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Comprehensive Analytical Study of Structural Reclamation in Aging Flexible Pavement

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Abstract

The progressive deterioration of flexible pavements, driven by increasing traffic loads, environmental influences, and material aging, necessitates the implementation of effective structural reclamation strategies to restore functional performance and extend service life. This study focuses on a critical segment of the Libyan coastal road network, specifically the 27.5 km part from Tripoli Street Bridge to Al-Krarim Gate. An analytical and quantitative investigation is undertaken to evaluate the structural condition and rehabilitation potential of the existing flexible pavement system, with particular attention to distress mechanisms, material degradation, and the effectiveness of various rehabilitation techniques. The assessment integrates field investigations, laboratory testing, based on AASHTO 1993, and to evaluate pavement distress, base soil strength, and asphalt concrete layers performance; Pavement Condition Index (PCI) values and core sample analyses are employed to determine the extent of structural failure. Visual distress surveys supplement the data to provide a comprehensive understanding of surface and sub-surface conditions. Analytical modeling, based on layered elastic theory is used to simulate pavement response under rehabilitated conditions and forecast long-term performance under loading. The study examines several rehabilitation methods, including full-depth reclamation (FDR), cold in-place recycling (CIR), and mechanical stabilization using cementitious additives. Each method is evaluated based on structural capacity enhancement, cost-efficiency, and service life extension. Results demonstrate that the selection of reclamation techniques tailored to subgrade conditions and traffic loads significantly improves structural performance and minimizes maintenance needs. The study concludes that full-depth repaving offers the most sustainable and economically viable solution for restoring the targeted roadway section.

Keywords: *Flexible pavement, Pavement structural reclamation, Pavement rehabilitation, Full-depth reclamation (FDR), Cold in-place recycling (CIR).*

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Introduction

Transportation infrastructure forms the backbone of national development by facilitating trade, social interaction, and economic activities [1]. Among various infrastructure components, road networks are particularly vital, acting as arteries that connect cities, industries, ports, and residential areas. Flexible pavements, characterized by their ability to withstand loads through layered elastic behavior, are the predominant pavement type in many countries due to their cost-efficiency and relative ease of construction and maintenance. However, these pavements are highly susceptible to performance deterioration over time, driven by environmental exposure, increasing traffic volumes, especially heavy axle loads, material aging, and insufficient maintenance. As the lifecycle of flexible pavements progresses, the need for comprehensive evaluation and timely intervention becomes critical to avoid catastrophic failure and economic loss.

In many developing countries, including Libya, flexible pavements are experiencing accelerated degradation due to a confluence of factors: aging infrastructure, exponential traffic growth, harsh climatic conditions, limited drainage systems, and overloaded vehicles. One prominent example of such infrastructure stress is found in the Libyan coastal highway, specifically in the 27.5 km road segment stretching from Tripoli Street Bridge to Al-Kararim Gate. This roadway segment plays a pivotal role in connecting key industrial, residential, and logistical zones. Originally constructed several decades ago to accommodate lower traffic demands, the road's design did not anticipate the significant increase in heavy vehicle traffic, resulting in visible and structural deterioration. The strategic importance of this corridor underscores the need for a scientifically driven rehabilitation effort that considers the unique regional challenges and integrates advanced engineering solutions.

The observed deterioration along the pavement corridor varies from superficial surface defects—such as rutting, cracking, and potholing—to deeper structural failures involving subgrade weakening and material disintegration. These distresses undermine both the structural capacity of the pavement and the safety and comfort of road users. Additionally, the frequent disruptions caused by emergency maintenance not only extend travel time and logistics delays but also impose significant financial burdens—both direct and indirect. Visual surveys and Pavement Condition Index (PCI) evaluations confirm the severity of deterioration, with the network registering a critically low PCI average of 39.91 for the year 2023. This rating, classified as ‘Very Poor’ under ASTM D6433-07[2], signals widespread failure not only at the surface but throughout the pavement structure.

To address the complexity of the issue, this study adopts a comprehensive methodology integrating surface inspection, subsurface geotechnical investigation, traffic analysis, material testing, and structural modeling. Three rehabilitation techniques are examined in this research: full-depth replacement of granular layers, foamed asphalt stabilization, and cement stabilization. Each method is analyzed in terms of its structural improvement potential, durability, cost implications, and compatibility with local construction practices [3]. The motivation for this research arises from a broader infrastructural challenge prevalent in developing nations—namely, the lack of preventive maintenance planning and underutilization of advanced rehabilitation technologies. In Libya, pavement management often relies on reactive measures, leading to premature and costly road failures. This study contributes by applying a structured, performance-based evaluation framework adapted to local conditions, incorporating standards such as the AASHTO Guide (1993) [4], ASTM PCI methodology, and analytical tools including finite element analysis (FEA) and layered elastic theory [5].

The investigative process begins with surface and subsurface evaluations, comprising core sampling and geotechnical testing—specifically, sieve analysis, Atterberg limits, Proctor compaction, CBR, and DCP tests. These tests reveal variations in pavement layer thicknesses, widespread subgrade weaknesses, and poor gradation in existing base materials. Such findings confirm the need for deep rehabilitation measures, as the failure is not confined to the surface. Simultaneously, traffic data was collected from key junctions to determine the Equivalent Single Axle Load (ESAL) over a projected design period of 20 years. The analysis was conducted with an assumed traffic growth rate of 4%. Though heavy trucks represent a small fraction of overall traffic, they exert disproportionately high stresses due to their axle loads. One standard truck, for instance, inflicts damage equivalent to thousands of passenger vehicles, necessitating a pavement structure capable of efficiently distributing such loads throughout its design life [4]. The Level of Service (LOS) analysis revealed deficiencies in the current road capacity, particularly between the Tripoli and Benghazi bridges, where congestion and lane interference significantly reduce operational efficiency. Based on current and forecasted demand, this segment requires expansion to four lanes in each direction, while three lanes per direction are recommended for other segments to maintain acceptable LOS ratings.

