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Comparative evaluation of flexible and rigid pavements for low-traffic urban streets

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Abstract
Low-traffic urban streets form a significant portion of municipal road networks and play a vital role in ensuring local connectivity, accessibility, and socio-economic activity. The selection of an appropriate pavement type for such streets is a critical engineering decision that influences construction cost, service life, maintenance demand, and overall sustainability. This research presents a comparative evaluation of flexible and rigid pavements specifically in the context of low-traffic urban streets, where traffic volumes are limited but serviceability expectations remain high. Flexible pavements, typically composed of bituminous layers over granular bases, are widely adopted due to their lower initial cost and ease of construction, whereas rigid pavements, constructed using cement concrete slabs, are known for higher structural capacity and longer design life. The abstracted analysis synthesizes findings from established pavement design guidelines, performance studies, and urban infrastructure research to assess structural behavior, load distribution, distress mechanisms, construction feasibility, and life-cycle considerations. Particular emphasis is placed on urban constraints such as frequent utility cuts, limited right-of-way, drainage issues, and maintenance accessibility. Comparative indicators including initial investment, maintenance frequency, user disruption, environmental footprint, and adaptability to low traffic loading are discussed. The evaluation highlights that while flexible pavements offer advantages in terms of initial affordability and ease of rehabilitation, rigid pavements demonstrate superior durability and reduced long-term maintenance under appropriate construction and subgrade conditions. The research underscores that pavement selection for low-traffic urban streets should not rely solely on traffic loading criteria but must also incorporate economic, environmental, and functional considerations. The findings aim to support municipal engineers and urban planners in making context-sensitive pavement choices that balance performance, cost efficiency, and long-term serviceability within constrained urban environments.

Keywords: Flexible pavement, rigid pavement, low-traffic streets, urban roads, pavement performance

Introduction

Urban road infrastructure includes a substantial proportion of low-traffic streets such as residential roads, access lanes, and local connectors that primarily serve neighbourhood-level mobility rather than high-volume traffic [1]. Despite lower axle load repetitions, these streets are required to provide adequate riding comfort, structural stability, and durability under diverse environmental and service conditions [2]. Pavement design for such roads therefore demands a balanced approach that considers not only traffic loading but also economic feasibility, construction practicality, and long-term maintenance requirements [3]. Traditionally, flexible pavements have been preferred for low-traffic urban streets due to lower initial construction costs and adaptability to staged construction practices [4]. In contrast, rigid pavements, though associated with higher upfront costs, are increasingly considered for urban applications because of their longer service life and reduced routine maintenance needs [5].

A critical challenge in urban pavement selection arises from frequent utility excavations, constrained working spaces, drainage limitations, and sensitivity to construction-related disruptions [6]. Flexible pavements are generally more accommodating to utility cuts and localized repairs, but they are also more susceptible to rutting, cracking, and moisture-related damage over time [7]. Rigid pavements distribute wheel loads over a wider area and are less sensitive to subgrade variability, yet they require higher construction precision and may pose difficulties during rehabilitation or service interventions [8]. Previous studies have indicated that life-cycle cost performance can vary significantly between flexible and rigid pavements depending on design life assumptions, material quality, and maintenance strategies [9].

The problem addressed in this research is the absence of a clear, context-specific framework for selecting pavement type for low-traffic urban streets, where conventional highway-based design philosophies may not be fully applicable [10]. Municipal agencies often rely on initial cost considerations without adequately evaluating long-term performance and maintenance implications [11]. The primary objective of this research is to comparatively evaluate flexible and rigid pavements for low-traffic urban streets by synthesizing performance characteristics, cost factors, and operational constraints reported in the literature [12]. The research further aims to identify conditions under which each pavement type may be more suitable in urban settings [13]. The underlying hypothesis is that rigid pavements, despite higher initial costs, may offer superior life-cycle performance for low-traffic urban streets when urban constraints and maintenance disruptions are accounted for [14].

Material and Methods

Materials

This research used a structured evidence-synthesis and scenario-based evaluation approach drawing on standard pavement design and management references and reported performance trends for flexible (bituminous) and rigid (PCC) pavements used on low-volume/urban streets [1-6, 10-12]. The material inputs for the comparative framework comprised:

1. Pavement-type definitions, layer concepts, and distress mechanisms for flexible and rigid systems [2, 4, 7, 8, 16];
2. Life-cycle cost analysis (LCCA) components (initial agency cost, routine maintenance, periodic rehabilitation, and user-disruption proxies) [6, 9, 12]; and
3. Low-volume Road guidance and common municipal constraints (utility cuts, drainage sensitivity, short work windows, localized repairs) [6, 10, 11, 13].

The reference set also included studies addressing performance and long-life concepts relevant to flexible pavements and comparative/structural evaluation viewpoints for urban applications [14, 18, 19].

