Feasibility of Employing Prestressed Precast Concrete Pavement with Welded Wire Mesh: A Sustainable Solution

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Abstract

The critical role of road infrastructure in shaping a nation's economic landscape is widely acknowledged. The global pursuit of sustainable and cost-effective road infrastructure has led to the adoption of Prestressed Precast Concrete technology. Specifically, Prestressed Precast Concrete Pavement (PPCP) has emerged as a transformative approach, involving the production of precast pavement panels at dedicated construction yards, followed by their transportation to the project site and subsequent tensioning. Welded Wire Reinforcement (WWR), a prefabricated high-strength welded wire arranged in rectangular grids, plays a pivotal role in this innovation. PPCP implemented along with WWR not only expedites construction but also elevates the quality and durability of pavements. In this paper, a method is introduced for the construction of an economically viable and sustainable pavement system using PPCP with WWR. This pioneering approach elucidates its benefits and presents a detailed cost-benefit analysis. This paper aims to shed light on a pragmatic and forward-looking solution for road infrastructure, aligning with the essentials of sustainability, economic viability, and quality.

Keywords

Prestressed Precast Concrete Pavement, Welded Wire Reinforcement, Cost-benefit Analysis, Sustainability and Economic Feasibility.

1. Introduction

The development of a nation's road network holds significant importance in fostering socio-economic growth. In the context of Bangladesh, similar to numerous developing nations, road infrastructure plays a crucial role as a lifeline, connecting various regions, facilitating trade and commerce, and improving the overall quality of life for its citizens. The escalating demand for enhanced road transport infrastructure in Bangladesh are stimulated by the country's expanding economy and rapidly growing population.

The development of infrastructure (especially in transportation, energy, and telecommunications) has played a pivotal role in driving the economic advancement of the region. Public investment at the national scale has demonstrated a direct correlation with GDP growth, with certain assessments indicating that, on average, each 1% augmentation in infrastructure assets elevates GDP by 0.08% (Arvis et al. 2011).

Bangladesh, a developing nation, is strongly committed to advancing its infrastructure. In the 2023-24 budget, a substantial portion of funds is allocated to the construction industry, with about 28.9% of the Annual Development Project (ADP) directed towards transportation and communication projects. Notably, the ADP constitutes nearly 35% of the total annual budget, underscoring the significant priority placed on enhancing infrastructure, transportation, and communication networks. This investment aims to boost economic growth and enhance the quality of life for citizens (Sarwar 2023).

In the pursuit of sustainable road solutions that not only cut down on maintenance and operational costs but also handle the constant rise in traffic, rigid pavements (especially cast-in-place concrete pavements) have become the preferred option. This choice is backed by a careful assessment of life cycle costs. Rigid pavements are known for their durability and minimal maintenance needs, making them a financially sound choice over the long term. Developing road transport infrastructure requires substantial capital investment (Hamim et al. 2021). Moreover, due to the ever-increasing traffic, fast construction is the need of the hour (Syed and Sonparote 2020).

To find a sustainable road solution that demands minimal maintenance and operational costs while accommodating the ever-increasing traffic volumes, developing countries, including Bangladesh, have turned their attention to rigid pavements. The preference for rigid pavements over conventional flexible ones is driven by a comprehensive consideration of life cycle costs (Kale et al. 2016). However, a persistent concern has been the extended duration required for the construction of traditional cast-in-place concrete pavements, commonly known as rigid pavements.

To expedite the construction process and address this challenge, the construction industry has increasingly embraced precast construction practices, as documented by (L.-M. Chang and Chen, 2012). Precast construction methods have been well-established worldwide for constructing not only roads but also buildings and bridges, among others (Tomek, 2017). In recent years, precast concrete pavements have gained global recognition for their ability to provide superior quality control and deliver swift and durable construction results. This approach has garnered substantial popularity due to its efficacy in meeting the demands of modern infrastructure projects.

Welded Wire Reinforcement (WWR) is a notable component in this construction methodology. WWR is a form of prefabricated reinforcement, characterized by parallel high-strength wires welded together in rectangular grids, adhering to the standards outlined in ACI 318/19 (Ahmed et al. 2023). Its long-standing use in the construction industry is attributed to the multitude of benefits it offers, such as the reduction of construction periods, material savings, and a comprehensive decrease in project costs (Gilbert and Smith 2006).