The study evaluates three distinct proposals:

1. Proposal 1 involves complete removal and replacement of the granular base—most appropriate where elevation must remain unchanged, such as under bridge clearances. Where feasible, vertical layering is optimized for better stress distribution.
2. Proposal 2 employs foamed asphalt for in-situ stabilization of existing base materials [6]. While this method enhances stiffness and reduces material waste, it requires meticulous control of recycled content quality and incurs relatively high costs.
3. Proposal 3 incorporates cement stabilization of the subgrade followed by a new granular base layer [7]. This hybrid approach aims to reduce shrinkage cracking and transition stress between stiff and flexible layers [8].

Using AASHTO design equations, each alternative was assessed to determine required layer thicknesses and Structural Numbers (SN). A parallel cost analysis, based on Libyan market prices, showed that although Proposal 3 offered the lowest cost, Proposal 1 was technically superior due to its full renewal of degraded layers and proven longevity under Libyan field conditions. This research yields several scientific contributions. It validates a performance-based, locally-adapted design methodology; it bridges empirical field data with theoretical modeling; and it addresses the mismatch between modern rehabilitation technologies and outdated local practices. Moreover, it integrates traffic performance metrics—such as LOS and service life expectations—into structural pavement evaluation, enhancing both technical and functional sustainability [9].

In summary, the research delivers a practical, data-oriented blueprint for reclaiming aging flexible pavements in Libya. It advocates for transitioning from reactive maintenance toward planned, preventive strategies grounded in modern engineering practices. Such a shift ensures safer, more efficient, and more durable road infrastructure. The study encourages national stakeholders to adopt long-term planning, introduce recycling and stabilization techniques, and promote collaboration among engineers, urban planners, and policy authorities [0]. Future research directions may explore the integration of climate resilience into pavement design, predictive AI-based maintenance models, and comprehensive life-cycle assessments of various rehabilitation techniques. These pathways not only align with global sustainability goals but also strengthen the resilience and cost-effectiveness of transport infrastructure in resource-constrained regions.

Initial inspection to assess the road visually condition.

An initial inspection of the road was conducted by traveling along its route and taking some measurements to assess its current condition. Technical and historical information regarding previous construction and maintenance works was also collected. Accordingly, the road was divided into four sections based on location, width, number of lanes, severity of damage, and traffic volume (4.750 km, 1.875 km, 14.520 km, and 6.355 km). The first section with a length of 4.75 km, consists of two carriageways with six lanes separated by a central median. It is characterized by a non-constant width and very high traffic density. 80 % of the road surface condition is moderate to above average damage. The remaining sections two lanes in each direction, they are old and 65% damaged in varying degrees above average to severe. However, very high traffic density was observed and traffic flow sometimes stops due to the collapse of pavement layers and the presence of branches and services along the road. However, some parts of the first section (Tripoli Bridge to Benghazi Bridge – 4.750 km length) suffers severe damage because it was built more than four decades ago and was designed for a small traffic volume and has not undergone comprehensive maintenance of the base layers. Accordingly, can say that the current condition of the road in terms of functional and service performance is estimated at 35 %. Thus, the engineering decision is to carry out comprehensive maintenance and rehabilitation of the road pavement layers and to raise the service level of the road.

Pavement Functional Assessment (PFA).

Basically, Ride Quality, Safety, Skid Resistance, Surface Drainage, Visibility, and User Perception are the important aspects of functional assessment (PFA), on other words, PFA refers to the evaluation of a road pavement's ability to serve its intended purpose, focusing on characteristics that directly affect the user experience, primarily ride quality and safety. It assesses how well the pavement performs from the perspective of a vehicle traveling on it. Moreover, commonly used indicators and methods are International Roughness Index (IRI), Pavement Condition Index (PCI), and Pavement Serviceability Index (PSI) / Present Serviceability Rating (PSR).

However, this study focused on determination PCI that considers structural distress, by incorporates surface distresses like rutting, patching, and roughness. For this purpose, utilize Micro PAVER software, which is the most effective and widely used program for this task.

Pavement Condition Index (PCI)

Constructed on the PCI value technique, the project was divided into two main branches based on traffic direction. The first branch is a 27.5 km long west-east traffic direction, named (R) to represent the right side, consisting of six sectors. The second branch is 21.14 km long east -west traffic direction, named (L) to represent the left side, and divided into five sectors, as shown in table 1. The division of these branches into sectors considers factors such as pavement structure, traffic flow, construction date, surface type, and condition.

