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Research Article

A Comprehensive Review on High-Performance Concrete with Crumb Rubber for Enhancing the Structural Efficiency and Durability of Pre-Stressed Railway Sleepers

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ABSTRACT

The increasing demand for durable, sustainable, and impact-resistant railway infrastructure has accelerated the exploration of alternative materials for prestressed concrete sleepers. High-Performance Concrete (HPC), characterised by superior strength, refined microstructure, and enhanced durability, offers significant advantages over conventional concrete; however, its inherent brittleness under high-impact and cyclic loading remains a challenge. Incorporating crumb rubber (CR), derived from waste vehicle tyres, into HPC presents a promising solution by combining mechanical resilience with environmental sustainability. This review critically examines the mechanical behaviour, durability characteristics, structural performance, and finite element modelling (FEM) insights of CR-HPC sleepers, drawing upon recent experimental and analytical studies. Results consistently demonstrate that moderate CR inclusion enhances ductility, impact resistance, crack-bridging capacity, and fatigue life while maintaining compressive strength within acceptable limits for sleeper applications. CR-HPC also contributes significantly to sustainability by reducing landfill waste, lowering the environmental footprint, and extending sleeper service life. Despite these advantages, research gaps exist in long-term field performance, ITZ behaviour under prestressing, large-scale fatigue testing, and advanced numerical modelling. The paper concludes with future directions for optimising CR-HPC mix design, adopting AI-based prediction tools, and developing standardised design guidelines for next-generation resilient railway sleepers.

Keywords: High-Performance Concrete; Crumb Rubber; Prestressed Railway Sleepers; Mechanical Behaviour; Durability; Finite Element Analysis.

1. Introduction

The economic advancement of a globalised world, along with the industrial progress of multiple nations, and the mass movement of people, makes railway transportation one of the most important means of mobility systems in the world[1]. When compared to road and air transportation, railways have a number

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of other advantages, such as being economic, safe, energy efficient, environmentally friendly, and having greater carrying capacity. The uploaded document highlights how the swift advancement of global commerce and the soaring population of the world have significantly increased the use of railways, making railways the most preferred means of transport for long-distance travel. Railway tracks consist of several components, such as rails, ballast, fasteners, and subgrade[2]. The performance, reliability and infrastructure of railway tracks are of utmost importance; however, in this context, railway sleepers, also known as ties, play an important role in the safe, stable, and efficient functioning of train operations. Railway sleepers, also known as ties, play an important role in the safe, stable and efficient functioning of train operations. Some of the important factors that railway sleepers, also known as ties, play an important role in the safe, stable and efficient functioning of train operations. Some of the important factors that railway sleepers contribute to, along with the rigidity and strength of a railroad track is the insulating rail electrochemically, and also aid in mitigating the railroad track from vibrations and noise, and in the [3]. Distribution of wheel loads to the ballast. In addition to all these functions, railway sleepers also aid in the longitudinal and lateral movement of the rail.

The user's documents state that incorrectly designed sleepers, poor quality ballast, and undetermined loading can greatly impact the alignment and the performance of the rail systems. If the railway infrastructure is to be stable long-term, the material, strength, and durability of the sleepers need to be of high quality [4]. Certain materials have historically been used for the manufacturing of sleepers, such as timber, steel, and reinforced or prestressed concrete. Timber sleepers, which were once used the most, are the least economically viable now. This is because high-quality wood is increasingly hard to find, along with timber having an extremely short lifespan due to biological degradation, and the chemicals used in wood preservation cause a large environmental impact [5]. Even though steel sleepers pose greater strength and are lighter, uneven ballast support, corrosion, and a high level of noise, along with poor reaction to electrochemical, cause a large downside for steel. To improve the track stability and durability, pre-stressed concrete sleepers are now becoming the standard in most countries. Even though these do offer a large number of advantages, traditional concrete still poses a number of negatives. These can include brittle failures from high-impact forces, large service cracking, and high-energy inputs in the manufacturing process [6].

