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Cost-Effectiveness Analysis of Design Methods for Rigid and Flexible Pavement: A Case Study of Urban Road

Asadullah Ziar[1],*, Shahzada Ulfat[2], Zainullah Serat[3] and Mohammad Ashraf Armal[1]

[1]*Department of Civil Engineering, Ghazni Technical University, Afghanistan*

[2]*Department of Civil Engineering, Kandahar University, Afghanistan*

[3]*Department of Energy Engineering, Ghazni Technical University, Afghanistan*

Abstract: Roads play a vital role in a country's economic, cultural, and social development, which turns a significant portion of the government's budget yearly. Expenses for road construction include design, material acquisition, construction equipment, maintenance, rehabilitation, and overall operations, requiring substantial government investment. A meticulous evaluation of alternatives is essential before implementing such projects. This study aims to comprehensively analyze the cost-effectiveness of three design methods (American Association of State Highway and Transportation Officials (AASHTO), Asphalt Institute (AI), Portland Cement Association (PCA)) on an 8 km urban road, considering initial construction costs. Traffic data collected over 2 years resulted in a total estimated traffic load of 2.16×10^6 equivalent single axle load for the road. The findings indicate that flexible pavement is more cost-effective than rigid pavement. Among flexible pavement design methods (AASHTO and AI), AI emerges as the most cost-effective. For rigid pavement design methods (AASHTO and PCA), PCA proves to be the most cost-effective, while rigid pavement stands out as the most expensive option.

Keywords: rigid and flexible pavement, cost-effectiveness, design parameters, design methods

1. Introduction

Throughout the history of civil engineering, transportation has held a critical role as a fundamental component. The construction of roads, bridges, pipelines, tunnels, canals, railroads, ports, and harbors has been integral to the profession and has significantly contributed to its public perception. As urban centers expanded, civil engineers took on additional responsibilities in developing and managing transit facilities, encompassing street railways and elevated and underground systems [1].

Road transportation stands as the most inclusive means of providing extensive services to everyone. This mode of transport offers unparalleled flexibility concerning routes, directions, travel time, and speed. Moreover, it uniquely enables door-to-door service, making it possible to reach destinations directly and efficiently [2].

Throughout history, the advancement of society has been closely tied to the need for efficient transportation. A well-developed transportation system is crucial for the progress of any country, serving as the backbone of its economic growth. Transportation indeed holds a crucial role in facilitating the seamless movement of both people and goods, utilizing diverse modes such as road, rail, water, and air to establish efficient connections between various locations [3].

A nation's progress relies on the presence of a robust transportation system encompassing roads, railways, waterways, and airways. An efficiently developed transportation system plays a vital role in fostering economic growth. By establishing a reliable transportation network, people can enjoy secure, swift, comfortable, and convenient means of communication, which is indispensable for effectively distributing diverse goods within a country. This fundamental aspect holds significant importance for the country's economic, industrial, and environmental welfare [4].

The presence of a well-developed transportation system within a country serves as a significant indicator of its economic growth and progress in social development [5].

In recent times, the expenses linked to highway pavement construction, maintenance, and rehabilitation have considerably risen. As a result, there is a growing need for optimized pavement maintenance planning, aiming to minimize the overall life cycle cost of pavements while simultaneously maximizing their performance. To achieve this, it has become essential for highway agencies to adopt efficient tools and methodologies that facilitate effective decision-making. Specifically in terms of its initial cost of construction which the primary factor in deciding the type of pavement is its initial cost [6, 7].

The current study focuses on an 8 km urban road located in Kandahar City and centers around the initial cost of construction. The study has two primary objectives: Firstly, it aims to design both flexible and rigid pavements using three distinct methods, American

*__Corresponding author:__ Asadullah Ziar, Department of Civil Engineering, Ghazni Technical University, Afghanistan. Email: asad.ziar2020@gmail.com

Association of State Highway and Transportation Officials (AASHTO), Asphalt Institute (AI), and Portland Cement Association (PCA). Secondly, the main objective of the research is to conduct a comparative cost analysis for each design method, considering both flexible and rigid pavement options.