Another innovative approach is the adoption of Prestressed Precast Concrete Pavements (PPCP), similar to traditional Precast Concrete Pavements (PCP). PPCP involves the post-tensioning of individual precast panels in the direction of the traffic. Crucially, ducts designed for post-tensioning are embedded in the precast panels during their construction. This strategic inclusion not only reduces construction time but also enhances the riding quality of the pavement (Kim et al. 2021; Tomek 2017; Vaitkus et al. 2021).

This research strives to identify the most economically viable pavement construction type, especially in the context of developing nations like Bangladesh. Through a thorough analysis of existing literature and research findings, the goal is to inform infrastructure decisions that not only adhere to economic discretion but also enhance the quality and efficiency of road construction projects.

2. Methodology

The methodology employed for this study is designed to comprehensively address the concept and practical implementation of constructing Prestressed Precast Concrete Pavement (PPCP). The research framework encompasses multiple critical parameters and components crucial to the construction of PPCP. These parameters include the construction process itself, the determination of PPCP panel thickness, panel size considerations, prestressing force calculations, reinforcement strategies, lean concrete base design, and the selection of a suitable wearing course.

2.1. Construction of PPCP

PPCP can be defined as a pavement in which a horizontal compressive stress has been introduced prior to the application of the traffic load (Jiang et al. 2022). The basic schematic drawings for PPCP are shown in Figure 1 and Figure 2.

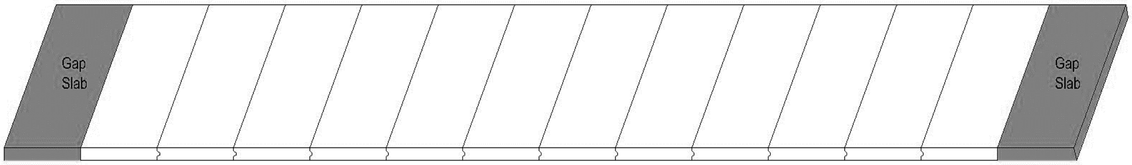

Figure 1. Schematic diagram showing end stressing of PPCP

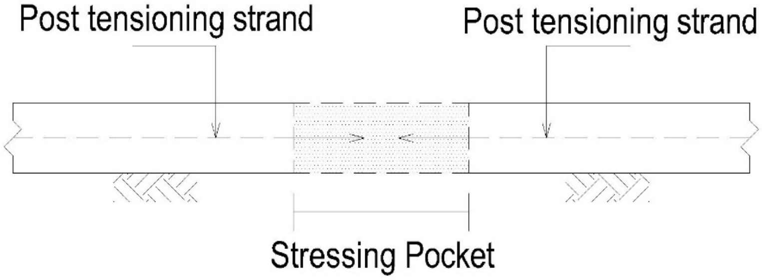

Figure 2. Concept of end stressing

2.2. Thickness of PPCP Panels

There are some of the complex factors that influence PPCP panel thickness, such as anticipated traffic loads, subgrade conditions, and environmental considerations. The thickness of the panels is to selected by considering the stress developed which is expressed by the formulae proposed by Syed and Sonparote (2020).

$$\sigma = A + B \times \left(\frac{\gamma \times h^2}{k \times l^2}\right) + C \times \left(\frac{P \times h}{k \times l^4}\right) + D \times \Delta T - P_f$$

Where,
A = refer Table 1;
B = refer Table 1;
C = refer Table 1;
D = refer Table 1;
γ = density of concrete (kN/m^3);
h = thickness of panel (m);
k = effective modulus of sub-grade reaction (MPa/m);
l = radius of relative stiffness (m) = = $\sqrt[4]{(E \times h^3)/(12 \times (1-\mu^2) \times k)}$
E = modulus of elasticity of concrete;
μ = poisons ratio of concrete;
P = single/tandem rear axle load (kN).
ΔT = maximum temperature difference (°C);
P_f = effective prestress after considering losses (MPa).

Table 1. Parametric values of the equation of Syed and Sonaparote (2020).