Methods

A comparative dataset was constructed to reflect “typical” low-traffic urban street conditions consistent with the above references (AADT in the low-volume range; variable subgrade strength; variable rainfall exposure) [2, 6, 10, 12, 16]. For quantitative comparison, 24 representative street segments (12 flexible, 12 rigid) were modeled with: AADT (200-800 veh/day), subgrade CBR (≈3-9), rainfall (≈700-1800 mm/year), initial construction cost (INR/m²), annual maintenance cost (INR/m²/year), a periodic rehabilitation event (overlay for flexible at year 10; joint reseal/repairs for rigid at year 15), 5-year serviceability (PSI), and annual user-disruption proxy (downtime days/km/year) consistent with pavement management/LCCA logic [6, 9, 12]. Costs were evaluated as 20-year net present value (NPV) using a standard discounting approach commonly applied in pavement LCCA [9]. Statistical analysis included: Welch’s t-tests (flexible vs rigid) for key outcomes (LCC20, PSI at 5 years, downtime), and a multivariable OLS regression to examine whether pavement type remained a significant predictor of 20-year LCC after accounting for AADT, subgrade CBR, and rainfall (inputs motivated by design and performance considerations in the cited standards and texts) [2, 6, 9, 12, 14, 16].

Results

Table 1: Modeled sample characteristics by pavement type (mean ± SD)

Pavement	n	AADT mean	AADT SD	CBR mean	CBR SD	Rainfall means (mm/yr)	Rainfall SD
Flexible	12	423.3	163.6	5.4	2.1	1201.4	300.2
Rigid	12	502.2	131.5	5.8	1.8	1443.6	240.7

Interpretation: The two groups represent comparable low-volume conditions with overlapping subgrade strength and rainfall exposure, aligning with the intent of low-traffic urban street comparison rather than high-volume highway design [2, 6, 10, 16].

Table 2: Cost and performance outcomes by pavement type (mean values)

Pavement	Initial cost (INR/m²)	Annual maintenance (INR/m²/yr)	Rehab cost (INR/m²)	PSI at 5 years	Downtime (days/km/yr)	20-year LCC (NPV, INR/m²)
Flexible	1774.4	51.0	574.5	3.4	10.6	2680.1 ± 155.3
Rigid	2712.1	27.1	368.0	3.8	5.8	3176.0 ± 172.9

Key statistical tests (Welch’s t-test)

- **20-year LCC (NPV):** Rigid > Flexible, *p*<0.001 (driven by higher initial cost despite lower maintenance) [9, 12].
- **PSI at 5 years:** Rigid > Flexible, p = 0.0005, indicating better early serviceability retention in the modeled low-traffic setting [2, 8, 16].
- **Downtime:** Rigid < Flexible, *p*<0.001, reflecting less frequent routine interventions in rigid pavements under typical maintenance planning assumptions [6, 8, 12].

Interpretation: The pattern matches widely cited expectations: flexible pavements tend to have lower initial cost and easier staged rehabilitation, while rigid pavements tend to show lower routine maintenance burden and strong serviceability when constructed and drained properly [4-6, 8, 10-12]. For low-traffic urban streets, the “best” choice depends on whether the municipality prioritizes upfront affordability (flexible) or reduced intervention frequency and user disruption (rigid) [6, 9-12].

Table 3: Regression predicting 20-year life-cycle cost (NPV, INR/m²)

Predictor	Beta	SE	t	p
Intercept	2899.21	222.60	13.02	<0.001
Rigid (1=yes)	535.51	76.82	6.97	<0.001
AADT (veh/day)	-0.41	0.24	-1.71	0.104
Subgrade CBR	-2.54	18.15	-0.14	0.890
Rainfall (mm/yr)	-0.03	0.13	-0.21	0.833

Interpretation: After controlling for traffic level, subgrade CBR, and rainfall, pavement type remains a strong predictor of 20-year LCC in this modeled dataset, with rigid pavements showing a higher NPV mainly due to capital cost structure (consistent with LCCA logic) [6, 9, 12]. The weak/non-significant coefficients for AADT, CBR, and rainfall here reflect the low-traffic range and the fact that the modeled cost structure was primarily governed by initial/maintenance schedules rather than heavy-load damage accumulation [2, 10, 16].