In pavement engineering, the term "flexible" refers to pavements that consist of an asphalt concrete layer on top, while "rigid" pavements have a top layer (slab) made of cement concrete. The primary difference between these two types lies in how they distribute wheel load stresses. In flexible pavements, the wheel load stresses from vehicles are distributed to the lower layers of the pavement through grain-to-grain contact within the granular structure. This mechanism allows the pavement layers to work together in a cooperative manner to bear the loads and provide a flexible response to traffic-induced stresses, contributing to the overall durability and performance of the pavement [8]. Rigid pavements, on the other hand, distribute the load through slab action, functioning similarly to an elastic plate resting on a viscous medium. These pavements are constructed using Plain Cement Concrete (PCC) and are analyzed through plate theory, which takes into account an elastic plate resting on a viscous foundation, rather than the layer theory employed in the case of flexible pavements [7].

2. Literature Review

Conducting an accurate evaluation of various alternatives is imperative to ensure prudent decision-making before the implementation and design of roadway projects. As a result, numerous studies have been conducted to compare asphalt and concrete pavements, taking into account several factors, for example, Ketema et al.'s [9] study results indicated that the initial cost of rigid pavement was approximately twice as much as that of flexible pavement. However, over time, it was found that the maintenance cost per kilometer for flexible pavement was 7.9 Million ETB higher than that of rigid pavement, attributed to the ongoing maintenance expenses throughout its design life. The study conducted by Jain et al. [2] highlights that the key advantage of flexible pavements lies in their adaptability and ability to be strengthened gradually as traffic demands grow. Moreover, they offer the sustainable and cost-effective benefit of surface milling and recycling for rehabilitation, making them environmentally friendly. Another appealing aspect is their lower initial investment and maintenance costs in comparison to rigid pavements. On the other hand, rigid pavements may involve higher initial expenses, but they compensate by requiring less maintenance and having longer design lifespans, resulting in a durable long-term solution. Each type of pavement has its merits, and the choice depends on specific project requirements, budget constraints, and sustainability goals. According to Adow et al.'s [10] study, the research indicated that the initial cost of asphalt pavement was lower than that of concrete pavement. However, when taking into account the life cycle costs, concrete pavement was found to be more cost-effective in the long run compared to asphalt pavement. Similarly, Mohod and Kadam's [7] research showed that the life cycle cost of flexible pavement would be approximately 19% higher than that of rigid pavement after 20 years. Despite the higher initial cost of rigid pavement, a comparative analysis of the total cost of the pavements over their lifespan revealed that rigid pavement is more cost-effective than flexible pavement.

Additionally, Padmaja and Tejaswi [11] conducted research on a 2.4 km road in Vijayawada in 2019, and the results demonstrated that the cost of rigid pavement was double than that of flexible pavement. However, previous studies were limited to a body of knowledge in this region, especially in Afghanistan. As it explores relatively novel techniques and emphasizes the importance of cost-effectiveness analysis of different design methods in decision-making, the findings provide valuable insights for policymakers and stakeholders involved in road construction projects, enabling them to optimize resource allocation and make informed choices when selecting design methods for pavement construction.

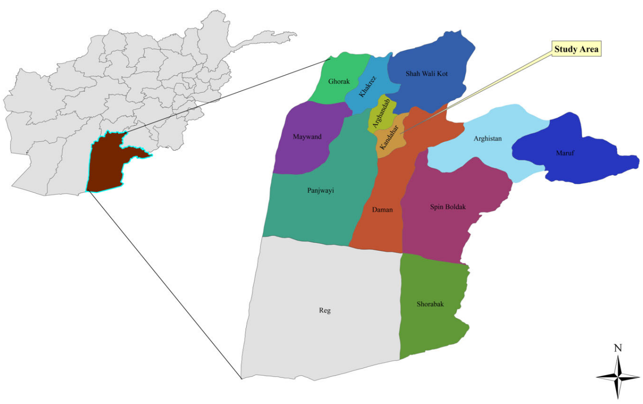
3. Research Methodology

3.1. Study area and site information

The province of Kandahar is situated in the far southeastern corner of Afghanistan and falls within the southern regional planning zone. It shares borders with Pakistan to the southeast, Zabul Province to the northeast, Uruzgan to the north, and Helmand Province to the west [12]. The city of Kandahar itself covers an area of approximately 250 km^2, accounting for a fraction of the province's total territory, which spans 47,676 km^2. With an elevation of around 1005 m above sea level, Kandahar is the second most important city in the country after Kabul [13].