Axle type	k	With tied shoulder				Without tied shoulder			
		A	B	C	D	A	B	C	D
Single Axle	<80	0.008	-6.12	2.36	0.0266	-0.149	-2.6	3.13	0.0297
	80–150	0.080	-9.69	2.09	0.0409	-0.119	-2.99	2.78	0.0456
	>150	0.042	3.26	1.62	0.0522	-0.238	7.02	2.41	0.0585
Tandem Axle	<80	-0.188	0.93	1.03	0.0207	-0.223	2.73	1.34	0.0229
	80–150	-0.174	1.21	0.87	0.0364	-0.276	5.78	1.14	0.0404
	>150	-0.210	3.88	0.73	0.0506	-0.300	9.88	0.97	0.0543

The formula of Syed and Sonparote (2020) takes the following parameters into consideration.

i. Temperature variation
ii. Vehicle stress
iii. Material properties
iv. Effect of prestressing
v. Effect of Shoulder

2.3. Size of PPCP Panels

The selection of panel size in Prestressed Precast Concrete Pavement (PPCP) is a critical decision that involves finding a balance between various factors. Panel size has a significant impact on both the ease of handling during construction and the overall project cost and construction time. A panel size of 2.4 meters along the length of the pavement and 3.6 meters along the width of the pavement emerges as an optimal choice (Mishra et al. 2013).

2.4. Prestressing Force

The aim of prestressing is to reduce the thickness of the pavement. Prestressing reduce the tensile stress generated from the vehicular movement. Besides reduced thickness results in reduced project cost. Syed and Sonparote (2020) suggested the optimum thickness and prestressing force which is presented in Table 2

Traffic intensity	Prestress (MPa)	Thickness (mm)
Low traffic intensity	0	275
	0.12	250
	0.52	225
	1.29	200
	2.33	175
Medium traffic intensity	0	275
	0.29	250
	0.84	225
	1.78	200
High traffic intensity	0	300
	0.321	275
	0.814	250
	1.527	225
	2.52	200

L.-M. Chang and Chen (2012) suggested to ensure that the elongation of the posttensioning strands after stressing should not exceed 10% of the theoretical elongation as shown in equation below

$$\delta = \frac{PL}{E_s A_s + E_e A_e}$$

Where,
δ = deformation
P = prestressing force
L = length of the slab
E_s = modulus of elasticity of steel
A_s = surface area of steel
E_e = modulus of elasticity of epoxy
A_e = surface area of epoxy

Tayabji et al. (2013) suggests to have an effective Prestress of 0.7 MPa after the losses due to friction between panels, creep, shrinkage and steel relaxation.

2.5. Reinforcement

The stress due to vehicular load has nominal effect on the rigid pavement (Smith and Snyder 2017). The main purpose of reinforcement is to counter the stresses generated while lifting the panel (Tayabji and Tyson 2017). However cracks are often observed on the concrete pavements due to weathering action. Welded Wire Reinforcement (WWR) not only reduces the construction costs but also performs better in reducing visible cracks (Ahmed et al. 2023). On the other hand ACI 318 R-14 (*ACI 318*, 2014) allows WWR with f_y = 550 MPa to be used in pavements. Use of WWR is illustrated in Figure 3.

2.6. Lean Concrete Base

According to the findings presented by Mishra et al. (2013), it is recommended to position the precast concrete panels onto a lean concrete base once it attains a minimum strength of 5 MPa. The primary objective of this lean concrete base is to serve as a safeguard, shielding the pavement from environmental factors such as corrosion and erosion.

2.7. Wearing Course

In spite of having numerous advantages like rapid construction and reduced cost, the PPCP has a higher average International Roughness Index (IRI) (Jiang et al. 2022). Which might not give a pleasing riding experience. Therefore, a bitumen wearing course maybe applied for better riding experience.