Table 1. The sectors of the two branches

Branches	Sector Code	Kilometer station		Average width of sector (m)	Sector Length (m)	Area (m^2)	Construction Date	Maintenance Date
		From	To					
L	L1	00+000	00+700	10	5600	7،000	1971	1986
	L2	00+700	06+500	10	3700	58،000	1986	2002
	L3	06+500	11+100	8	4900	36،800	1986	2002
	L4	11+100	14+800	9	2350	33،300	1996	2002
	L5	14+800	21+140	9	5600	50،400	1996	2002
R	R1	00+000	00+650	14	650	9،100	1971	2008
	R2	00+650	04+000	14	3350	46،900	1971	2008
	R3	04+000	05+200	15	1200	18،000	1971	2002
	R4	05+200	13+200	8	8000	64،000	1971	2002
	R5	13+200	19+800	8	6600	52،000	1971	2002
	R6	19+800	27+100	9	7300	65،700	1971	2009

PCI Evaluation

According to the standard guidelines of ASTM D 6433-07 (ASTM, 2007) for classifying distress types, severity levels, and methods of measurement and recording. Representative samples of network sections were inspected to identify various distress types. The number of representative samples required for each section within the road branches was determined using the statistical equation 1, with a 95% confidence level, and equation 2, to detarmen spacing interval for selecting random samples.

$$n = \frac{N \times s^2}{\left(\frac{e^2}{4}\right) \times (N-1) + s^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(1)$$

Where**:**
N: Total number of sample units in the section
n: Minimum number of representative sample units to be inspected ($n \geq 5$)
s: Standard deviation (taken as 10 for asphalt concrete pavements)
e: Acceptable error in estimating the section's PCI value (commonly ±5 PCI points)

$$i = \frac{N}{n} \dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots\dots\dots\dots\dots\dots\dots\dots\dots.(2)$$

Where:
i: Spacing interval for selecting random samples

With each road branch divided into sections, the total number of sample units (N), the required number of representative samples (n), and the spacing interval (i) were calculated for each section. These parameters were summarized in Table 2. After determining the required number of samples and their corresponding spacing intervals, field sampling and evaluation procedures were conducted accordingly. In each sample unit, all visible distresses are identified by type such as cracking (alligator, block, longitudinal, transverse), surface deformations (rutting, shoving, depressions), surface defects (raveling, bleeding, polishing), patch failures, and potholes as well as by severity level (low, medium, or high) and quantity (measured in length, area, or count). The collected data and necessary measurements were then entered into the MicroPAVER software to evaluate the Pavement Condition Index (PCI) in accordance with the ASTM D6433-07 standard. The evaluation results presented in table 3.

Table 2. Summary of Total and Representative Samples and Spacing Interval for Each Section in Branches L and R

Branches	Sector Code	From Station	To Station	*N*	*n*	*i*
L	L1	00+000	00+700	18	9	2.0
	L2	00+700	06+500	145	15	9.7
	L3	06+500	11+100	115	15	7.7
	L4	11+100	14+800	93	14	6.6
	L5	14+800	21+1400	156	15	10.4
R	R1	00+000	00+650	17	9	1.9
	R2	00+650	04+000	84	14	6.0
	R3	04+000	05+200	30	11	2.7
	R4	05+200	13+200	200	15	13.3
	R5	13+200	19+800	165	15	11.0
	R6	19+800	27+100	183	15	12.2

Table 3. PCI evaluation results

Sector Code	Kilometer station		Distress				
	From	To	PCI		Distress Classification %		
					Loads	Climate	Other
L1	00+000	00+700	16	Serious	74	18	8
L2	00+700	06+500	42	Poor	68	10	22
L3	06+500	11+100	61	Fair	53	19	28
L4	11+100	14+800	20	Serious	82	6	12
L5	14+800	20+400	34	Very Poor	69	10	21
R1	00+000	00+650	25	Serious	52	41	7
R2	00+650	04+000	60	Fair	59	21	20
R3	04+000	05+200	10	Failed	70	21	9
R4	05+200	13+200	62	Fair	14	57	29
R5	13+200	19+800	53	Poor	32	52	16
R6	19+800	27+100	54	Poor	79	14	7

The causes of pavement deterioration across the entire network were analyzed as shown in Figure. 1. The results indicate that traffic loads represent the primary cause of pavement deterioration at 60%, followed by climatic factors at 24%, and then other causes at 16%.

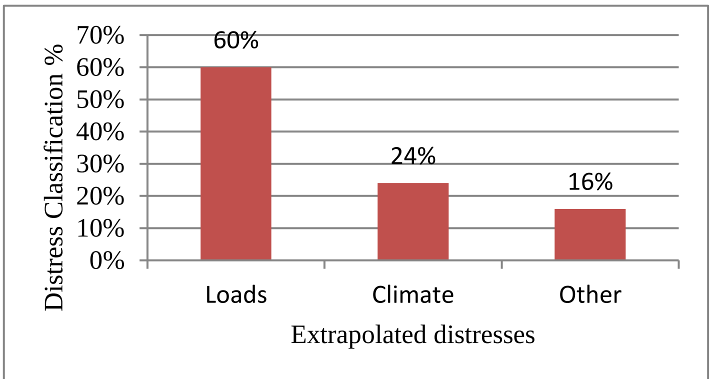


Figure 1. Illustrating the percentage of pavement deterioration causes

Evaluation Outcomes

The evaluation results showed that the average Pavement Condition Index (PCI) for the entire network for the year 2023 was 39.91%, which classifies the pavement condition as Very Poor, indicating that the road requires rehabilitation or comprehensive reclamation. This leads to recommends determining the maintenance method based on laboratory analyses of the existing pavement layers, service requirements, traffic volume, and the owner's instructions.