Fig 1. Prestressed Concrete Railway Sleepers Placed on Ballasted Track Bed

Researchers and the industry have embraced High-Performance Concrete (HPC) as a solution to the next generation of sleeper design challenges. HPC has high compressive strength, lower permeability, increased

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durability, and improved resistance to fatigue and impact force, coupled with a longer service life, rendering it ideal for high-speed rail, metros, heavy haul, and long welded rail operations [7]. However, for sleeper design, the tilting roads of HPC, British, and other European countries have used rubber-modified concrete, perceived as a solution to some of the design problems, such as overly aggressive impact force. At the same time, the global problem of the disposal of waste vehicle tyres has been addressed with a sustainable solution, and the use of track in rubber (RMC) as a partial replacement for concrete, as you have referenced in your paper, is a solution to the problem of track running in rubber in India[8]. Concrete with crumb rubber (CR) is a concrete track with CR obtained by grinding used vehicle tires into small particles; it has part of the CR concrete track the useful properties of CR. Concrete tends to have lower ductility, toughness, impact resistance, and energy absorption capacity. The ability of CR-modified concrete to withstand repeated dynamic loading and impact forces makes it applicable to railway sleepers. As noted in your file, the addition of rubber particles improves behaviour under dynamic stresses due to increased elasticity, deformation resistance, and bond flexibility [9]. In the concrete industry, CR in HPC is referred to as composite concrete, Crumb Rubber-Modified High-Performance Concrete (CR-HPC), and combines the mechanical and durability characteristics of HPC and the flexibility, damping, and crack control of rubber. The creation of such an engineering material exemplifies circular economy principles by upcycling waste tyre rubber. Additionally, CR-HPC will likely reduce maintenance, improve the lifespan of tracks, and reduce the associated risks of track safety due to sleeper degradation [10].

In recent years, multiple studies have explored the material, mechanical, and durability properties of CR-HPC for railway sleepers. CR-HPC railway sleepers have seen a variety of studies over the past few years that analyse the materials, mechanics, and durability of the emerging technology. Previous studies show that the addition of CR may decrease a sleeper's compressive strength but increase flexural strength, ductility, and impact resistance, which occurs over millions of sleep cycles of millions over time. CR particles help dampen vibrations, reducing the attrition of ballast and increasing the lifespan of the interface [6]. The uploaded documents also mentioned that the studies conducted, which included impact testing and static bending strength tests, outlined the feasibility of rubberised HPC sleepers in railway applications. The evolution of computational modelling further supports the utilisation of CR-HPC sleepers. As outlined in your document, Finite Element Method (FEM) simulations analyse the distribution of stress and dynamic behaviour of concrete sleepers for performance under load in railway operations. The models and laboratory tests show evidence suggesting that CR-HPC sleepers are superior to traditional concrete sleepers in resisting stress concentrations and cracking. The contemporary demands of global railways include higher speeds, larger axle loads, and lower maintenance. The application of CR-HPC concrete sleepers is predicted to solve these extensive modern demands. Crumb rubber-modified high-performance concrete (HPC) helps with recycling tyres and has mechanical performance benefits as a new, classified as eco, pre-stressed concrete sleeper alternative. It helps with the mechanical recycling of waste and reduces long-term costs [7].

2. Background and Evolution of Railway Sleeper Materials

The evolution of railway sleeper materials reflects more than a century of technological advancement, structural optimisation, and the growing demand for sustainability in railway infrastructure [11]. From over a century of technological advancement, structural refinement and a growing need for sustainability in railway infrastructure, the development of railway sleeper materials has come a long way. The first rail systems used timber, the most adaptable and easiest to install material. As mentioned in the review uploaded by Chavan and Malu, hardwoods like Sal and Deodar were serviceable due to their natural resilience and low cost, but timber's biological and moisture degradation led to a need for alternative

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materials long before timber. The first rail systems used timber, the most adaptable and easy-to-install material for fastening systems, and the most damaging material. Increasing axle loads, faster train speeds, and harsher service environments exposed the limited engineering of timber [12]. The next big change was the introduction of steel sleepers, which, in comparison to timber, really helped with the engineering of rail systems. However, steel sleepers brought their own challenges. They were not very interlockable to ballast, and in the case of the inverted trough profile, they were very easy to overlook. As mentioned in the same review, they are also very poor at ballast interlock, and service failures occur from not shimming, contrary to the usual level of ballast interlock control. Steel is also more conductive, fatigue crackable, and corrosive. Consequently, although steel rectified some structural deficiencies of timber, its operational and environmental shortcomings hindered steel from becoming the universal remedy.