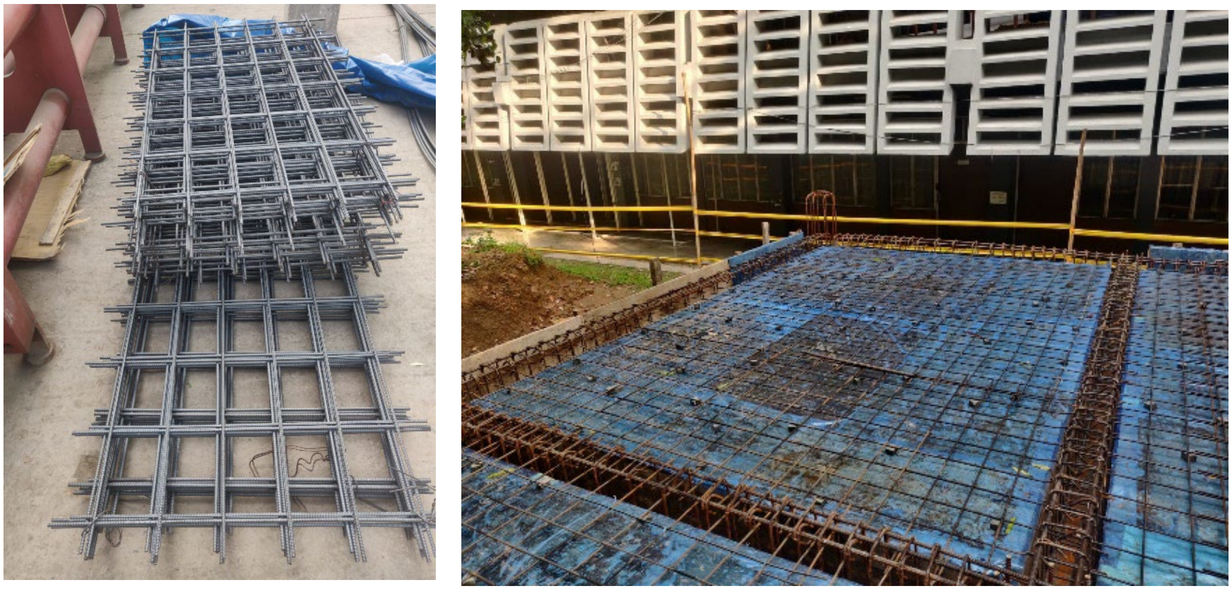

Figure 3. Use of Welded Wire Reinforcement (WWR) in slab construction

3. Cost-benefit Analysis

To gain a comprehensive understanding of the newly proposed pavement system, which offers significant economic advantages, it is imperative to delve into the cross-sectional profile of each pavement type. A closer examination reveals notable disparities, particularly in terms of depth requirements. Hamim et al. (2021) found in his study that traditional flexible pavement demands a substantial depth of approximately 1270 millimeters, while rigid pavement systems require a comparatively shallower depth of around 850 millimeters as shown in Figure 4.

However, the proposed technology by significantly reduces both the thickness of the concrete slab and the overall depth of the pavement system. In this innovative approach, the concrete section only requires a thickness of approximately 200 millimeters, complemented by a 75 millimeter lean concrete base and a 50 millimeter bituminous wearing course as illustrated in Figure 5. This substantial reduction in thickness has far-reaching implications, particularly in terms of cost savings for the entire project. It underscores the cost-efficiency and economic viability of the proposed pavement system, which has the potential to transform the landscape of road construction practices.