Geotechnical Investigation

Continuingly for evaluating the full depth of pavement layers to make an informed technical decision regarding the appropriate thickness and category of layer needed for road maintenance and rehabilitation. The study relied on engineering standards based on the evaluation of the materials composing the existing pavement layers. Test samples were taken from investigative pits (Test Pits) that extended through the full depth of the pavement layers. These pits were strategically distributed to ensure a comprehensive understanding of the pavement structure. Where, locations for these investigative borings were selected in the most severely damaged parts of the road, and also based on the road's construction history, figure 2 presents pits location along the road. A comprehensive series of laboratory and field tests were conducted to evaluate the properties of the pavement layers, including the granular base, subbase, and subgrade soil. These tests comprised sieve analysis to determine particle size distribution, Atterberg limits to assess plasticity characteristics, moisture content measurement, laboratory compaction tests (Proctor) to establish optimum dry density, and field density tests to evaluate actual compaction levels. Additionally, the Los Angeles abrasion test was performed to assess aggregate durability, alongside the California Bearing Ratio (CBR) test conducted in the laboratory, and the Dynamic Cone Penetrometer (DCP) test for in-situ evaluation of soil strength. For the asphalt pavement layers, tests included asphalt content extraction, the Marshall stability and flow test to evaluate strength and deformation characteristics, as well as analysis of volumetric properties such as air voids and compaction percentage.

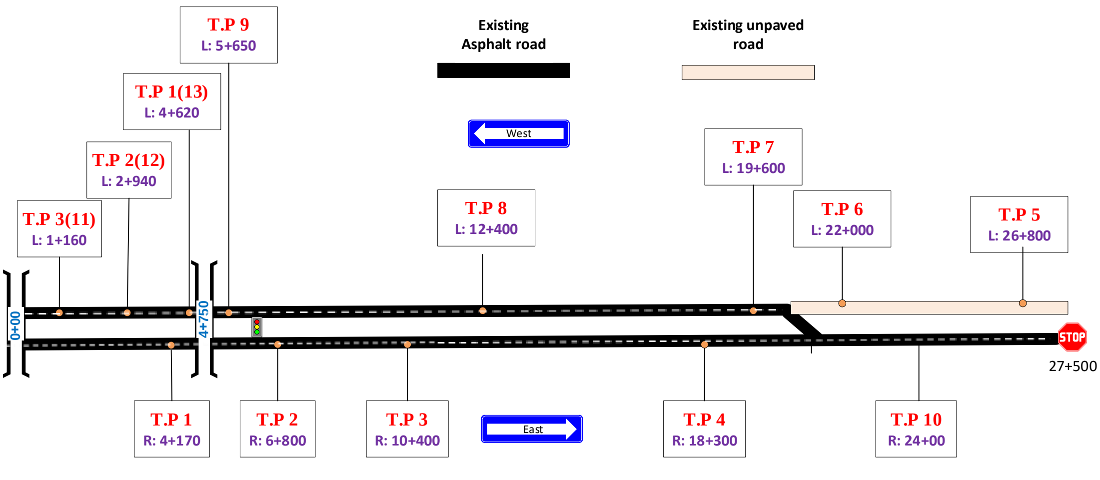


Figure 2. investigative pit's locations

The results from borehole sampling revealed significant variability in the thickness and quality of the surface pavement layers, indicating inconsistencies in construction. Moreover, approximately 90% of the granular base layer, although composed of generally good materials, did not often meet the standard graduation requirements. In certain sections, the subgrade soil was found to be weak and in need of improvement. These findings strongly suggest that the rehabilitation works will need to comprehensively address all pavement layers due to the evident deterioration in structural performance and quality.

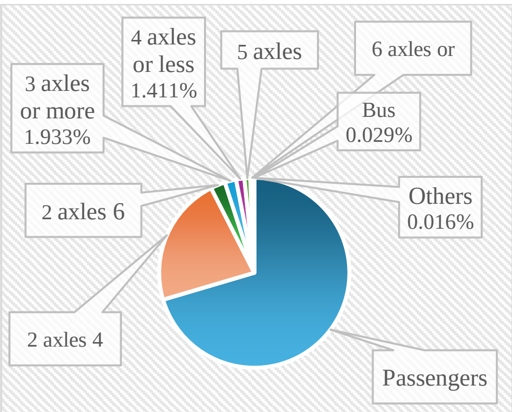
Traffic Volume Survey

As part of the current performance assessment of the Coastal Road within the Misurata urban boundary, a detailed traffic volume survey was conducted to collect accurate data regarding vehicle numbers, directions, and classifications. The collected data serve as a fundamental input for determining the functional classification of the road, the number and type of lanes required, and the functional classification of each lane. Additionally, the information is essential for the structural design of pavement layers. Traffic counts were carried out at two strategic intersections in the city of Misurata: The first at the (location I) Al-Khrouba intersection with the Coastal Road (western entrance to the city). The second at the (location II) intersection of the Heavy Transport Road with the Coastal Road (eastern entrance to the city).

