Review

Advancements in Sustainable Prestressed Concrete Bridge Technologies: A Comprehensive Review

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Abstract: Advancements in prestressed concrete bridge technology have increasingly focused on sustainability in response to growing environmental concerns. This review examines recent innovations in integrating recycled concrete aggregates (RCA) and supplementary cementitious materials (SCMs) within prestressed concrete to conserve resources, reduce waste, and lower carbon emissions. Sustainable prestressing techniques, including the use of fiber-reinforced polymer (FRP) tendons and shape memory alloys (SMAs), increase the durability of prestressed concrete bridges, extend service life, and minimize maintenance needs, thereby reducing environmental impact. Key methodologies, such as lifecycle assessment (LCA) and performance-based design, are highlighted for their roles in optimizing structural performance while reducing the ecological footprint. Despite the benefits, barriers to widespread adoption remain, including technical limitations, economic challenges, and regulatory constraints. To address these issues, this review proposes further research on material development, updated design guidelines, cost–benefit analyses, and supportive policy initiatives. The findings confirm that integrating sustainable materials and advanced technologies in prestressed concrete bridge construction offers environmental advantages without compromising structural integrity. Collaborative efforts among engineers, researchers, policy-makers, and educators are essential to overcoming these barriers and advancing sustainable, resilient infrastructure.

Keywords: sustainable prestressed concrete; recycled concrete aggregates; supplementary cementitious material; fiber-reinforced; lifecycle assessment; environmental impact; structural durability

Citation: Komarizadehasl, S.; Amin, A.; Xia, Y.; Turmo, J. Advancements in Sustainable Prestressed Concrete Bridge Technologies: A Comprehensive Review. *Prestress Technology* **2024**, *4*, 01-25. https://doi.org/10.59238/j.pt.2024.04.001

Received: 30/10/2024
Accepted: 19/12/2024
Published: 30/12/2024

Publisher's Note: Prestress technology stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1 Introduction

The construction industry is increasingly emphasizing sustainability to address environmental concerns such as resource depletion, high energy consumption, and greenhouse gas emissions. Prestressed concrete bridge construction, a critical component of infrastructure development, is no exception. Recent advancements in prestressed technologies aim to enhance sustainability, incorporate green designs, and set the stage for future innovations [1-5]. Figure 1 provides an overview of these advancements, showcasing key milestones and innovations that have shaped the industry.

Prestressed concrete bridges offer several advantages over traditional reinforced concrete structures, including improved load-bearing capacity, material efficiency, and enhanced durability [6-13]. However, conventional prestressed concrete relies heavily on nonrenewable resources and energy-intensive materials such as cement and steel, contributing significantly to environmental degradation [14-16]. This reliance presents a challenge in aligning bridge construction practices [17] with global sustainability goals [18-21].

In response to these challenges, researchers and engineers have explored the use of sustainable materials and innovative technologies in prestressed concrete bridges [22-24]. The incorporation of recycled concrete aggregates (RCA) and supplementary cementitious materials (SCMs) has shown promise in reducing the environmental impact of concrete production. Additionally, advancements in design methodologies and the adoption of smart technologies aim [25] to optimize material usage and extend the service life of bridges, further contributing to sustainability [26-30].

Figure 1 Evolution of sustainable practices in prestressed concrete bridge construction over the past decade.

Despite these efforts, there is a gap in the literature regarding a comprehensive review of recent advancements in sustainable prestressed concrete technologies for bridge construction. Specifically, findings from the past five years need to be consolidated to understand how these innovations address environmental challenges and to identify future research directions.

This paper aims to fill this gap by providing a detailed review of the latest developments in prestressed concrete technologies for bridge construction, focusing on sustainability, green construction, and future trends. The contributions of this review are threefold: (1) synthesizing recent research on sustainable materials and methods in prestressed bridge construction, (2) highlighting innovative design and analysis techniques that promote environmental sustainability, and (3) identifying challenges and proposing future research directions to advance the field.

The manuscript is organized as follows. Section 2 discusses sustainable materials used in prestressed concrete, including recycled concrete aggregates and supplementary cementitious materials. Section 3 explores innovative sustainable prestressing techniques that reduce environmental impacts. Section 4 examines design and analysis methods emphasizing sustainability, such as lifecycle assessment and performance-based design. Section 5 identifies challenges and future research opportunities. Finally, Section 6 provides conclusions and recommendations based on the findings of this review.

2 Sustainable Materials in Prestressed Concrete

The integration of sustainable materials into prestressed concrete bridges is crucial for reducing environmental impacts and promoting green construction practices. This section reviews recent advancements in the use of recycled concrete aggregates, supplementary cementitious materials, and alternative prestressing materials in prestressed concrete applications.

2.1 Use of Recycled Concrete Aggregates

Recycled concrete aggregates (RCA) are derived from crushing and processing demolished concrete structures. The utilization of RCA in new concrete reduces the demand for natural aggregates and minimizes construction waste, aligning with sustainability goals. However, incorporating RCA into prestressed concrete presents challenges because of their variable properties.

2.1.1 Properties of RCA in Prestressed Concrete

Compared with natural aggregates, RCA typically exhibit greater water absorption, lower density, and weaker interfacial transition zones. These characteristics can affect the mechanical properties and durability of prestressed concrete.

Modifications in mix design are necessary to account for these differences. The elastic modulus of concrete containing RCA can be estimated via a modified empirical formula as follows [31]:

$$E_c = \alpha \times 4700\sqrt{f_c'} \tag{1}$$

where:

E_c represents the elastic modulus of the concrete, in MPa;
f_c' represents the compressive strength of the concrete, in MPa;
α represents the reduction factor (<1) based on the RCA content.

The reduction factor α accounts for the decrease in stiffness due to the inclusion of RCA. Research indicates that with up to 30% replacement of natural aggregates, the mechanical properties remain within acceptable ranges for prestressed applications, according to Table 1.