The introduction of prestressed concrete sleepers marked a transformative shift in railway engineering. The use of prestressed concrete sleepers created a revolution in railway engineering. It becomes the global standard easily, and for good reason, rapidly becoming the new standard for the construction of railway lines, especially for the fast and heavy hauling networks. However, it does not come without problems. Concrete sleepers are expensive, heavy, and some even become brittle and fail under heavy shocks and chemical exposure. They are also very difficult and expensive to maintain. Li, You, and Kaewunruen (2022) defined concrete in detail and demonstrated prestressed sleepers from finite-element simulations and field data, describing them as more than likely to crack at the midspan and rail-seat from under transverse loading of (seated dynamic) and impacts of 100-750 kN [7]. These impacts take place in the heavy haul conditions. The parallel research made on composites, and polymer-based sleepers, specifically the glass fibre reinforced polymer, and other variants of the plastic composite, and even synthetic composite, is more than likely to emphasise the more than equally interesting research on composite sleepers. However, the lack of field data, the expenses, and the strategies in the production of composites and polymer-based sleepers are almost more than just the cost of the concrete they are used to replace. As a result, they have not become common in many markets.

The last few decades and Zamora-Castro et al. (2021) explain that sustainability and waste tyre management rubber's elasticity and rubber's ductility and damping properties aid concrete mix construction show improved impact resistance and absorption. Even though there are compressive strength concerns, Moolchandani et al. (2024) provide evidence of crumb rubber's flexural ductility improvements and support and durability enhancements, whose application in sleeper designs whose quality construction requires toughness and resistance to fatigue support. Concrete and rubber-modified materials sustain, and high-performance metamorphosis sleeper materials, advanced materials, timber and rubber. Materials. From materials evolving to meet the modern railway's operational demands, it illustrates the construction of the sleeper. It shows the evolving construction to meet the modern operational demands of the railways [13].

Table 1: Comparative Review of Rubberised Concrete Innovations and Their Applicability to Railway Prestressed Sleepers

Sr. No.	Author et al. & Year	Purpose / Concrete Type	Rubber Content	Strength Results	Impact / Fatigue / Energy	Durability Findings	Sleeper-Level Takeaway
1	Khalifa et al., [14]	Full-scale prestressed sleepers using	6% CR + 0.5% PP fibre	Strength > sleeper flexural	Better crack control, high toughness	Cement-free sustainable design	Fully meets sleeper structural criteria

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Sr. No.	Author et al. & Year	Purpose / Concrete Type	Rubber Content	Strength Results	Impact / Fatigue / Energy	Durability Findings	Sleeper-Level Takeaway
		modified HPC		requirement			
2	Zhai et al., [15]	Modified crumb rubber concrete (CRC) for durability	Modified CRC (not % based)	Strength regain = 63.5%	Frost damage resistance improved	Frost +400%, permeability +110%	Suitable for harsh environmental conditions
3	Pham et al., 2024[16]	UHPC + rubber (UHPRuC) for mechanical + CO_2 reduction	Up to 40% CR	Flexural strength loss < compressive loss	Improved vibration damping	CO_2 emissions reduced by 37%	Good balance of sustainability & performance
4	Chen et al., 2021[17]	Pretreated rubberised concrete for dynamic behaviour	10–15% CR	14% compressive strength reduction	Damping increases by 62%	Pretreatment enhances durability	Optimum CR ≈ 15% for sleepers
5	Hameed et al., 2016 [18]	Rubber concrete for prestressed sleepers	15% CR	Target strength 50–55 MPa achieved	Impact strength ↑ 60%	Good fatigue & impact performance	Suitable for sleeper applications
6	Siahkouhi et al., 2022 [19]	Rubber prestressed sleeper behaviour	Rubber sleeper (no % defined)	Crack resistance ↑ 20%	Delay in crack initiation	Better structural cracking resistance	Stronger crack initiation performance
7	Han et al., 2023 [20]	CRC under elevated temperature	0–20% CR	Strength at 300°C = 104→80%	Toughness increases under heat	Strength at 700°C = 36→29%	CR increases plasticity at high temps
8	Gill et al., 2023 [21]	Rubberised geopolymer concrete	0–15% CR	Strength loss ≤ 17%	Moderate toughness improvement	Acid and temp resistance studied	Suitable up to 15% CR
9	Yasser et al., 2023 [22]	Durability of rubber concrete	0–20% CR	35% loss at 15% CR	Improved sorptivity + resistance	Detailed RCPT, acid,	Clear durability