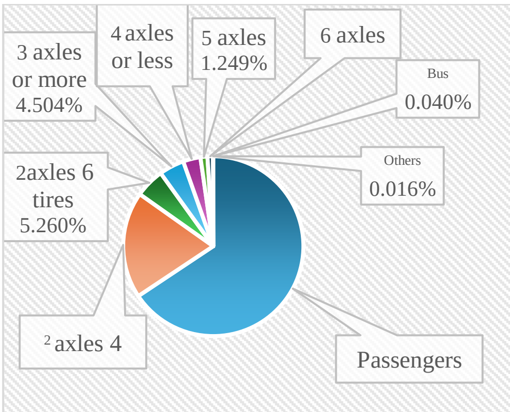
Vehicle counts were recorded over specified time intervals to determine the Average Daily Traffic (ADT), which was then used to estimate the Annual Average Daily Traffic (AADT), following the standard traffic count methodology. Figure 3 illustrates vehicle classification ratios at the location I and Location II. Overall, vehicle distribution patterns were found to be relatively consistent across both locations. The combined proportion of light and heavy transport vehicles was approximately 30%. Notably, heavy vehicle traffic did not exceed 8% at the location I and was around 15% at the location 2.

From an engineering perspective, private and light transport vehicles may have a limited impact on the structural design of pavement layers, although they play a more significant role in determining the Level of Service (LOS). In contrast, heavy vehicles, despite their relatively small numbers, have a disproportionately large effect on pavement deterioration due to their high axle loads. For instance, the passage of a single heavy truck can cause as much damage as 2,500 to 27,500 passenger's vehicles, depending on the truck's axle load.

To put it another way, the structural damage caused by 2,500 private cars is equivalent to that caused by a single application of the standard axle load (W18 = 18 kip). As a result, heavy vehicles are a critical factor in calculating the Equivalent Single-Axle Load (ESAL) and play a direct role in the structural performance evaluation of the roadway.



(a)



(b)

Figure 3. Percentage of vehicles –(a) location I, (b) location II

Level of Service (LOS)

In major road maintenance projects, it is critically important to determine the Level of Service (LOS) to assess whether the road requires widening. A low LOS directly impacts travel time, leading to user dissatisfaction and negatively affecting the economic and service aspects of the country—especially when the road is strategic, as in this case. The number of lanes significantly influences the design load per lane, making this study focus on identifying the current LOS based on traffic volume and the number of existing lanes to determine if additional lanes are necessary. The road can be divided into four sections based on the number of lanes and width: Section 1 (Tripoli Bridge to Benghazi Bridge – km 0+000 to km 4+750) consists of two carriageways, each 14–15 meters wide, with three lanes per direction. However, due to the location in the southern entrance of the city center, high density of intersections, and surrounding commercial activity, the effective number of operating lanes is only two, as the third is often used by slow-moving vehicles. This causes significant congestion. Section 2 (Benghazi Bridge to Heavy Transport Intersection – km 4+750 to km 6+620) consists of two carriageways, each 10–12 meters wide with two lanes per direction. Despite fewer intersections, traffic is dense, mainly due to the high volume of vehicles accessing or exiting to the heavy transport road. Section 3 (Heavy Transport Intersection to end of dual carriageway – km 6+620 to km 21+140) also consists of two carriageways, each 8–9 meters wide, with two lanes per direction. The number of intersections is relatively low, with moderate to high traffic density. Section 4 (End of dual carriageway to Al-Kararim Gate – km 21+140 to km 27+500) consists of a single carriageway, 8.5–9.5 meters wide, with one lane per direction and very high traffic density due to the incomplete dualization of this segment.

LOS calculations were performed based on traffic survey data at two key locations: Location I (Kharouba Intersection) showed a poor LOS (E to D) for vehicles entering or exiting the city from the west, while Location II (Heavy Transport Intersection) had an acceptable LOS (around C) for traffic from the east, which may be temporarily acceptable for a collector-type road. However, considering that maintenance is planned for a 20-year service life and a 4% annual traffic growth rate, LOS is expected to deteriorate further over time, which is undesirable from economic, service, and technical standpoints. Thus, the required number of lanes was calculated to maintain acceptable LOS across the road's lifetime. The results showed that to achieve a good LOS (B) from Tripoli Bridge to Benghazi Bridge (km 0+000 to km 4+750), the road must have four lanes per direction instead of three, and to achieve an acceptable LOS (C) from Benghazi Bridge to the end of the road at Al-Kararim Gate (km 6+620 to km 27+500), the road should have three lanes per direction instead of two. By implementing these upgrades, the road maintenance project will fulfill the required service level throughout its 20-year design life, ensuring efficient and sustainable performance [1].

Design Loads

Based on the data previously collected—including traffic surveys, required Level of Service (LOS), and geotechnical characteristics of the existing pavement layers—a comprehensive design and rehabilitation strategy has been formulated. This strategy aims to ensure high durability and satisfactory performance of the roadway throughout its design life. Field investigations and data collection regarding vehicle loads revealed substantial variations in vehicle types, particularly in terms of axle number, type, and configuration. It was observed that trucks with similar gross weights could exhibit different axle configurations, which significantly influence pavement response.

From an engineering perspective, the thickness of pavement layers is directly affected by axle loads and their configurations. For instance, a specific load applied through a single axle causes more structural damage than the same load distributed across a tandem axle. Generally, the structural damage tends to decrease as the number of axles increases, depending on their type and arrangement.