Table 1 Summary of recent studies on RCA usage in prestressed concrete

Author(s)	RCA replacement Level (%)	Compressive strength (MPa)	Elastic modulus (GPa)	Key findings
McGinnis M et al. 2024 [32]	0	50.6	-	Replacing up to 60% of natural aggregate with recycled aggregate (RA) seems to have little impact on the compressive strength of concrete for hollow core slab production.
	20	48.4	-	
	30	48.3	-	
	60	45.6	-	
Ferreira M et al. (2024) [9]	0	26.2	20.5	Using RCA does not affect the concrete breakout strength, response of headed bars and stress of concrete cones.
	30	26.7	20.4	
	100	27.2	16.6	
Brandes, M.R. & Kurama, Y.C. (2016) [33]	0	45	32	RCA up to 50% replacement is feasible with acceptable reductions in strength and modulus. 100% RCA causes significant performance drops.
	25	42	30	
	50	39	27	
	100	37	24	
Li, W., et al. (2023) [34]	0	50	31	Prestressed concrete can sustain up to 60% RCA with minimal strength loss, but 100% RCA shows significant reductions in both strength and modulus.
	30	47	29	
	60	45	27	
	100	42	24	

Table 1 Continued

Author(s)	RCA replacement Level (%)	Compressive strength (MPa)	Elastic modulus (GPa)	Key findings
Zeger SIERENS (2022) [35]	0	61	39.34	High-quality RCA does not influence the strength development at 7 to 28 days. No clear effect of RCA on the increase in elastic modulus is observed.
	10	58.50	37.90	
	20	57.61	39.12	
	50	57.87	37.91	
	100	55.58	35.67	
Kumar et al. (2023) [36]	0	60	41.43	Mechanically treated RCA can have physical, mechanical, and durability properties closer to those of NAC.
	75	60.5	38.74	
	94	61	38.67	
	95	62	39.62	
Zhao, H., et al. (2017) [37]	0	52	33	RCA up to 40% shows minor reductions in strength and modulus. 60% RCA remains acceptable for use in prestressed applications, though creep and shrinkage increase.
	20	50	31	
	40	47	29	
	60	44	27	
Dawood M et al. (2023) [38]	0	47	30	RCA up to 60% performs adequately for prestressed concrete. Beyond this level (90% RCA), there are significant reductions in mechanical properties.
	30	45	28	
	60	42	26	
	90	40	25	
Zhao, Y., & Zhang, J. [39]	0	48	31	RCA up to 40% remains within acceptable mechanical properties. At 60%, fatigue resistance drops, and creep and shrinkage increase significantly.
	20	45	29	
	40	42	27	
	60	38	25	

2.1.2 Recent Research and Applications

Recent studies have extensively investigated the integration of Recycled Concrete Aggregates (RCA) in prestressed concrete, focusing on maintaining mechanical performance while increasing sustainability [40]. These studies have explored various RCA replacement levels to understand their effects on properties such as compressive strength and elastic modulus. Key techniques, such as presoaking RCA to improve workability and the use of mineral admixtures to enhance durability, have been employed to counterbalance the inherent variability of RCA [32]. Table 1 summarizes recent research findings, detailing the effects of different RCA replacement percentages on the compressive strength and elastic modulus of prestressed concrete, as well as other relevant observations.

The data presented in Table 1 highlight the variability in the mechanical properties when RCA are used in prestressed concrete. This demonstrates that RCA replacement levels up to 30% yield compressive strength and elastic modulus values comparable to those of conventional aggregates, with limited reductions in performance. However, higher replacement levels, particularly above 60%, are associated with significant decreases in both strength and modulus, highlighting the importance of careful mixing and quality control when RCA is used in prestressed applications.

2.2 *Supplementary Cementitious Materials*

Supplementary Cementitious Materials (SCMs), such as fly ash, slag, and silica fume, are industrial byproducts that can partially replace Portland cement in concrete. Their use reduces the carbon dioxide emissions associated with cement production and enhances certain concrete properties.

2.2.1 Impact on Concrete Performance

SCMs contribute to pozzolanic reactions, which refine the pore structure and improve durability [41]. The general pozzolanic reaction is represented as follows [42]:

$$SiO_2(from\ SCM) + Ca(OH)_2 + H_2O \rightarrow C - S - H(Calcium\ Silicate\ Hydrate) \quad (2)$$

This reaction consumes calcium hydroxide, a byproduct of cement hydration, and forms additional C-S-H gel, increasing the strength and reducing permeability.

The inclusion of SCMs affects the water-to-cementitious material ratio (w/cm). Adjustments are made using activity coefficients to account for the varying reactivities of SCMs [43]:

$$Effective\ W/C = \frac{w}{C + k \times SCM} \quad (3)$$

where:

W represents the water content, in kg/m^3;

C represents the cement content, in kg/m^3;

SCM represents the SCM content, in kg/m^3;

k represents the efficiency factor.

2.2.2 Recent Developments

Recent research has highlighted the benefits of SCMs in prestressed concrete:

(1) High-Volume Fly Ash (HVFA) with RCA concrete: Cement production is a major contributor to global CO_2 emissions, driving the need for more sustainable alternatives in concrete construction. High-Volume Fly Ash (HVFA) concrete, which uses up to 50% fly ash as a replacement for cement, is a promising solution that maintains strength and improves durability while reducing environmental impact. The pozzolanic properties of fly ash, as well as its lower water-to-cementitious material ratios, help HVFA concrete achieve comparable or even greater long-term compressive strengths. Studies have shown that optimizing fly ash content, alongside partially replacing coarse aggregates with RCA and fine aggregates with dredged marine sand (DMS), can produce HVFA concrete mixtures with a target compressive strength of 30 MPa, effectively balancing sustainability and structural performance [44]. Even though this compressive strength is not suitable for prestressing technologies, it is a starting point.

(2) Silica Fume Addition with RCA: Silica fume (SF) has proven to be an effective additive for enhancing the mechanical properties and durability of concrete, especially in mixtures that include RCA. Its fine particle size helps to fill voids in the matrix, which improves the density of the concrete, reduces the porosity, and enhances the interfacial transition zone (ITZ) between the RCA and the binder. Studies indicate that adding SF at an optimal level (approximately 8–10%) can significantly improve the compressive strength and durability of RCA-based concrete by promoting the formation of denser hydration products. However, adding more than the optimal amount may lead to unwanted expansion and microcracking, which can compromise strength and durability [45].

(3) Combination of SCMs: Synergistic effects lead to superior performance [46].

For example, Zhang et al. [47] reported that prestressed concrete with 30% slag replacement exhibited improved durability without compromising early-age strength.

2.3 *Alternative Prestressed Materials*

Exploring alternative materials for prestressed tendons contributes to sustainability by reducing the reliance on traditional steel and enhancing durability.

Fiber-reinforced polymer (FRP) tendons, which are made from carbon, glass, or basalt fibers, exhibit high tensile strength and corrosion resistance. The stress–strain relationship of FRP tendons is linear–elastic until failure, resulting in a lack of ductility of the steel [48].