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Sr. No.	Author et al. & Year	Purpose / Concrete Type	Rubber Content	Strength Results	Impact / Fatigue / Energy	Durability Findings	Sleeper-Level Takeaway
						absorption data	performance limits
10	Aown et al., [23]	Impact resistance of rubber concrete	Treated vs untreated rubber	Impact absorption ↑ 41–59%	High dynamic energy absorption	Not the primary focus	Useful for high-impact sleeper zones
11	Alizadeh et al., 2024 [24]	Strength recovery through rubber modifiers	25% fine agg. replaced	Compressive strength ↑ 60.4%	Moderate energy absorption	Enhanced mechanical recovery	Rubber modifiers restore strength
12	Hasan et al., 2024 [25]	CR + hybrid fibres (HHF)	5% CR + 1% fibre	+3.6% compressive, +8.56% tensile	Improved impact & toughness	Not primary	Best synergy at low CR + fibre
13	Micro-CRC Sleeper Study	Micro-crumb rubber concrete sleepers	Micro CR (fine powder size)	Strength > 55 MPa	Damping ↑ 42%	Lower vibration damage	Meets sleeper stiffness & damping
14	Choi et al., 2024 [26]	Field vs FE modal testing of sleepers	Rubber not % based	FE = 125.30 Hz, Field = 122.96 Hz	Damping behaviour assessed	Modal accuracy error = 1.87%	Useful for sleeper health monitoring
15	Choi et al., [27]	Ballast stiffness vs vibration	Support stiffness varied	Frequency reduces with stiffness drop	247 → 198 → 136 Hz	Identifies support degradation	Diagnostic tool for track maintenance

3. High-Performance Concrete (HPC): Composition & Behaviour

High-Performance Concrete or HPC is elevated from conventional concrete due to advancements in the cementitious material technology field. Improvements in strength, microstructural characteristics, durability, and permeability in cementitious materials have allowed for the creation of concrete that is far superior to that of conventional concrete. Scholars indicate the strength of HPC to be the result of the unique engineering and material selection, as a result of the composition. This is seen as a lower water-to-cement ratio, use of high-range water-reducing admixtures, and the use of mineral additives such as slag, fume, or ashy silica. He et al. (2023) show that rubberised high-performance concretes create a unique interaction between crumb rubber and cementitious phases. The microstructural refinement results in silica fume compensating for the rubber particle soft inclusion effect. The review shows that the main

compressive strength and modulus of elasticity contributions of rubber are the result of the low hydrophobic bonding and higher stiffness of the rubber. The HPC mix with silica fume and fly ash is the primary contributor to the strength of the interfacial transition zone (ITZ). Farhad Aslani et al. (Referenced in He et al., 2023) studied particle-size effects and observed that larger rubber particles were the cause of greater reductions in compressive strength due to more micro-crack formation, while fine crumb rubber more evenly dispersed stress [28]. Their results confirm that the microstructure of high-performance concrete the silica fume and high pozzolanic reactivity, improves, so lessens the detrimental effects of rubber aggregates.