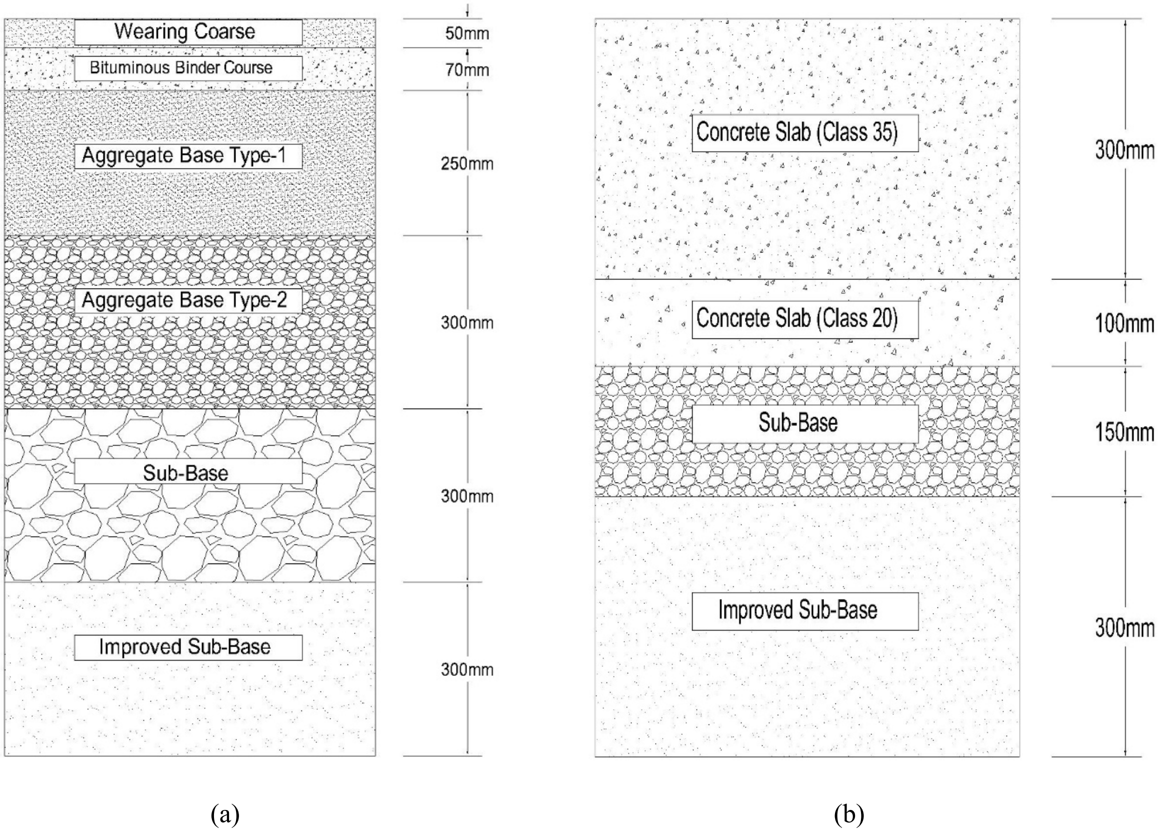

Figure 4. (a) Cross-sectional profile of flexible pavement (b) Cross-sectional profile of rigid pavement (Hamim et al. 2021)

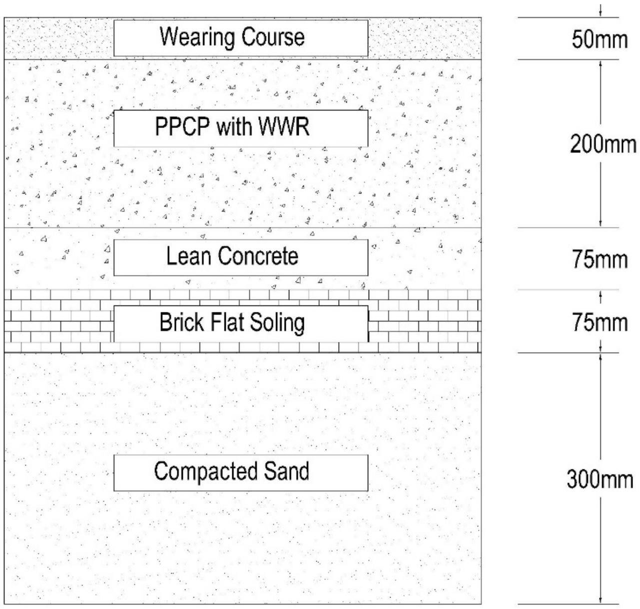

Figure 5. Cross-sectional profile of proposed pavement of PPCP with WWR

The research conducted by Hamim et al. (2021) has shed light on a crucial aspect of pavement systems. Their findings indicate that the initial construction cost of rigid pavement surpasses that of flexible pavement by approximately 11.75%. However, when considering the life cycle cost, flexible pavement emerges as the costlier option, with a margin of 38.3% over rigid pavement. This cost analysis emphasizes the economic intricacies involved in choosing between these two pavement types.

The specific section of the pavement examined in the study is visually represented in Figure 5, providing a tangible reference for the research. Notably, rigid pavement construction typically requires an extended curing period of around 28 days, which poses economic challenges by impeding the road network's development (Jain et al. 2013).

The introduction of precast pavement technology promises to revolutionize road construction by drastically reducing the waiting time for road installation, from 21 days to just a single day (L. Chang et al. 2004). This remarkable reduction not only yields substantial economic benefits but also enhances the quality control of the construction process. Furthermore, the incorporation of prestressed precast concrete slabs offers a double benefit. Firstly, it leads to a significant reduction in the thickness of the concrete slab, owing to the enhanced efficiency of pre-tensioned construction methods. Secondly, prestressing contributes to superior durability, particularly in the face of heavy traffic loads, ensuring a longer service life for the pavement. The cost benefit analysis of the proposed system is illustrated in Figure 6.