The tensile capacity is calculated as follows [49]:

$$P_{FRP} = A_{FRP} \times f_{FRP} \tag{4}$$

where:

P_{FRP} represents the maximum tensile force;

A_{FRP} represents the cross-sectional area;

f_{FRP} represents the ultimate tensile strength.

Design considerations must account for the reduced ductility and different bond characteristics compared with those of steel.

2.4 *Summary and Implications*

The adoption of sustainable materials in prestressed concrete bridges contributes to environmental goals without significantly compromising structural integrity. Careful mix design adjustments and an understanding of material properties are essential. Ongoing research continues to address these challenges and expand the applicability of these materials in practice. Figure 2 illustrates the integration of sustainable materials, including RCA and SCMs, into prestressed concrete, emphasizing their role in promoting sustainability within bridge construction.

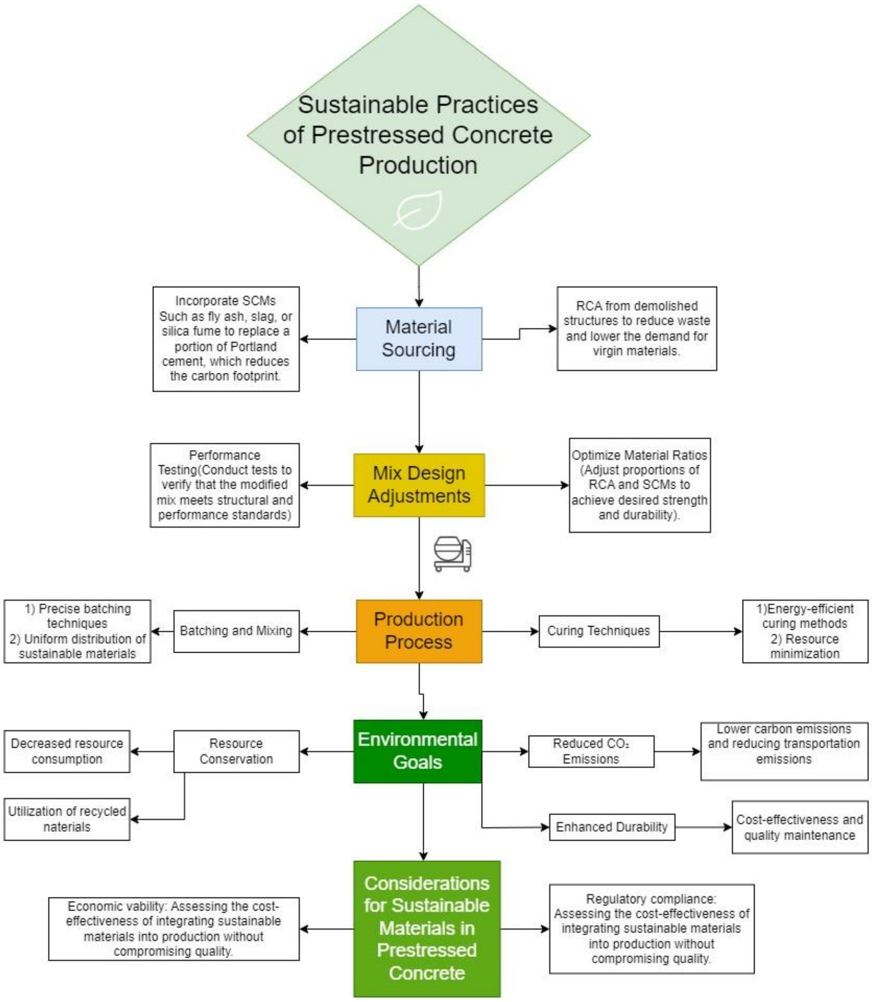

Figure 2 Integration of sustainable materials into prestressed concrete

3 Innovative Sustainable Prestressing Techniques

Recent advancements in prestressing techniques have emphasized sustainability by reducing environmental impacts and enhancing structural efficiency. This section reviews innovative methods that contribute to green construction in prestressed concrete bridges, focusing on low-carbon prestressing methods and the integration of smart technologies.

3.1 Low-Carbon Prestressing Methods

Minimizing the carbon footprint associated with prestressing processes is crucial for sustainable bridge construction. Innovations in manufacturing and onsite practices aim to decrease energy consumption and greenhouse gas emissions.

3.1.1 Energy-Efficient Production Processes

The production of prestressed steel is energy intensive and contributes significantly to carbon emissions. Recent developments have introduced more energy-efficient manufacturing techniques:

(1) Thermo-Mechanical Treatment: This treatment enhances the mechanical properties of steel tendons without additional alloying elements, reducing energy usage and resource consumption [50].

(2) Use of Recycled Steel: Incorporating recycled steel scrap in the production of prestressed tendons lower the demand for virgin materials and reduces emissions.

The environmental impact [51] can be quantified via embodied energy calculations:

$$Embodied\ Energy = \sum_{i=1}^{n} (Q_i \times E_i) \tag{5}$$

where

Q_i represents the quantity of material i used (mass, volume, or area);

E_i represents the embodied energy per unit of material i (MJ/kg, MJ/m^3, etc.);

n represents the number of materials/components involved in the system.

Reducing Q_i or E_i through efficient processes directly decreases the embodied energy of the materials used.

3.1.2 On-site Practices Reducing the Environmental Impact

Innovative construction practices contribute to sustainability:

(1) Prefabrication and Modular Construction: Off-site fabrication of prestressed elements enhances quality control, reduces material waste, and minimizes on-site energy consumption.

(2) Advanced Tensioning Equipment: Compared with traditional hydraulic methods, electrically powered or automated tensioning systems improve efficiency and reduce energy usage.

(3) Optimized Prestressing Levels: Utilizing computational methods to determine the optimal prestress force reduces material usage without compromising structural performance.

3.2 Smart and Adaptive Prestressing Systems

Integrating smart technologies into prestressed concrete bridges enhances sustainability by extending the service life, reducing maintenance needs, and improving safety.

3.2.1 Self-monitoring Structures

Embedding sensors within prestressed concrete structures allows real-time monitoring of structural health:

(1) Fiber Optic Sensors: Measure strain and temperature and detect early signs of corrosion along the prestressing tendons [25].
(2) Wireless Sensor Networks: Enable remote monitoring and data collection, reducing the need for frequent physical inspections.