The high-reactivity mineral additive implementation in HPC by Zamora-Castro et al. (2021) suggested the existence of synergy between rubber particles and supplementary cementitious materials (SCMs). SCM-enhanced HPC, as proposed, is able to diminish pore connectivity and overlapping rubber particle deficiencies. This is due to rubber particles being bonded in a deficient manner, as particles are not interfaced with other binder materials [13]. This signifies that no single additive can explain the great improvements that are due to the designed microstructure of the HPC. While investigating modified HPC mixtures with crumb rubber, Moolchandani et al. (2024) noted that the presence of mineral admixtures like fly ash and silica fume fosters long-term positive durability, mitigation of carbonation, and diffusion of chloride penetration, which are the hallmarks of positive performance. Although compressive strength reduces by a marginal 8-18%, the flexural toughness and ductility HPC–rubber blends attain are especially useful for designing fatigue-sensitive materials like prestressed concrete sleepers. The HPC mechanical advantage is further highlighted in the uploaded sleeper structural evaluations [29]. Kaewunruen et al. (2018) FE-based sleeper assessment verifies that sleeper failure is predominantly at the rail-seat and mid-span, where the dynamic stresses are above 100–750 kN. The researchers highlight that compared to normal concrete mixes, HPC exhibits more resilience to cyclic fatigue and crack propagation, making it a more appropriate option for prestressed sleepers [6].

Similarly, the review on material suitability for sleepers highlights that HPC incorporating crumb rubber achieves:

- higher damping and energy absorption,
- reduced brittle failure,
- improved impact resistance,
- Enhanced vibration attenuation.
- These benefits are critical for rail transportation systems operating under high-impact and high-frequency loading.

Lastly, Wag et al. (2023) stated that the pretreatment of rubber particles, via NaOH, cement paste coating, or grinding, improves ITZ quality, which gives the solid enhancements of strength and stiffness by 10–17%. This further improves the structural performance of the HPC–rubber composites. Overall, the research confirms that the best performance of crumb rubber and HPC ratio proves to give the best performance and justifiably supports the use of prestressed concrete sleepers. They have engineered a material that can withstand extreme mechanical stresses with a resilient, micro, porous, and ductile structure [30].

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Table 2: Summary of Key Studies on HPC with Crumb Rubber

Author & Year	Mix / Study Details	Key Findings	Relevance to Sleeper Design
He et al. (2023)	HPC incorporating crumb rubber at 0–30% replacement	Demonstrated significant improvement in ductility, impact damping, and energy absorption; observed reduction in compressive strength and elastic modulus	Ideal for high-impact regions of sleepers, particularly rail-seat zones exposed to dynamic loading
Farhad Aslani et al.	Study on rubber particle size influence in HPC	Larger rubber particles caused greater strength reduction; finer rubber particles dispersed stresses more uniformly and produced improved mechanical behaviour.	Supports optimisation of CR particle size distribution for sleeper-grade HPC mixes
Zamora-Castro et al. (2021)	HPC modified with supplementary cementitious materials (SCMs) and crumb rubber	SCMs (silica fume, fly ash) refined the pore structure, strengthened the ITZ, and reduced CR-induced porosity.	Enhances long-term durability of sleepers, especially against moisture, abrasion, and chemical exposure
Moolchandani et al. (2024)	HPC blended with silica fume/fly ash and crumb rubber	Reported increased toughness, flexural ductility, and fatigue performance with only a moderate loss in compressive strength	Improves resistance to cyclic rail loads and delays crack initiation under repeated wheel impacts
Li, You & Kaewunruen (2022)	Finite element (FE) modelling of prestressed sleepers	Identified critical failure zones (rail-seat, mid-span); showed that high-performance mixes reduce crack propagation under extreme dynamic loads	Provides analytical justification for adopting HPC mixtures to extend sleeper service life
Chen et al. (2023)	Pre-treatment of rubber aggregates (NaOH, cement coating)	Achieved 10–17% improvement in strength and stiffness; improved ITZ bonding and reduced micro-cracking	Rubber pre-treatment enhances the structural reliability and stiffness required for sleeper applications