Data from the Libyan Roads and Bridges Authority, which specify allowable axle loads on public roads, were utilized along with field measurements of loaded vehicles (transporting different types of goods) and data gathered from loading/unloading stations at industrial and commercial facilities. These inputs were used to calculate the Equivalent Axle Load Factor (EALF) following the AASHTO (AASHTO, 1993) Guide for Design of Pavement Structures (1993), a widely recognized international reference adopted by many countries including Libya. Furthermore, the Design Equivalent Single Axle Load (ESAL) was estimated based on traffic survey data. The Average Daily Traffic (ADT) in the design direction was 13,679 vehicles at Location I (Kharouba Intersection) and 7,942 at Location II (Heavy Transport Intersection). Assuming a 20-year design life, a 4% annual growth rate, and 60% traffic load distribution in the design lane, the total design ESAL was calculated to be 92,473,802.

Design and Rehabilitation of Pavement Layers

The results of the above analyses confirm the necessity of implementing extensive maintenance and rehabilitation efforts to meet the current and projected traffic demands over a 20-year period with an annual growth rate of 4%. table 4 summarizes the outcomes of the engineering evaluations and proposed solutions.

Table 4. Results of engineering works carried out in the previous parts

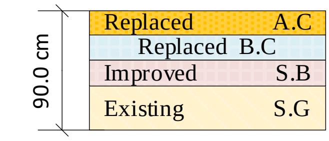
N	Description	Results	Opinion and Evaluation
1	Initial visual inspection	The current road condition is estimated in terms of functional and service performance 35%	Serious maintenance and rehabilitation of the pavement layers and also raising the level of service of the road
2	Find the value of existing pavement condition index	PCI-Rate (2023) is 39.9 (Very poor)	Rehabilitation of asphalt concrete layers completely (might requires advanced technologies or to remove it and construct new layers)
3	Geotechnical Investigation	Unevenness in the thickness of surface paving layers. Granular base materials often do not meet gradient requirements and sometimes do not conform to specifications as a granular base layer.	1- In case of maintaining the current road level replacement of a 20 cm thick granular base layer. The scraped granular base layer may use as an sub-base layer for the added lane. 2- In the event that the road level can be raised: a layer is added to add a granular base layer with a thickness of 20 cm. 3- Recycling the granular base layer (using foamed asphalt or cement)
4	Existing road - Level of Service (LOS)	Level of Service (LOS) The current service level of the road is acceptable to weak but will weaken further over time	To achieve good service (LOS=B), the number of lanes must be increased, one lane in each direction for the sector from Tripoli 0+00 to Benghazi 4+750. Also to achieve good service (LOS=C) the number of lanes must be three lanes in each direction for the sector from Benghazi Bridge 4+750 to end of the road at 27+500.
5	Design Equivalent Axle Load (ESAL)	Design Equivalent Axle Load (ESAL) in the current road situation the design equivalent is very large ≈ ($139\times10^{6.}$)	In the current state of the road the design equivalent load value is very large ≈ (139×10^{6}.). This requires large paving layer thickness and is uneconomical nevertheless adding a lane to each track will reduce the equivalent load value to become ≈ (93×10^{6}). It is the most appropriate option to achieve a good level of service in addition to being the most appropriate solution from an economic and technical point of view.

8.1 Pavement Thickness Analysis

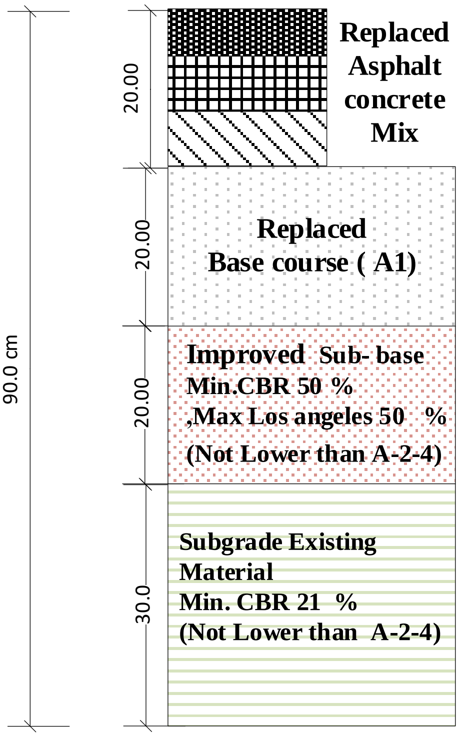
The Flexible Pavement Design Tool was used in accordance with the AASHTO (AASHTO, 1993) manual to estimate the necessary layer thicknesses [4]. Three design proposals were compared:

1. **Proposal 1**: Replace the granular base layer with a new layer in the segment where elevation cannot be changed (to maintain clearance between bridges and roadway). In other segments (without bridges), a new granular base layer can either be added or replaced. (details in table 5).

Table 5. Proposal 1 replace the granular base

Parameter	Initial Serviceability (Po)	Terminal Serviceability (p_t)	Reliability Level R	Standard Deviation	ESALs(W18)	
Value	4.2	2.5	90 %	0.45	92473802	

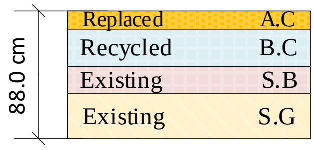
Layer	**(N) New (E) Existing Layer**	**Thickness (cm)**	**Coefficient, a(i)** ***Layer Coefficient***	**SN** ***Structural Number***	**Provided SN**	**Required SN**	**Adequateness check**
Wearing Asph.Mix	N	6.0	0.42	0.99	6.46	5.80	Provided > Required **Yes**
Binder Asph.Mix	N	7.0	0.42	1.16			
Base Asph.Mix	N	7.0	0.42	1.16			
Base Course	N	20.0	0.14	1.10			
Subbase	E	20.0	0.11	0.87			
Subgrade	E	30.0	0.10	1.18			