The implementation of structural health monitoring (SHM) systems improves maintenance efficiency and can be represented via reliability models [52]:

$$\beta = \frac{\mu R - \mu S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{6}$$

where
β represents the reliability index;
μR represents the mean value of the resistance (capacity of the structure);
μS represents the mean value of the load effects (demand on the structure);
σ_R represents the standard deviation of the resistance;
σ_s represents the standard deviation of the load effects.

By continuously updating β, engineers can proactively address issues before they lead to significant problems.

3.2.2 Adaptive Prestressing Techniques

Adaptive or active prestressing systems adjust the level of prestress in response to environmental conditions or changes in load.

(1) Shape Memory Alloys (SMAs): Shape Memory Alloys (SMAs), particularly Fe-based SMAs, offer a promising approach for prestressing in reinforced concrete (RC) applications because of their unique shape memory effect (SME) and cost-effectiveness. When activated by heat, these alloys return to their original shape, generating a recovery stress that effectively prestresses the structure. Recent studies have demonstrated that Fe–SMA strips can increase the shear capacity of RC beams by 25–45%, particularly when applied in U-wrap or strip configurations. The activation process reduces crack width and delays the onset of shear cracking, improving both durability and serviceability. Although Ni–Ti SMAs have traditionally been used, Fe-based SMAs are gaining popularity in civil engineering because of their stable recovery stress and enhanced corrosion resistance [53].
(2) Electrically Controlled Tendons: Electrically controlled tendons are an innovative prestressing solution that allows for precise, adjustable control over tension within concrete structures. By incorporating materials such as electroactive polymers or shape memory alloys, these tendons can be activated through electrical currents, enabling real-time adjustment of prestress forces on the basis of structural requirements or external loads [54]. The application of electrical currents to certain materials can modify their stress state, allowing for dynamic prestress control.

3.3 Summary and Implications

Innovative sustainable prestressing techniques significantly contribute to reducing the environmental impact of bridge construction. By adopting low-carbon methods and integrating smart technologies, the industry can achieve sustainability goals while improving structural performance and longevity [55-58]. These advancements represent a progressive shift toward more sustainable infrastructure development [59,60]. Figure 3 presents a graphical representation of innovative sustainable prestressing techniques, including low-carbon production methods and smart systems, highlighting their contribution to enhancing structural performance and reducing environmental impacts in prestressed concrete bridge construction.

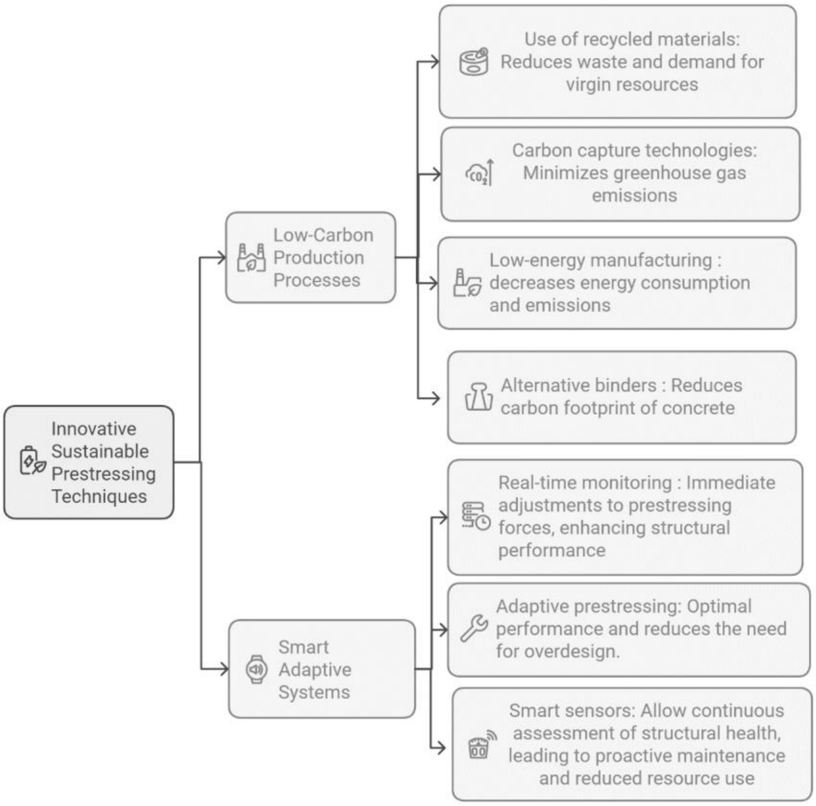

Figure 3 Innovative sustainable prestressing techniques

Table 2 underscores the advancements in prestressing techniques aimed at enhancing sustainability. While the integration of CFRP tendons and recycled steel shows promise in reducing long-term maintenance and carbon emissions, challenges such as high initial costs and design complexities must be addressed. The table also highlights the potential of smart tendons with embedded sensors, which provide real-time monitoring capabilities, thereby contributing to predictive maintenance and improved safety, although sensor reliability and cost remain significant barriers. It also addresses solutions such as Internal Unbonded Tendons [61-64], Magnesium Alloy Tendons [65] or Prestressing with Bio-based Composites [66].

Table 2 Innovative prestressing techniques, sustainability benefits, challenges, and recent applications

Technique	Description	Sustainability benefits	Challenges	Recent applications
Carbon Fiber Reinforced Polymer (CFRP) Tendons [67-69]	Lightweight, corrosion-resistant tendons used instead of steel in prestressed concrete.	Short-term maintenance, longer lifespan, lighter, corrosion-resistant.	High initial cost, complex anchorage design.	Applied in bridge retrofits and new construction (Japan, USA, and Europe).
Recycled Steel in Prestressing [70]	Incorporating recycled steel for tendons to reduce environmental impact.	Reduces demand for virgin steel, promotes circular economy.	May reduce mechanical properties compared to virgin steel.	Pilot applications in prestressed concrete girders (USA and Germany).

Technique	Description	Sustainability benefits	Challenges	Recent applications
Internal Unbonded Tendons [61-64]	Tendons left unbonded for easier adjustment and posttensioning inspection.	Easier inspection maintenance.	Design complexity, slippage in the tendons over time.	Used in long-span bridge projects (Australia and Canada).
Post-tensioning with Recycled Aggregates [71]	Use of recycled aggregate (RCA) in posttensioned concrete structures.	Reduces virgin aggregate consumption.	Potential reduction in concrete strength, increased variability in materials	Applied in infrastructure projects, like highways and bridges (Netherlands and UK).
Smart Tendons with Embedded Sensors [72-75]	Tendons embedded with sensors for real-time structural health monitoring.	Enables predictive maintenance, enhances safety and longevity.	High upfront cost, sensor reliability concerns.	Used in large bridge and infrastructure projects (South Korea and USA).