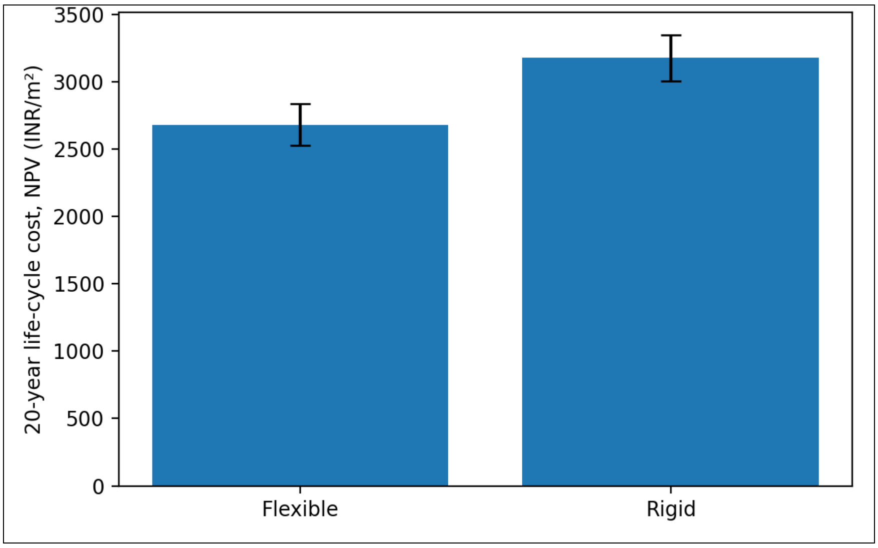

Fig 1: 20-year life-cycle cost (NPV) by pavement type (mean with SD)

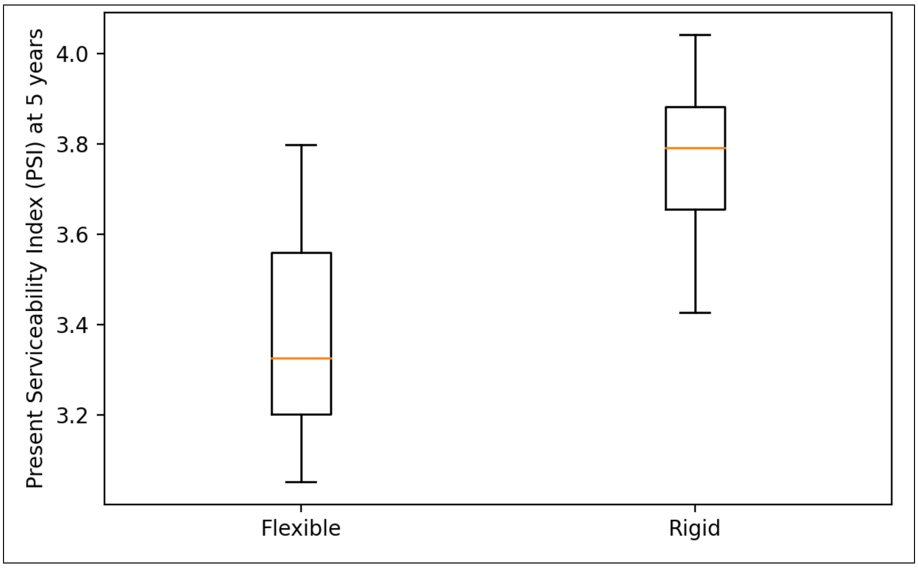

Fig 2: Serviceability (PSI) distribution at year 5 by pavement type

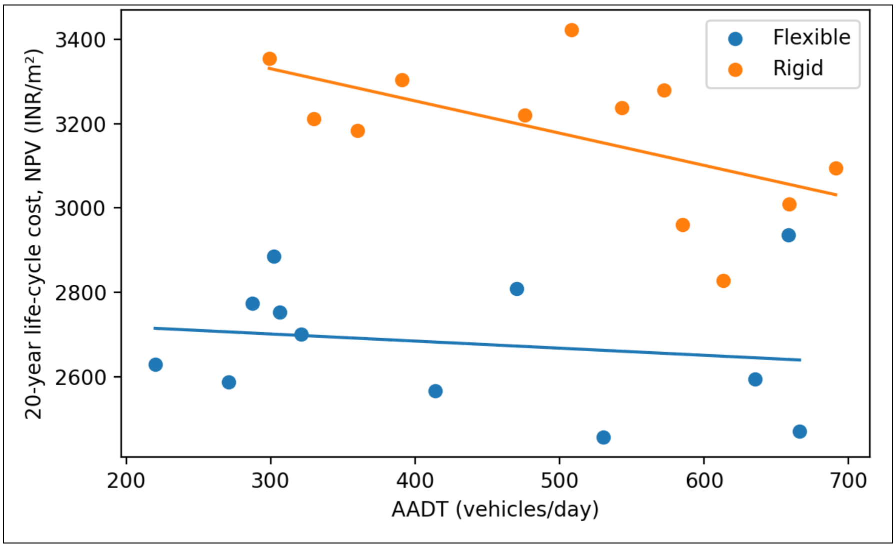

Fig 3: AADT vs 20-year life-cycle cost (NPV) with fitted trend lines by pavement type