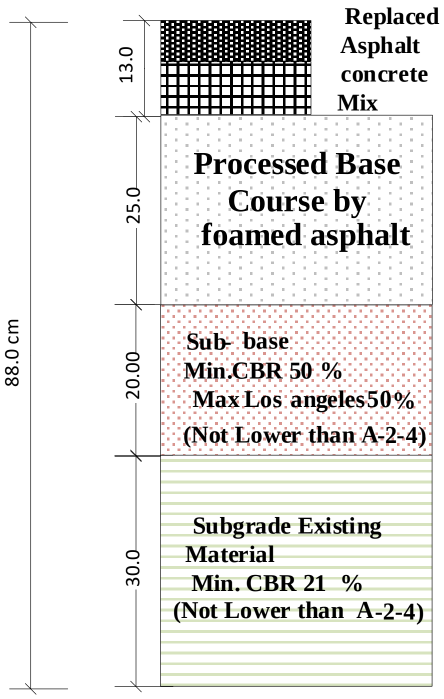
2. **Proposal 2**: Recycle the existing granular base layer to a depth of 25 cm by increasing the layer coefficient from 0.14 to 0.20 using foamed asphalt as a stabilizing agent. (details in table 6).

Table 6. Proposal 2 recycle the existing granular base using foamed asphalt

Parameter	Initial Serviceability (Po)	Terminal Serviceability (pt)	Reliability Level R	Standard Deviation	ESALs(W18)
Value	4.2	2.5	90 %	0.45	92473802

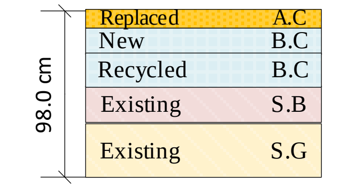


Layer	(N) New (E) Existing Layer	Thickness (cm)	Coefficient, a(i) *Layer Coefficient*	SN *Structural Number*	Provided SN	Required SN	Adequateness check
Wearing Asph.Mix	N	6.0	0.42	0.99	6.16	5.80	Provided > Required **Yes**
Binder Asph.Mix	N	7.0	0.42	1.16			
Base Asph.Mix	non	--	--	--			
Base Course	E	25.0	0.20	1.97			
Subbase	E	20.0	0.11	0.87			
Subgrade	E	30.0	*0.10*	1.18			

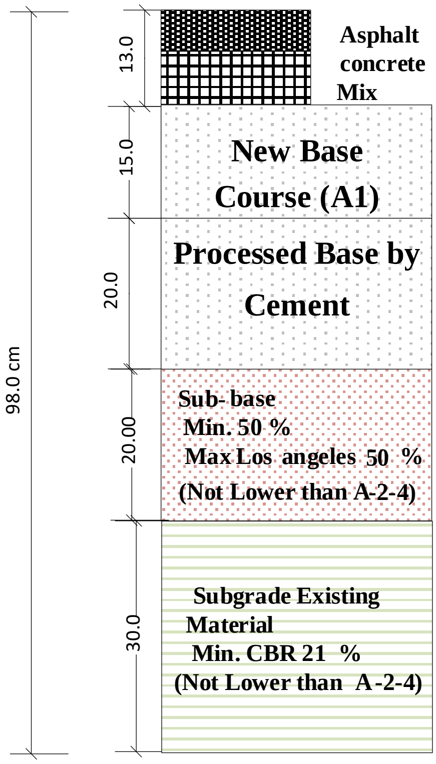


3. **Proposal 3**: Recycle the foundation layer to a depth of 20 cm using cement as a stabilizer, increasing the layer coefficient from 0.14 to 0.20. A 15 cm granular base layer is added above the treated layer to prevent reflective cracking and to minimize stress concentrations due to stiffness variation. (details in table 7).

Table 7. Proposal 3 recycle the existing granular base using cement as a stabilizer

Parameter	Initial Serviceability (Po)	Terminal Serviceability (p_t)	Reliability Level R	Standard Deviation	ESALs(W18)	
Value	4.2	2.5	90 %	0.45	92473802	

Layer	(N) New (E) Existing Layer	Thickness (cm)	Coefficient, a(i) *Layer Coefficient*	SN *Structural Number*	Provided SN	Required SN	Adequateness check
Wearing Asph.Mix	N	6.0	0.42	0.99	6.6	5.80	Provided > Required **Yes**
Binder Asph.Mix	N	7.0	0.42	1.16			
Base Asph.Mix	N	15.0	0.14	0.83			
Base Course	E	20.0	0.20	1.57			
Subbase	E	20.0	0.11	0.87			
Subgrade	E	30.0	0.10	1.18			



1. Cost Comparison of Maintenance Alternatives

Table 8 presents a comparative analysis of the cost of the three proposals. Cost estimates were derived from the official Indicative Price Guide for Road and Bridge Works, by Decree No. 459 of 2022 issued by the Prime Minister of the Government of National Unity. Recycling costs were based on current market rates.

- Proposal 3 had the **lowest implementation cost**.
- Proposal 1 had a **6.7% higher cost** than Proposal 3.
- Proposal 2 showed a **14.5% higher cost** than Proposal 3.