4 Design and Analysis Strategies for Sustainable Bridge Engineering

This section delves into advanced methodologies for incorporating sustainability into bridge design and analysis, emphasizing LCA, performance-based design, durability optimization, and sustainable maintenance practices to balance structural performance with environmental considerations.

4.1 Lifecycle Assessment for Sustainable Bridge Design

4.1.1 Evaluating Environmental Impacts

The LCA process for bridge design involves the following phases:

Goal and Scope Definition: Establishing the objectives, system boundaries, and functional units for the assessment.

Inventory Analysis: Collecting data on energy and material inputs and outputs throughout the bridge's lifecycle.

Impact Assessment: Evaluating potential environmental effects via indicators such as global warming potential (GWP), acidification, and resource depletion.

Interpretation: Analyzing results to make informed decisions for improving sustainability.

The total environmental impact E can be expressed as follows [76]:

$$E=\sum_{i=1}^{n}(Q_i\times E_i) \tag{7}$$

where

E represents the total volume of environmental impact;

Q_i represents the quantity of process i (e.g., energy consumed, material used, and emissions generated);

E_i represents the environmental impact factor of process i.

4.1.2 Incorporation into Design Codes

Recent efforts have been made to integrate LCA into bridge design standards:

ISO 21930:2017: Provides core rules for environmental product declarations of construction products [46].

EN 15804: Establishes sustainability standards for construction projects in Europe [77].

These codes encourage designers to consider environmental impacts alongside structural requirements, promoting a holistic approach to sustainability.

4.1.3 Case Studies

Studies have demonstrated significant reductions in environmental impacts through LCA-informed design:

Material Selection: Choosing low-impact materials such as SCMs and RCA reduces the GWP.

Design Optimization: Adjusting structural dimensions and prestress levels to minimize material usage without compromising performance.

Table 3 presents examples of the LCA results for prestressed concrete bridges, which are organized into the following columns: bridge design, sustainable design choice, total GWP in kg CO_2 equivalent, energy consumption in MJ, resource depletion percentage, and key findings.

Table 3 Examples of LCA results for prestressed concrete bridges

Bridge design	Sustainable design choice	Total GWP (kg CO_2 eq.)	Energy consumption (MJ)	Resource depletion (%Reduction)	Key findings
Conventional bridge (baseline) [78]	No sustainable alternatives used.	100,000	1,200,000	0%	Standard bridge design but considerable environmental impacts.
Bridge with recycled aggregates (25% RCA) [79]	25% recycled coarse aggregates in concrete.	85,000 (-15%)	1,050,000 (-12.5%)	12%	Reduced GWP and energy use due to less cement, with marginal impact on strength.
Bridge with SCMs (30% fly ash) [80]	30% fly ash replacement for cement.	72,000 (-28%)	950,000 (-20%)	18%	Significant reductions in GWP and energy use due to the lower carbon footprint of fly ash.
Bridge with ground granulated blast-furnace slag (50% slag cement) [81]	50% ground granulated blast-furnace slag (GGBS)	65,000 (-35%)	900,000 (-25%)	25%	Major reductions in cement content with improved durability and lower carbon emissions.
Bridge with CFRP tendons [82]	Carbon fiber-reinforced polymer (CFRP) tendons.	80, (-20%)	1,000,000 (-16%)	8%	Reduced need for maintenance and longer lifespan but high energy consumption in CFRP production.
Bridge with embedded sensors (smart tendons) [83]	Embedded sensors in tendons for real-time SHM.	78,000 (-22%)	980,000 (-18%)	10%	Enhanced durability and real-time health monitoring, which reduce life cycle impacts.
Bridge with bio-based composites [84]	Bio-based composites in nonstructural components.	60,000 (-40%)	850,000 (-29%)	30%	Largest reduction in resource depletion and significant reduction in GWP for non-load-bearing elements.

Table 3 offers a comprehensive comparison of the lifecycle environmental impacts of various sustainable design choices for prestressed concrete bridges. The findings illustrate those bridges incorporating RCA and SCMs show substantial reductions in GWP and energy consumption, without compromising structural integrity. Notably, bridges using 50% GGBS as a replacement for Portland cement achieved a 35% reduction in CO_2 emissions, emphasizing the environmental benefits of SCMs in reducing the carbon footprint of concrete infrastructure.

4.2 Performance-Based Sustainable Design

Performance-based design (PBD) focuses on achieving specific performance objectives rather than adhering to prescriptive code requirements. Incorporating sustainability into PBD involves balancing structural performance with environmental considerations.

4.2.1 Balancing Structural and Environmental Objectives

In sustainable PBD, designers establish performance criteria that include the following:

Structural Performance: Strength, serviceability, durability, and resilience.

Environmental Performance: Resource efficiency, energy consumption, emissions, and recyclability.

To optimize these criteria, multi-objective optimization methods help designers find the most effective trade-offs, considering environmental impact reduction without sacrificing structural integrity [85].

4.2.2 Optimization Techniques

Optimization models help identify design solutions that meet performance goals while minimizing environmental impacts.

(1) Multi-Objective Optimization

Multi-Objective Optimization [86] considers several goals simultaneously, including eliminating the environmental impact $f_{env}(x)$, maximizing the structural performance $f_{perf}(x)$, and minimizing the cost $f_{cost}(x)$:

$$\min_{x}\{f_{cost}(x), f_{env}(x), -f_{perf}(x)\} \tag{8}$$

The above formula is subject to the following:

Design constraints (e.g., strength and deflection limits)

Material and geometric variables x

Techniques like the Pareto Front, which are used to identify optimal solutions.

(2) Genetic Algorithms

Genetic Algorithms (GAs) mimic natural selection to explore a wide array of design variables. Through iterative processes of selection, crossover, and mutation, GAs efficiently converge on optimal solutions that balance complex, nonlinear relationships typical in sustainable bridge design [87].

4.2.3 Case Studies

Optimized Girder Design: The cross-sectional area of girders is reduced while using high-strength materials to maintain performance, leading to material savings and lower environmental impacts.

Material Substitution: A portion of cement is replaced with SCMs in the concrete mix, which is a method optimized for both structural performance and decreasing the GWP.