The road under consideration is located in Kandahar City's 12th district and spans a length of 8000 m with a width of 11 m. Figure 1 displays the location of Kandahar City, which serves as the study area for the present work.

Figure 1
Map of Kandahar city



3.2. Methodological framework of the study

The chart in Figure 2 comprised the methodological steps used to achieve the study objectives.

3.3. Data collection tools and processing

To collect the necessary data, we employed two primary methods: cameras and data collection sheets. The cameras were strategically placed at specific locations to capture real-time traffic patterns and movements. This allowed us to obtain accurate information about vehicle flow and types.

In addition to the camera-based data collection, we used data collection sheets as shown in Figure 3. These sheets were designed to capture specific details about each vehicle passing through the selected locations. Our surveying team meticulously recorded information such as vehicle types and their numbers. This manual data collection process complemented the camera

Figure 2
Flow chart of the study

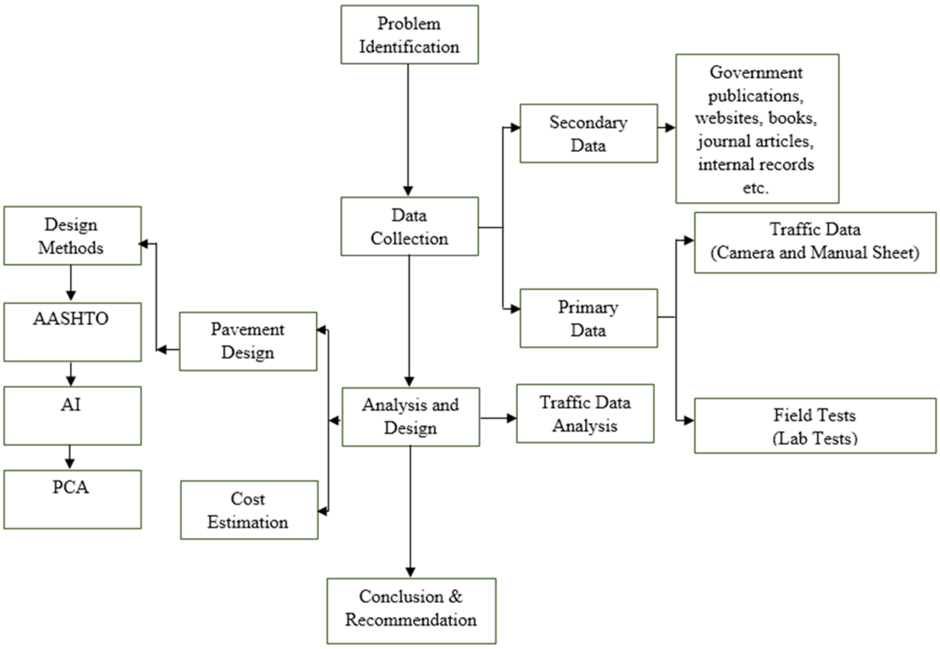


Figure 3
Sample of manual data collection sheets

Direction:								Start			End			Location:		Date			
Vehicles Classification		Class (A)	Class (A-1)	Class (1)	Class (2)	Class (3)	Class (3 a)	Class (4)	Class (5)	Class (6)	Class (7)	Class (8)	Class (9)	Class (10)	Class (11)	Class (12)	Class (13)	Class (B)	Remarks
Figure		Animal Carts	Reksha & Reksha Freight	Motorcycle & Bicycle	Passenger Cars	Four Tire Single Unit	Mini Buses	Buses	Two Axle Six Tire Single Unit	Three Axle Single Unit	Four or more Axle Tandem	Four or more Axle Single Trailer	Five Axle Semi Trailer	Six or more Axle Single Trailer	Five or More Axle Multi Trailer	Six Axle Multi Trailer	Siven or more Axle Multi Trailer	Tractor and Agriculture Machinery	
Equivalency Factors			0																
From	TO																		
7:00AM	8:00AM																		
8:00AM	9:00AM																		
9:00 AM	10:00AM																		
10:00AM	11:00AM																		
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3:00PM	4:00PM																		
4:00PM	5:00PM																		
5:00PM	6:00PM																		
6:00PM	7:00PM																		
Total Per Week																			
																		Total	
																		Night Factor	
																		Seasonal Factor	
																		Tourism & Gust Factor	
																		Growth Rate Factor	
																		Grand Total	

footage and provided valuable insights into the characteristics of the observed traffic.