4. Crumb Rubber in Concrete

The incorporation of crumb rubber (CR) into concrete has emerged as an innovative and sustainable approach to enhance the mechanical resilience and energy-absorbing capacity of cementitious composites. Integrating crumb rubber (CR) in concrete has become a new practical and eco-friendly way to improve the mechanical strength and energy absorption of a cementitious composite [31]. Crumb rubber is made through a processing method of end-of-life vehicle tyres, by using either ambient grinding, which rips rubber apart at room temperature to create rough and irregular particles, or cryogenic grinding, which involves freezing rubber and then fracturing it into smooth and uniformly shaped particles. Crumb rubber

is characterised by numerous concrete performance-affecting attributes. One of the attributes is the density, which is much less than that of the concrete mixes' mineral aggregates, resulting in a concrete mix weight reduction. The diminutive moisture-sapping ability affects moisture distribution and the bonding of the cement matrix [32]. Material flexibility, along with high elongation and low elastic modulus, tends to provide a micro shock-absorbing capacity under loading. Rubber also has a dampening ability that improves vibration absorption and reduces concrete's chances of experiencing brittle failure modes or catastrophic failure. Incorporating crumb rubber into concrete gives it a lot of positive attributes. The most important thing is that it improves the ductility of concrete, enabling the rubberised concrete to deform more before experiencing a failure. This is an important ability to have on structural elements that are impacted mechanically on a regular basis, like railway sleepers. Crumb rubber also aids in impact resistance and energy absorption by dissipating stress waves through particle deformation. The rubber's elastic nature helps in crystal arrest, which means it delays the occurrence of larger cracks by redistributing matrix stresses. All of this makes CR-modified concrete appropriate for applications that need more fatigue life and resilience.

There are some notable drawbacks to using crumb rubber. Nearly all literature describes a reduction in compressive strength as a consequence of the softer nature of rubber in contrast to the mineral aggregates. The rubber's hydrophobic and smooth surface increases the ITZ, which should otherwise increase strength. Rubber also tends to create a greater number of air voids. This impacts the density and stiffness of the concrete. Apart from these drawbacks, some modifications can greatly improve bonding, offset the strength loss, and optimise the mix for structural uses, such as the prestressed concrete sleepers. Using mineral admixtures, nano materials, or surface-treated rubber are such modifications [33].

Table 3: Key Research Contributions on Crumb Rubber in Concrete

Author & Year	Research Focus	Key Findings on Crumb Rubber (CR)	Relevance to Structural / Sleeper Applications
LI et al. (2016) [34]	Behaviour of rubberised high-performance concrete	Reported reduced compressive strength but significantly improved ductility, damping, and crack-resistance in CR-HPC	Enhances impact performance and fatigue resistance in prestressed concrete sleepers
Zamora-Castro et al. (2021)[13]	HPC incorporating supplementary cementitious materials (SCMs) with CR	Demonstrated that SCMs refine the ITZ, reduce porosity, and counteract bonding deficiencies caused by rubber	Improves long-term durability and service life of sleeper concrete
Chen et al. (2023) [28]	Pre-treatment of crumb rubber particles	Found that NaOH washing and cement-slurry coating enhanced strength and stiffness by 10–17%	Improves rubber–cement bonding, critical for prestressed sleeper performance
Moolchandani et al. (2024)[29]	Mechanical and durability behaviour of CR-modified HPC	Observed significant improvements in toughness, energy absorption, and flexural capacity despite moderate strength loss	Supports higher fatigue life under repeated axle loads in railway sleepers

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Author & Year	Research Focus	Key Findings on Crumb Rubber (CR)	Relevance to Structural / Sleeper Applications
Li, You & Kaewunruen (2022) [7]	Finite-element evaluation of sleeper behaviour	Showed that materials with higher toughness reduce crack initiation at the rail-seat and mid-span zones	Confirms the suitability of CR-HPC for modern sleeper design and safety

The existing research shows that Crumb Rubber (CR) considerably changes multiple facets of concrete use in railway sleepers, in positive ways. He et al. (2023) showed that while CR reduces compressive strength, it improves ductility and damping, both of which are vital for load absorption from a train's high impact [28]. By contrast, Zamora-Castro et al. (2021) showed that the negative effects of CR on porosity can be enhanced with supplementary cementitious materials, which strengthened microstructural integrity [13]. Chen et al. (2023) extended this by showing that rubber pre-treatments significantly improve the interfacial transition zone (ITZ) and strengthen the rubber-cement bond. Moolchandani et al. (2024) confirmed the increased energy dissipation and toughness for fatigue resistance [29].