Figure 4 depicts the trade-off between environmental impact and structural performance for different design solutions, and a Pareto front is used to demonstrate the optimization of sustainability and performance in prestressed concrete bridge designs.

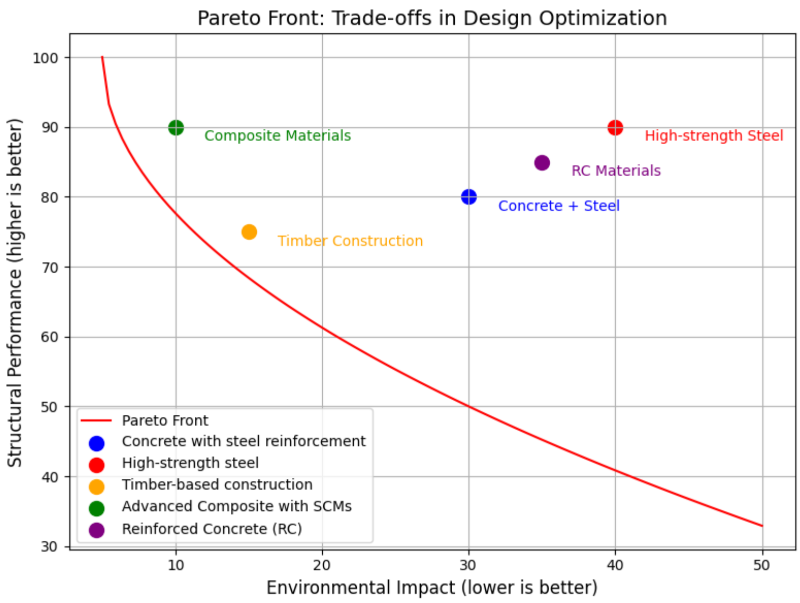

Figure 4 Graphical representation of a Pareto Front, showing the trade-off between environmental impact and structural performance for various design solutions.

Figure 4 demonstrates the trade-offs between structural performance and environmental impact involved in design optimization via a Pareto front. The curve shows that achieving higher structural performance often leads to increased environmental impact, particularly for high-strength steel and RC materials. Materials such as timber and advanced composites with SCMs offer an optimal balance, achieving higher structural performance with significantly lower environmental impact. The placement of composite materials near the top left of the curve indicates that these materials provide the best compromise, achieving high performance with minimal environmental costs. The graph underscores the importance of selecting materials that align with sustainability goals without sacrificing structural integrity.

4.3 Durability Design for Extended Service Life

Designing for durability enhances sustainability by extending the service life of bridges and reducing the frequency of repairs and replacements.

4.3.1 Durability Modeling

Predictive models assess the potential degradation mechanisms over time:

Chloride Ingress: Modeled via Fick's Second Law [88]:

$$C(x,t) = C_s\left(1 - erf\left(\frac{x}{2\sqrt{D_t}}\right)\right) \quad (9)$$

where

$C(x,t)$ represents the chloride concentration at depth x and time t;

C_s represents the surface chloride concentration;

D_t represents the apparent diffusion coefficient;

erf represents the error function.

Carbonation Depth: Estimated with the following [89]:

$$d_c = k\sqrt{t} \quad (10)$$

where

d_c represents the carbonation depth;

k represents the carbonation coefficient;

t represents the carbonation time.

4.3.2 Service Life Prediction

The service life t_s can be estimated by setting the critical concentration or depth at which reinforcement corrosion initiates as follows [90]:

$$t_s = \left(\frac{C_{crit}}{C_s}\right)^2 \times \left(\frac{1}{D_t}\right) \tag{11}$$

where

t_s represents the service life (time to corrosion initiation);

C_{crit} represents the critical chloride concentration at which the reinforcement starts to corrode;

C_s represents the surface chloride concentration (chloride concentration at the concrete surface);

D_t represents the effective diffusion coefficient of chloride ions in concrete (m^2/s).

The design of concrete mixtures and cover depths to delay the initiation of corrosion extends t_s, enhancing sustainability.

4.3.3 Sustainable Maintenance Strategies

Implementing proactive maintenance based on durability models reduces lifecycle costs and environmental impacts:

Preventive Maintenance: Scheduled interventions before significant deterioration occurs.

Condition-Based Maintenance: Using SHM data to plan maintenance activities effectively.

4.4 Summary and Implications

Integrating sustainability into the design and analysis of prestressed concrete bridges involves comprehensive assessment and optimization techniques. Lifecycle assessment provides insights into environmental impacts, whereas performance-based design and optimization ensure that structures meet both performance and sustainability objectives. Durability-focused design extends service life, reducing resource consumption over time. Collectively, these approaches contribute to the development of sustainable infrastructure. Table 4 provides a summary of the design and analysis methods for sustainability in prestressed concrete bridge engineering.

Table 4 Summary of the design and analysis methods for achieving sustainability in prestressed concrete bridge engineering

Method	Description	Benefits	Limitations	Applicability
Life Cycle Assessment (LCA) [91-94]	A method to assess the environmental impacts of a structure throughout its entire lifecycle, from material extraction to demolition and disposal.	• Provides a holistic view of environmental impact. • Helps identify resource-efficient stages. • Supports sustainable material selection and process improvements.	• Can be time-consuming and data-intensive. • May require specialized software. • Results depend on the quality of data available.	Useful for comparing environmental impacts of different designs and materials. Often used for large-scale infrastructure projects to guide material and process choices.

Method	Description	Benefits	Limitations	Applicability
Performance-based Design (PBD) [95-98]	A design methodology focusing on achieving desired structural performance under different loading conditions, including sustainability goals (e.g., energy efficiency and low material use).	• Allows optimized use of materials and resources. • Enhances resilience. • Can reduce costs over time through optimized design.	• Requires advanced analysis tools. • May be more complex than traditional designs. • Risk of overoptimization if not properly managed.	Best suited for projects with specific performance targets, e.g., long lifespan and resilience to environmental hazards.
Optimization Techniques [99-102]	Mathematical techniques (e.g., genetic algorithms and neural networks) used to minimize or maximize performance measures such as material usage, cost, or structural weight.	• Can result in significant material savings and cost reductions. • Balances multiple objectives such as cost, sustainability, and durability. • Enables novel design approaches.	• Requires substantial computational resources. • May not always yield practical solutions. • Complex setup and calibration.	Suitable for large, complex bridge projects where material efficiency and cost are crucial. Frequently used in early design for the optimization of structural forms.
Durability Design [103,104]	Focuses on designing structures with sufficient durability to extend the service life, minimizing maintenance and material use over time. Involves factors such as corrosion resistance, wear, and environmental impact.	• Extends the structure's service life. • Reduces the need for repairs and maintenance. • Minimizes lifecycle environmental impact.	• Can involve higher initial costs. • Needs a detailed understanding of materials and environmental exposure conditions. • Limited by standards and regulations.	Relevant for bridges in aggressive environments (e.g., coastal regions and high traffic areas). Essential for long-lived structures.
Green Concrete Technology [105,106]	Uses alternative materials (e.g., recycled aggregates and industrial byproducts such as fly ash or slag) to reduce carbon emissions in concrete production.	• Reduces CO_2 emissions. • Utilizes waste materials. • Can improve durability with certain additives.	• May require adjustments to mix designs. • Can exhibit variable performance based on the waste material sources. • High initial testing and certification costs.	Used in projects targeting net-zero emissions and promoting waste recycling.