Furthermore, it should be noted that the field tests for the California Bearing Ratio (CBR) of subgrade, sub-base, and base course materials were conducted by the Human Resources and Development Agency.

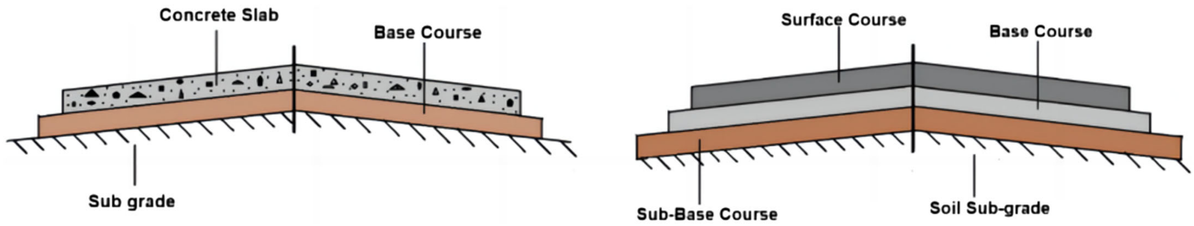
3.4. Pavement design

Two types of pavements are designed here:

1) Flexible pavement: This type of pavement distributes the stresses from wheel loads to lower layers by transferring them through the contact points within the granular structure. When the wheels exert load on the pavement, it spreads over a larger area, leading to reduced stress as it penetrates deeper into the layers [14], as shown in Figure 4 [15].

2) Rigid pavement: It consists of PCC slabs, which are placed either on a prepared sub-base of granular material or directly on a granular subgrade. PCC indeed stands for PCC, and it is a composite material made by mixing cement, fine aggregate (sand), and coarse aggregate without the inclusion of steel reinforcement [4], as shown in Figure 4 [15]. Rigid pavements possess enough bending resistance to distribute the stresses from wheel loads over a larger underlying surface [16].

Figure 4
Typical cross section of rigid pavement and flexible



3.5. Design methods

3.5.1. AASHTO method flexible pavement

The design procedure recommended by AASHTO is widely applied in the USA and utilizes empirical equations derived from extensive research and field testing. When designing flexible pavements, the method takes into account traffic loads, material properties, design life, and environmental factors. For rigid pavements, it employs plate theory, considering traffic loads, material properties, design life, and environmental factors. In general, the AASHTO method offers a systematic and established approach, ensuring the long-lasting durability and safety of roads and highways [17].

Design Inputs: From AASHTO 1993 design guide

1) Reliability (R)
2) Standard Deviation = 0.45
3) Serviceability (ΔPSI) = 2.5
4) Base Coarse (Ebs)
5) Sub-Base Coarse (Esb)
6) Sub-Grade Resilient Modulus (MR) = 15,000 psi, from Equation 2
7) W18 = 2.16 × 106 is collated by equation. 1
8) Drainage Coefficients
9) Layer Coefficients
10) Structural Numbers

Note: CBR of the subgrade is assumed to be 10 according to Table 2 [19] as shown below [17].

$$Design\ ESAL = \left(\sum pi * F_i\right)(ADT)(T)(A)(G)(Y)(D)(L)(365) \quad (1)$$

(a) **Reliability:** The reliability of the pavement design-performance process refers to the likelihood that a pavement section designed using this process will perform adequately and meet the desired performance criteria under the expected traffic and environmental conditions throughout the designated design period. It indicates the level of confidence that the designed pavement will withstand the anticipated stresses and remain in a satisfactory condition, ensuring its longevity and functional performance over time. Higher reliability values imply a greater assurance that the pavement will meet its intended performance expectations during its service life [15].

It is selected according to the AASHTO design guide from Table 1.

Table 1
Suggested level of reliability for various functional classification

Recommended level of reliability (%)		
Functional classification	Urban	Rural
Interstate and other freeways	85–99.9	80–99.9
Principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Note: for our project and road type $R = 85$ % according to the guide.

(b) **Resilient modulus of soil (MR):** The key parameter in characterizing the foundation for pavement design is the Soil Resilient Modulus (MR). MR represents the soil's stiffness or elasticity under dynamic loading conditions, and it can be determined using the following equation [18]:

$$MR(ib/in^2) = 1500 \times \text{CBR for fine-grain soil with soaked CBR} \leq 10 \quad (2)$$

(c) **Drainage coefficients:** The values M2 = 1 and M3 = 0.8, as per the AASHTO 1993 design guide, are selected for the base course and sub-base course, respectively. These values are determined based on the soil type and its drainage quality, as specified in Table 3 [15], illustrated below.

