
Suitability	Heavy traffic loads and long-term durability required	Heavy and continuous traffic, requiring high durability	High-stress environments like bridges, highways, and airfields

4 Conclusion

There are two main types of roadway pavements that are essential to the transportation infrastructure composite, rigid, and flexible. This study's primary objective is to present a comparative analysis of pavement appropriateness while accounting for longevity, durability, and cost-effectiveness, among other factors. The simulation can be utilised to gain a quantitative understanding of the dynamic strains and deflections present in a rigid pavement and flexible system. It is discovered that the impact of surface roughness on a slab structure's dynamic response is significant for the pavement structure's useable life span and can be taken into consideration during pavement design.

a. The load is distributed across the grains of flexible pavement, leading to a variety of failures include rutting, fatigue cracking, and thermal cracking. On the other hand, the absence of this grain-to-grain weight transfer phenomena in rigid pavement results in a decreased frequency of failures.

b. Compared to flexible pavement, rigid pavement lasts longer and requires less maintenance. Due to the absence of some failure mechanisms, rigid pavement lasts longer.
c. The cost-benefit ratio of rigid pavement over flexible pavement is higher, despite having a greater starting cost. This is evident when the entire cost of the pavement is evaluated throughout its whole lifespan.
d. Rigid pavement is more economically advantageous than flexible pavement throughout the course of its whole life cycle due to its greater flexural strength, resistance to failure, longer lifespan, and lower maintenance costs.

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