Table 8. Comparative analysis of the cost of the three proposals

Description	Proposal 1	Proposal 2	Proposal 3	Note
	Cost (Libyan Diner) per square meter			
Removal of the old granular foundation layer	6.0	0.0	6.0	* Refers to the granular layer material that will be recovered and reused as a sub base layer in the .construction of the new lanes
6Wearing- Asphalt concrete thickness cm	68.7	68.7	68.7	
Binder- Asphalt concrete thickness 7 cm	80.15	80.15	80.15	
Base- Asphalt concrete thickness 7 cm	80.15	0.0	0.0	
Granular base layer thickness 15 cm	0.0	0.0	20.213	
Granular foundation layer thickness 20 cm	26.95	0.0	0.0	
Recycling with bitumen	0.0	120	0.0	
Cement recycling	0.0	0.0	70	
Rc2	6.25	3.125	3.125	
mco	4.5	4.5	4.5	
Discounting the value of the material benefited from*	15.0	0.0	11.25	
Total cost per square meter	**257.70**	**276.475**	**241.438**	

CONCLUSION AND RECOMENDATIONS

The findings suggest that the deterioration of Libya's road network is not solely due to pavement layer design or composition, but also due to multiple contributing factors, including:

1. Delays in performing timely maintenance activities.
2. Roads exceeding their design life, particularly due to asphalt aging, where the material loses its elasticity and becomes brittle over time.
3. Obstruction of drainage systems and valley paths, resulting in water accumulation on roadway surfaces for extended periods.
4. Overloaded trucks, which exert excessive stresses on the pavement structure.

OPTIMAL RECLAMATION RECOMMENDATION.

Although recycling techniques using cement or foamed asphalt provide benefits such as cost reduction and increased structural strength, Naturally, the results of treatments are not guaranteed to be reliable. And these techniques require advanced implementation technologies and may introduce construction challenges, including:

- **Shrinkage cracking and construction joint issues** in cement-stabilized layers, especially over long sections (80–200 m), as well as differences in behavior between rigid (recycled) and flexible concrete layers, leading to early cracking due to stress concentrations.
- **Foamed asphalt**, while more flexible and similar in behavior to traditional asphalt, is limited by high material cost and difficulties in controlling the quality of recycled materials across the full layer depth.

Therefore, the study recommends Proposal 1 as the preferred maintenance option. This method follows a traditional approach that has proven reliable worldwide and has been successfully implemented in many Libyan road projects still in service today. Moreover, Proposal 1 ensures 100% renewal of all pavement layers with only a modest increase in cost (no more than 7 %) compared to Proposal 3. Given the strategic nature of the project, this cost difference is considered highly reasonable.

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دراسة تحليلية شاملة لاعادة التاهيل الإنشائي للرصف المرن المتقادم

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الملخص

التدهور التدريجي للرصف المرن، الناتج عن زيادة أحمال المرور والتأثيرات البيئية وتقادم المواد، يفرض الحاجة إلى تطبيق استراتيجيات فعّالة لإصلاح الهيكل الإنشائي من أجل استعادة الأداء الوظيفي وإطالة عمر الخدمة. تركز هذه الدراسة على مقطع حيوي من شبكة الطريق الساحلي الليبي، وتحديدًا الجزء الذي يبلغ طوله 27.5 كيلومترًا ويمتد من جسر شارع طرابلس إلى بوابة الكراريم. قد أُجريت دراسة تحليلية وكمّية لتقييم الحالة الإنشائية وإمكانيات إعادة التأهيل لنظام الرصف المرن القائم، مع التركيز على آليات التلف، وتدهور المواد، وفعالية تقنيات التأهيل المختلفة. وقد شملت عملية التقييم اعمال ميدانية، واختبارات معملية، وإجراءات معيارية تم تحديدها وفقًا لإرشادات AASHTO لتقييم التلف في الرصف، وقوة تربة الأساس، وأداء طبقات الخرسانة الأسفلتية. كما تم استخدام قيم مؤشر حالة الرصف (PCI) وتحليل عينات اللب لاستخلاص مدى الفشل الإنشائي. وتم دعم البيانات من خلال مسوحات بصرية لأشكال التلف لتوفير فهم شامل للظروف السطحية وتحت السطحية. وقد استخدم النمذجة التحليلية، بناءً على نظرية المرونة الطبقية، لمحاكاة استجابة الرصف بعد التأهيل وتوقع أدائه طويل الأمد تحت الأحمال. وتبحث الدراسة في عدة طرق لإعادة التأهيل، تشمل إعادة الإنشاء الكامل(Full–Depth Reclamation) ، وإعادة التدوير في الموقع على البارد(Cold In–Place Recycling) ، والتثبيت الميكانيكي باستخدام إضافات إسمنتية. وقد تم تقييم كل طريقة بناءً على تعزيز القدرة الإنشائية، وكفاءة التكلفة، وإطالة عمر الخدمة. وأظهرت النتائج أن اختيار تقنيات الإصلاح المناسبة لظروف التربة وأحمال المرور يُحسّن بشكل كبير الأداء الإنشائي ويقلل من احتياجات الصيانة. وتخلص الدراسة إلى أن إعادة الرصف الكامل تمثل الحل الأكثر استدامة وجدوى اقتصادية لإصلاح المقطع المستهدف من الطريق.

الكلمات المفتاحية: *الرصف المرن، إصلاح الهيكل الإنشائي للرصف، إعادة تأهيل الرصف، إعادة الإنشاء الكامل، إعادة التدوير في الموقع على البارد.*