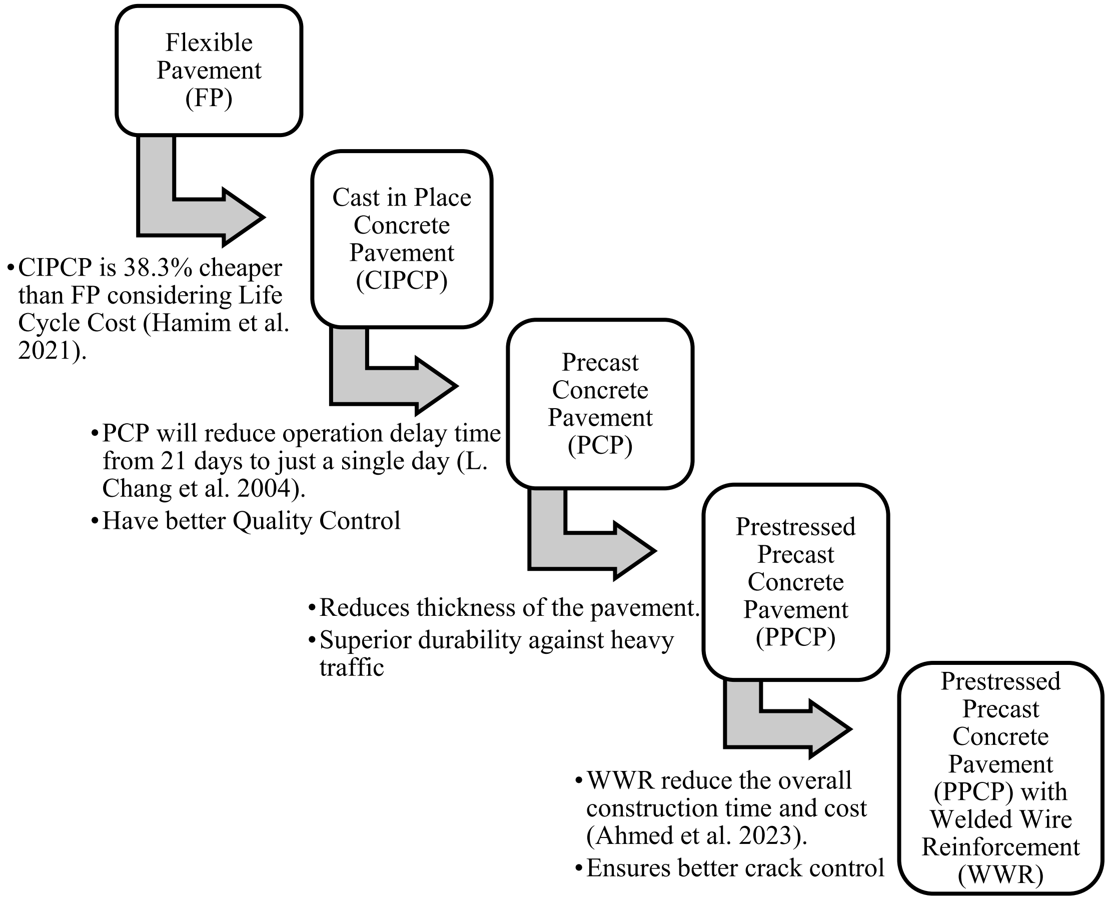

Figure 6. Flow diagram showing cost-benefit analysis of using PPCP with WWR

Lastly, the synergistic blend of prestressed precast pavements (PPCP) with Welded Wire Reinforcement (WWR) further optimizes the pavement construction. WWR introduces notable efficiency gains by reducing construction time and cost. Where, Ahmed et al. (2023) found that for a two way slab construction with 8mm WWR reduces 28% construction time and 33.3% of labor cost. Additionally, it offers enhanced control over crack formation, which could mitigate potential deterioration of the pavement system. This holistic approach, encompassing precast technology, prestressing, and WWR, presents a comprehensive strategy to address the complex challenges and demands of modern road construction.

4. Conclusion

In conclusion, the core objective of this study was to identify and recommend a pavement type that is not only cost-effective but also sustainable, especially in the challenging context of tropical weather and adverse traffic conditions which are often experienced in developing countries such as Bangladesh. The adoption of Prestressed Precast Concrete Pavement (PPCP) with Welded Wire Reinforcement (WWR) emerges as a promising solution, driven by its remarkable potential to expedite construction, reduce life cycle costs, and enhance overall pavement performance. The findings of this study, project a future where PPCP with WWR could become a prominent and widely embraced method in the pavement construction industry, particularly for achieving sustainability. This innovative approach represents a significant step forward in the pursuit of more resilient and economical road infrastructure, aligning with the evolving needs and challenges of developing nations. It underscores the importance of research and development in shaping the future of construction practices to meet the demands of both the present and future.

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Biographies

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