Method	Description	Benefits	Limitations	Applicability
Recycling and Reuse of Materials [107,108]	Involves reusing demolition waste, recycled aggregates, and repurposing concrete from old structures to reduce the environmental footprint.	• Reduces demand for virgin materials. • Minimizes waste. • Promotes circular economy principles.	• Can compromise strength and durability if not properly managed. • May increase construction time due to material processing.	Useful for projects focused on resource conservation and minimizing environmental footprint. Common in urban redevelopment projects.
Carbon Footprint Analysis [79,81,109,110]	Analyzes the carbon emissions associated with the concrete production process, construction, and the structure's lifecycle to reduce environmental impact.	• Provides a clear assessment of carbon emissions. • Helps identify key areas for emission reduction. • Aids in compliance with carbon reduction targets.	• Can be challenging to model emissions accurately. • Requires accurate data and careful accounting of indirect emissions. • Not always integrated into standard design practices.	Crucial for projects targeting net-zero carbon emissions and those under strict emissions regulations.
Structural Health Monitoring (SHM) [111]	Involves the use of sensors and data analytics to monitor the condition of structures, enabling early detection of issues such as corrosion or material degradation.	• Enhances long-term sustainability by reducing maintenance needs. • Provides real-time data for decision-making. • Extends the lifespan of structures by detecting damage early.	• High initial installation costs. • Data interpretation can be complex. • Requires ongoing maintenance of sensors and monitoring equipment.	Useful for long-span bridges or critical infrastructure where preventative maintenance is necessary to extend service life.

The analysis in Table 4 highlights the diverse range of methods available for incorporating sustainability into prestressed concrete bridge design. LCA and PBD are shown to offer significant environmental benefits by enabling resource-efficient and resilient design solutions. However, these approaches often require complex analysis tools and substantial computational resources. Optimization techniques and durability design demonstrate material savings and enhanced service life, although they necessitate advanced modeling capabilities. Green concrete technology and recycling methods provide considerable reductions in CO_2 emissions and resource consumption, yet challenges in performance variability and material processing remain. Overall, the table demonstrates that a combination of these methods can yield optimal sustainable outcomes, depending on the project goals and constraints.

 https://doi.org/10.59238/j.pt.2024.04.001

5 Discussion and Implications

Despite significant advancements in sustainable prestressed concrete bridge construction, several challenges impede the widespread adoption of these practices. This section discusses the technical, economic, and regulatory obstacles and outlines potential future research directions to overcome these barriers.

5.1 Advantages of Sustainable Prestressing Techniques

The materials shown in Figure 5, such as RCA, HVFA, and SF, notably enhance both durability and sustainability:

RCA: While RCA-based concrete generally has a lower compressive strength than traditional concrete does, optimized RCA mixtures can meet standard performance criteria while reducing the environmental impact associated with virgin aggregate mining.

HVFA: HVFA concrete significantly reduces CO_2 emissions while maintaining comparable strength and durability to conventional concrete, positioning it as an attractive choice for large-scale projects focused on reducing environmental footprints.

SF: The addition of SF improves concrete density, filling micro voids and enhancing the durability of RCA-based concrete by increasing resistance to cracking and permeability.

5.2 Advanced Prestressing Techniques

Figure 5 also highlights the potential of advanced techniques, such as Shape Memory Alloys (SMA) and Electrically Controlled Tendons, in achieving responsive and adaptive structures. SMA, especially Fe-based types, provides reliable prestress forces upon thermal activation, increasing crack resistance and delaying crack propagation. Electrically controlled tendons offer real-time adjustability, which can be highly beneficial in dynamic environments like bridges and high-rise buildings.

5.3 Challenges and Future Directions

Despite these benefits, several challenges need to be addressed to optimize these techniques:

Material Availability and Cost: While materials like Ni-Ti SMA are highly effective, they remain cost-prohibitive for widespread use. Although Fe-based SMAs are more affordable, further research is required to optimize their properties for practical applications.

Performance Consistency: RCA and HVFA mixtures can exhibit variability due to differences in source materials, necessitating rigorous quality control in practical applications.

Integration with SHM: Future studies should focus on merging advanced materials with SHM systems to enable real-time performance monitoring, proactive maintenance, and extended structural longevity.

5.4 Implications for Sustainable Infrastructure

The adoption of these sustainable materials and prestressing techniques promises a significant reduction in the carbon footprint of concrete structures while enhancing durability. Figure 5 outlines the key challenges in implementing sustainable practices in prestressed concrete bridge construction, categorizing them into technical, economic, and regulatory challenges. The figure also presents future research directions aimed at addressing these obstacles to enhance the adoption of sustainable solutions in the industry.