(d) **Structural numbers:** The calculations are derived from the design guide: $SN_1 = 2.3,\ SN_2 = 2.85,\ \text{and}\ SN_3 = 3.2$ [15].

(e) **Layer coefficients**: Base course and sub-base course are estimated from charts that illustrate the variations in granular base and sub-base layer coefficients (a2, a3) with different

Table 2
Typical CBR value for different soil

Material description	CBR
Thumb penetration into the wet clay soil	
Easy	<1
Possible	1
Difficult	2
Impossible	3+
A trace of a footprint left by a walking man	1
SC: clayey sand	10–20
CL: lean clays, sandy clays, gravelly clays	5–15
ML: silts, sandy silts	5–15
OL: organic silts, lean organic clays	4–8
CH: fat clays	3–5
MH: plastic silts	4–8
OH: Fat organic clays	3–5

Table 3
The MI values recommended for modifying the structure coefficients for untreated base and sub-base materials

Percent of time pavement structure is exposed to moisture levels approaching saturation				
Quality of drainage	Less than 1%	1–5%	5–25%	Greater than 25%
Excellent	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	1.05–0.95	0.95–0.75	0.75–0.40	0.40

base strength parameters, as outlined in the AASHTO 1993 design guide [15].

- Ebs = 28,000 psi
- Esb = 15,500 psi
- $a_1 = 0.44$
- $a_2 = 0.135$
- $a_3 = 0.11$

3.5.2. AI method flexible pavement

This approach is rooted in the mechanistic empirical methodology, utilizing the mechanistic multilayer theory alongside empirical failure criteria to calculate pavement thicknesses [17]. The design process encompasses two critical criteria: firstly, controlling the tensile strain at the bottom of the asphalt concrete layer to prevent fatigue cracking effectively and, secondly, limiting the compressive strain at the top of the subgrade to mitigate the potential for subgrade plastic deformation and rutting. These criteria play a pivotal role in safeguarding the long-term durability and performance of the pavement structure [20].

One key component of AI-driven pavement design is the incorporation of distress models. These models are crucial in predicting potential pavement deterioration and identifying distresses such as cracks, rutting, potholes, and surface wear over time. The integration of AI methods and distress models in pavement design represents a cutting-edge approach to enhance efficiency, accuracy, and durability of road infrastructure, and it has also led to more resilient, sustainable, and cost-effective road infrastructure, offering substantial benefits to transportation agencies, road users, and the environment [17, 21, 22].

The Design Chart for Full Depth and Hot Mix Asphalt (HMA) with untreated aggregate base are employed to determine the appropriate thickness of HMA for both full-depth and emulsified base. This determination relies on factors such as the number of equivalent single axle loads (ESALs) and the subgrade resilient modulus [17].

3.5.3. AASHTO and PCA method rigid pavement

Design inputs: From AASHTO 1993 design guide

1) Reliability (R) = 85% described in 3.5.1 section
2) Design Period (Y) = 15 year
3) W18 = 2.16 × 106 from Equation (2)
4) Standard Deviation (So) = 0.45
5) Sub-Grade Resilient Modulus (MR) = 15,000 psi, from Equation (1)
6) Sc = 600 psi
7) Serviceability (ΔPSI) = 2.5
8) Modulus of Subgrade Reaction $K = 600$ psi [17]
9) Ec= 4,030,509 psi from Equation (3)
10) J = 3.6
11) CD = 1.0 Drainage coefficient [17]

(a) **Elastic modulus of concrete *Ec***: The elastic modulus of concrete can be determined according to the procedure described in ASTMC469 or correlated with the compressive strength. The American Concrete Institute suggests the following correlation for estimating the elastic modulus of concrete from the compressive strength of concrete [23]:

$$Ec = 57,000(fc)^{0.5} \tag{3}$$

where *Ec* refers to the elastic modulus of concrete measured in pounds per square inch (psi), and *Fc* denotes the compressive strength of concrete also measured in pounds per square inch (psi).