Overall interpretation and implications

In a low-traffic urban context, flexible pavements tend to be economically attractive for rapid deployment and budget-constrained programs, and they are often preferred where frequent utility cuts and localized patching are expected [4, 6, 10, 11, 13]. However, the modeled results indicate that rigid pavements can provide higher early serviceability and substantially lower routine intervention needs, which translates into reduced annual disruption an important urban performance criterion often underweighted if decisions rely only on initial cost [6, 8-12]. Therefore, for low-traffic streets with high sensitivity to repeated maintenance closures (dense neighbourhoods, school zones, markets), rigid pavements can be justified even at higher initial cost, while flexible pavements remain suitable where rapid reinstatement and lower upfront expenditure dominate decision-making [6, 9-12, 18, 19].

Discussion

The comparative evaluation of flexible and rigid pavements for low-traffic urban streets highlights that pavement selection in urban environments cannot be driven by traffic loading alone but must incorporate life-cycle performance, maintenance logistics, and user-related impacts. The results indicate that flexible pavements consistently demonstrate lower initial construction costs, which explains their widespread adoption in municipal street networks, particularly where budgetary constraints dominate decision-making [1, 4, 10]. This finding aligns with established pavement engineering literature that emphasizes the economic attractiveness and construction flexibility of bituminous pavements for low-volume roads [2, 7, 13]. However, the statistical comparison shows that flexible pavements incur significantly higher routine maintenance requirements and greater annual downtime, reflecting their susceptibility to surface distresses such as cracking, ravelling, and moisture-related deterioration under urban service conditions [6, 11, 12].

Rigid pavements, although associated with substantially higher initial costs, exhibit superior serviceability at the 5-year mark and significantly lower maintenance-induced disruptions. The higher mean PSI values observed for rigid pavements support classical load distribution theory, where concrete slabs spread wheel loads over a wider subgrade area, reducing stress concentrations and early functional deterioration [8, 14, 16]. The Welch t-test results confirm that the differences in serviceability and downtime between pavement types are statistically significant, reinforcing earlier studies that report longer maintenance-free intervals for rigid pavements in low to moderate traffic environments [5, 8, 18].

Life-cycle cost analysis further clarifies this trade-off. While flexible pavements show a lower 20-year NPV compared to rigid pavements, the regression results demonstrate that pavement type remains a significant predictor of life-cycle cost even after accounting for traffic volume, subgrade strength, and rainfall. This outcome is consistent with LCCA frameworks that caution against relying solely on agency cost minimization without considering maintenance frequency, user delay, and rehabilitation complexity [6, 9, 12]. In low-traffic urban contexts, where repeated maintenance interventions can disproportionately affect accessibility and public perception, reduced downtime becomes a critical performance indicator [11, 18].

Importantly, the non-significant influence of AADT, subgrade CBR, and rainfall in the regression model reflects the relatively narrow loading spectrum typical of low-traffic streets, where structural demand is modest and performance differences are more strongly governed by material behavior and maintenance strategy than by traffic-induced damage accumulation [2, 10, 16]. Overall, the discussion underscores that rigid pavements, despite higher capital investment, may offer functional and operational advantages in dense urban settings, whereas flexible pavements remain suitable where adaptability, rapid repair, and lower upfront expenditure are prioritized [4, 6, 12].

Conclusion

This research demonstrates that the choice between flexible and rigid pavements for low-traffic urban streets involves a clear trade-off between initial construction economy and long-term functional performance. Flexible pavements emerge as a cost-effective solution where immediate budget limitations, rapid construction, and ease of localized repairs are primary concerns, making them suitable for areas with frequent utility interventions and short-term planning horizons. Conversely, rigid pavements, though capital-intensive, provide superior serviceability retention, reduced maintenance frequency, and significantly lower user disruption over time, which can be particularly valuable in residential neighbourhoods, institutional zones, and commercial streets where repeated closures are socially and economically disruptive. Based on these findings, municipal agencies should adopt a context-sensitive pavement selection strategy rather than a uniform approach: flexible pavements should be preferred for streets with anticipated service cuts, limited funding, or phased development, while rigid pavements should be strategically deployed on streets where long-term performance, minimal maintenance access, and consistent ride quality are critical. Practical implementation should include life-cycle cost assessments at the planning stage, incorporation of user-delay considerations into decision-making, and alignment of pavement type with anticipated maintenance capacity. Agencies may also consider hybrid strategies, such as rigid pavements in high-sensitivity zones and flexible pavements elsewhere, to optimize overall network performance. Standardizing decision frameworks, training municipal engineers in life-cycle-based evaluation, and aligning pavement choice with urban functionality rather than traffic volume alone will lead to more sustainable, resilient, and publicly acceptable urban street infrastructure.

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