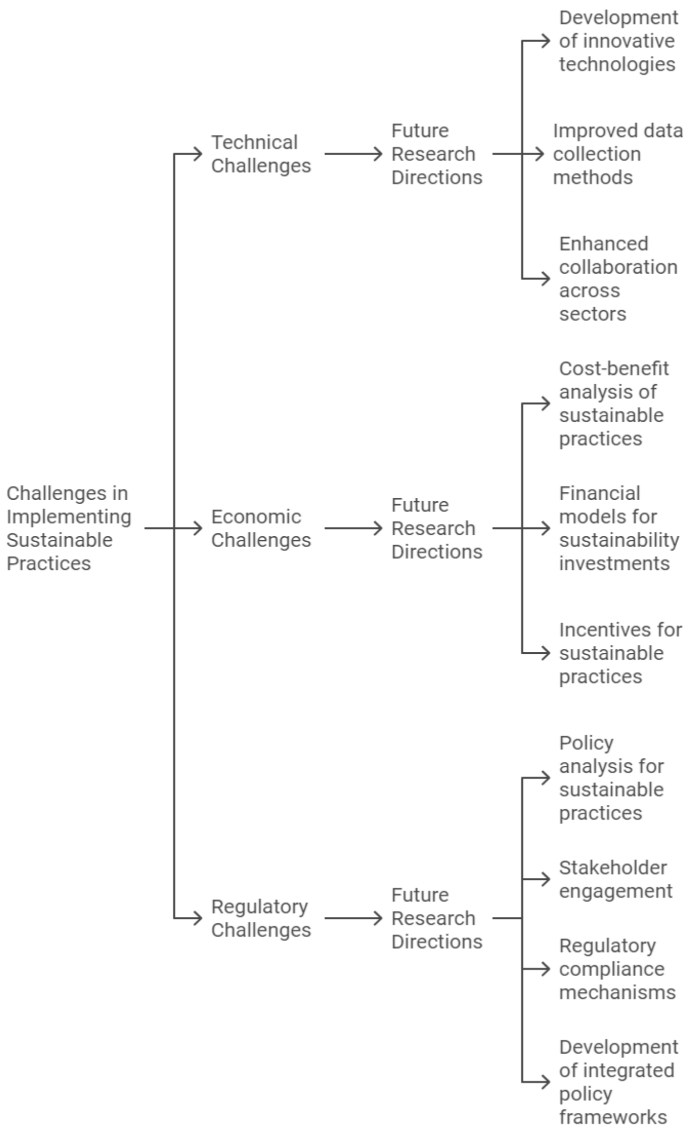

Figure 5 Challenges in implementing sustainable practices and the proposed future research directions to overcome them

6 Conclusions

Sustainable practices in prestressed concrete bridge construction have witnessed significant advancements over the past five years, addressing the urgent need to reduce environmental impacts and promote green construction. This review has synthesized recent developments in sustainable materials, innovative prestressing techniques, design methodologies, and real-world applications, highlighting their contributions to enhancing sustainability without compromising structural performance.

6.1 Key Findings

6.1.1 Sustainable Materials Integration

(1) The use of recycled concrete aggregates (RCA) and supplementary cementitious materials (SCMs) has proven feasible in prestressed concrete bridges, offering environmental benefits such as reduced resource consumption and lower carbon emissions.

(2) Alternative prestressing materials such as fiber-reinforced polymer (FRP) tendons and bio-based fibers contribute to durability and sustainability, although challenges remain in standardization and long-term performance assessment.

 https://doi.org/10.59238/j.pt.2024.04.001

6.1.2 Innovative Prestressing Techniques

(1) Low-carbon prestressing methods, including energy-efficient production processes and optimized on-site practices, reduce the carbon footprint associated with prestressing operations.
(2) Smart and adaptive systems, such as self-monitoring structures and adaptive prestressing using shape memory alloys (SMAs), enhance durability and extend service life, contributing to sustainability through reduced maintenance needs.

6.1.3 Design and Analysis for Sustainability:

(1) Lifecycle assessment (LCA) provides a comprehensive framework for evaluating and minimizing the environmental impacts of bridge construction over its entire lifespan.
(2) Performance-based sustainable design and optimization techniques enable the balance of structural performance with environmental objectives, leading to resource-efficient and high-performing bridge designs.
(3) Durability-focused design extends the service life of bridges, reducing the need for frequent repairs and replacements and thus conserving resources over time.

6.2 Recommendations for Practitioners

6.2.1 Adoption of Sustainable Materials

(1) The incorporation of RCA and SCMs into prestressed concrete where feasible ensures appropriate mix design adjustments and quality control measures.
(2) The use of alternative prestressing materials such as FRP tendons should be explored, considering the specific performance requirements and long-term durability needs.

6.2.2 Implementation of Innovative Techniques:

(1) Low-carbon production methods should be utilized, and construction practices should be optimized to increase energy efficiency and reduce emissions.
(2) Smart technologies and adaptive systems should be integrated to monitor structural health and extend service life, reducing lifecycle environmental impacts.

6.2.3 Integration of Sustainability in Design

(1) LCA and performance-based design approaches are employed to comprehensively assess and minimize environmental impacts throughout the bridge lifecycle.
(2) Optimization techniques are applied to achieve the best trade-offs between structural performance, cost, and environmental objectives.

6.3 Recommendations for Researchers

6.3.1 Material Development and Characterization:

(1) Research on enhancing the properties of RCAs and SCMs to improve their suitability for prestressed applications is needed.
(2) Innovative materials, such as bio-based composites and nano-enhanced materials, should be investigated to further enhance the sustainability and performance of these materials.

6.3.2 Development of Design Guidelines and Standards:

(1) Collaboration with industry stakeholders should occur to create standardized guidelines and codes that facilitate the use of sustainable materials and technologies in prestressed concrete bridges.
(2) Existing design methodologies should be updated to incorporate the latest research findings and technological advancements.

6.3.3 Addressing Implementation Challenges:

(1) Studies should be conducted to better understand and mitigate the technical, economic, and regulatory barriers hindering the adoption of sustainable practices.

(2) Educational initiatives and knowledge-sharing platforms should be promoted to increase awareness and expertise among engineers and construction professionals.

6.4 Concluding Remarks

The transition toward sustainable prestressed concrete bridge construction is both a necessity and an opportunity. Embracing sustainable materials and innovative technologies not only addresses environmental concerns but also paves the way for enhanced structural performance and extended service life. The challenges identified, while significant, are surmountable through concerted efforts in research, standardization, education, and policy development.

Future advancements depend on the continued collaboration among practitioners, researchers, policy-makers, and educators. By building on the progress of the past five years and actively pursuing the outlined future research directions, the industry can achieve a more sustainable and resilient infrastructure. The commitment to sustainability ensures that prestressed concrete bridges continue to serve society's needs while safeguarding environmental resources for future generations.

Conflict of interest: All the authors disclosed no relevant relationships.

Data availability statement: The data that support the findings of this study are available from the corresponding author, Xia, upon reasonable request.

Funding: The authors extend their sincere gratitude for the support provided by the projects PID2021-126405OB-C31, funded by FEDER funds—A Way to Make Europe and Spanish Ministry of Economy and Competitiveness MICIN/AEI/10.13039/501100011033/. This study is also supported by the Research & Development Program of China Railway Shanghai Group Corporation Limited (2023158)

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