(b) **Load transfer coefficient (J):** It is a crucial factor in rigid pavement design, accounting for the concrete pavement's ability to transfer loads across joints and cracks. By implementing load transfer devices and incorporating tied concrete shoulders, we achieve two significant outcomes: firstly, the amount of load transfer is greatly enhanced, ensuring better load distribution and overall pavement performance. Secondly, these measures effectively lower the load-transfer coefficient, reducing the stresses at joints and enhancing the pavement's durability. Together, these improvements contribute to a more robust and long-lasting pavement structure.

Table 4
Recommend load transfer coefficient for various pavement types and design conditions

Type of shoulder	Asphalt		Tied PCC	
Load transfer device	Yes	No	Yes	No
JPCP and JRCP	3.2	3.8–4.8	2.5–3.1	3.6–4.2
CRCP	2.9–3.3	N/A	2.3–2.9	N/A

Table 4 [15] shows recommend load transfer coefficient for various pavement types and design conditions [17].

4. Results and Costs Analysis

4.1. Designed thickness of flexible pavement

(a) **AASHTO Method:** Using the design inputs mentioned above, the design thickness is estimated according to the AASHTO 1993 design guide, as illustrated below.

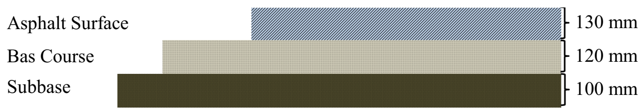
$$\bullet D_1 = \frac{SN_1}{a_1} = \frac{2.3}{0.44} = 5 \text{ in. (assumed 130 mm)}$$

$$\bullet D_2 = \frac{SN_2 - a_1 \times D_1}{a_2 \times m_2} = \frac{2.85 - 0.44 \times 5}{0.135 \times 1} = 4.8 \text{ in. (assumed 120 mm)}$$

$$\bullet D_3 = \frac{SN_3 - a_1 \times D_1 - a_2 \times D_2 \times m_2}{a3xm3} = \frac{3.2 - 0.44 \times 5 - 0.135x\ 4.8 \times 1}{0.11 \times 0.8} = 4\text{in. (assumed 100 mm)}$$

According to the provided design thickness illustrated in Figure 5, the estimated initial cost for constructing the desired road is US $1,729,302.00, as calculated from the bill of quantities.

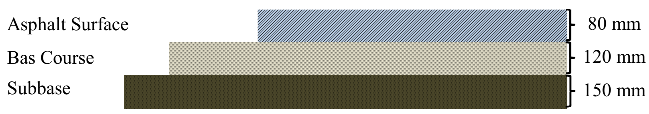
Figure 5
Design section of flexible pavement AASHTO method



AI method flexible pavement. The thickness of HMA and Emulsified Asphalt Mix (mixture of asphalt and water and an emulsifying agent), when used over an untreated aggregate base, are determined using design charts. The AI method provides the following results for the designed section [17].

The thickness of the Asphalt Surface is 3 inches (80 mm)
The thickness of the EAB (Emulsified Asphalt Base) is = 1.2 × 4 in. = 4.8 in. (120 mm).
Therefore, the initial cost of construction is US $1,064,186.00. The designed section can be seen in Figure 6.

Figure 6
Design section of EAB AI method



4.2. Designed thickness of rigid pavement

4.2.1. AASHTO method

Using the design inputs mentioned above, the design thickness is estimated according to the AASHTO 1993 design guide, as illustrated below.

D = 7.5 in. (assumed 190 mm) slab thickness
D = 5.9 in (assumed 150 mm) sub base course thickness
Therefore, the initial cost of construction is US $2,113,415.00. The designed sections can be seen in Figure 7.

Figure 7
Design section of rigid pavement AASHTO method

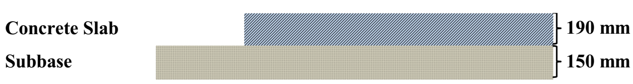
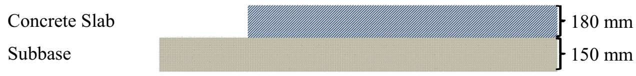


Figure 8
Design section of rigid pavement PCA method



Note: Figure 9 illustrates all types of pavements and their respective costs for different design methods

4.2.2. PCA method

The PCA introduced a new thickness-design method for concrete highways and streets in 1984, replacing the one published in 1966. This updated procedure is applicable to Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP), and Continuously Reinforced Concrete Pavement (CRCP). The PCA's innovative mechanistic design approach for rigid highway and street pavements considers two essential criteria related to slab fatigue cracking and subgrade erosion [20].

From PCA design methods guide, the following results are obtained:

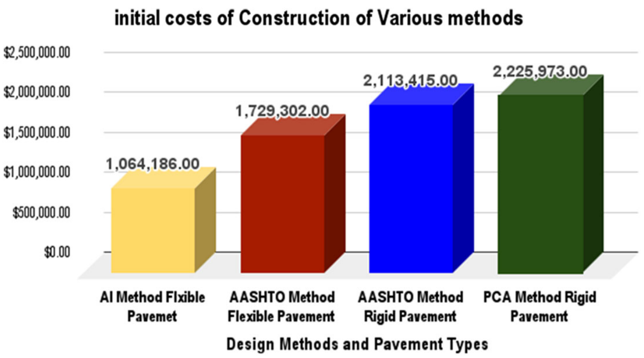
D = 7 in. (assumed 180 mm) slab thickness.
D= 5.9 in (assumed 150 mm) sub base course thickness

Therefore, the initial cost of construction is US $2,225,973.00. The designed sections can be seen in Figure 8.

Table 5
Comparison between properties of flexible and rigid pavements

Property	Rigid pavements	Flexible pavements
Subgrade deformations	No transfer to upper layers	Deformations transferred to upper layers
Flexural strength	High	Low
Load transfer	Flexural action	Grain to grain contact
Materials	Cement concrete, reinforced or pre-stressed concrete	Hot asphalt concrete, granular material
Subgrade requirements	Required	Significantly required
Thickness	Less	More
Surfacing on the subgrade	Directly laid	Not directly laid
Rolling of the surfacing	Is not needed	Is needed
Thermal stresses	Critical	No critical
Expansion joints needed	Yes	No
Vehicles fuel consumption	Less	More
Opening to traffic	15 days curing required before use	Ready for traffic within 48 h or less
Vulnerability to oils and chemicals	No	Yes
Night visibility	Good	Poor
Traffic noise generation	High	Low
Suitability for underground works	Difficult	Easy
Temperature effects	Stress is produced	No stress is produced
Response to excessive loading	Causes cracks	Causes rutting

Figure 9
Graphical representation of costs



In general, there are some other factors other than cost that affect the selection of pavement types that are drawn from past studies, as shown in Table 5 [24].

5. Conclusion

The present study introduces a decision-supporting model designed to assess and compare four pavement design methods: AASHTO flexible pavement design method, AI flexible pavement design method, AASHTO rigid pavement design method, and PCA rigid pavement design method. The evaluation is carried out for an 8 km road located in Kandahar City, Afghanistan, with a primary focus on their initial construction costs. It is important to note that this model solely considers the initial costs associated with different design methods. It is crucial to understand that the results of the three methods may not be entirely comparable, particularly in two aspects: Fatigue Life Prediction: The prediction of pavement life based on fatigue laws, which involves the relationship between the horizontal tensile strain at the bottom of the asphalt layer and the number of cycles to failure, differs among the methods, and Pavement Damage: The ratio between the expected traffic and the number of ESAL cycles that the pavement can endure varies among the methods.

The study's results can be summarized as follows:

(a) Pavement types:
- Flexible pavement is identified as the most cost-effective option among both flexible and rigid pavements.
- On the other hand, rigid pavement is found to be the most expensive choice among flexible and rigid pavements.

(b) Design methods:
- Within the flexible pavement design methods (AASHTO and AI), the AI method emerges as the most economical alternative.
- Regarding rigid pavement design methods (AASHTO and PCA), the PCA method proves to be the most economical option.

Recommendations

The developed model provides valuable insights into the initial construction costs of various pavement design methods. However, for comprehensive pavement selection decisions, it is essential to also consider other important factors, such as maintenance costs, rehabilitation expenses, and life cycle costs. To further enhance the understanding of cost-effectiveness in pavement selection, future researchers should conduct a detailed analysis encompassing the entire life cycle of pavements. This comprehensive analysis should encompass costs associated with maintenance, rehabilitation, and other long-term expenses, providing a more accurate and informed evaluation of pavement alternatives. By addressing these aspects, decision-makers can make well-informed choices that prioritize both cost-effectiveness and long-term sustainability in pavement infrastructure.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

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