5. Mechanical Performance of CR-HPC

The fundamental properties of Crumb Rubber-High Performance Concrete (CR-HPC) have been documented because of its application in structural components that are subjected to high impact and cyclic loading, such as prestressed railway sleepers. Most studies have documented a measurable decrease in compressive strength, which ranges from 10-40%. This decrease is dependent on the amount of rubber, the cohesion level of the rubber, and the surface properties of the rubber [35]. There is also an increase in flexural behaviour with the inclusion of moderate amounts of CR. Most of the literature data suggests that HPC with rubber improves flexural toughness, ductility after cracking, and the ability to bridge a cracked area, for CR levels of replacement between 5-15%. This characteristic is extremely valuable for railway sleepers because bending stresses are present at the rail-seat and midspan of the sleeper. CR-HPC also demonstrates the ability to deform without a sudden breach of failure [18]. The addition of certain levels of CR to high-performance concrete has been demonstrated to reduce the rate of micro- cracking that is typical of concrete, and increase the life of the structure under cyclic loading. One of the most important features of CR-HPC is its impact resistance. The rubber particles within the concrete act to absorb the micro shocks that occur at the rail-seat, between the ballast, and within the structure to prevent structural cracking and premature failure. This is especially important for the high-speed and heavy-haul rail networks, where substantial impact loads from dynamic wheel-rail affect the sleepers. Another significant advantage is CR-HPC's ability to absorb energy. Including CR makes the material tougher, meaning it can be deformed more and withstand cyclic and affect loading without failing structurally [36]. This improved toughening helps more stable sleeper performance under millions of load cycles. Overall, while the reduction of compressive strength is necessary, the mechanical improvements earned—greater ductility, toughening, impact response, and energy absorption—make CR-HPC highly beneficial for next-generation sleeper systems.

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6. Durability Characteristics

Durability performance plays a decisive role in evaluating sleeper materials, as these components endure aggressive environmental conditions, moisture fluctuations, chemical exposure, and continuous mechanical wear. The sleeper materials evaluation process considers the different types of durability performance because of the different components' exposure to aggressive environments, wet/dry cycles, chemicals, and abrasion. Because of the hydrophobic character and poor bond of crumb rubber, more porosity, and hence water absorption, may occur. However, the refined microstructure of high-performance concrete (HPC) with silica fume, fly ash, nano-silica, and slag counteracts the deficiency and reduces pore interconnectivity and seals the interfacial transition zone [37]. Therefore, several mixes of CR-HPC (Concrete Rubber-High Performance Concrete) maintained adequate levels of permeability for the sleeper exposure conditions. Concerning abrasion and facture, CR-HPC often outperforms conventional concrete. The rubber particles' ability to limit the formation of new cracks and to restrain the extension of existing ones reduces the number of conduits through which aggressive chemicals and sulfate ions penetrate the microstructure. This results in the deterioration rate in the aggressive soil or ballast that surrounds the sleeper, increasing the durability of the sleeper. The incorporation of CR also improved the freeze-thaw and temperature performance of the mixes. Rubber particles offer micro cushioning and elasticity, which lessen inter stresses caused by freeze-thaw cycles. This leads to fewer surface cracks, improved frost resistance, and better thermal shock performance compared to standard high-performance concrete. Such attributes are particularly pertinent to rail networks in colder climates, where freeze-thaw cycles can significantly reduce the life expectancy of sleepers [38].

There are both positive and negative aspects to the behaviour of crumb rubber concrete and fire. On one hand, the inclusion of rubber in the concrete does improve spalling, and the resultant reduction in strength and increase in porosity from rubber burning are negative. Even though spalling is less likely, the mechanical degradation that occurs after a fire is of greater concern with rubber concrete, so in relation to post-fire behaviours, rubber concrete needs more attention in fire-prone areas. All of this makes rubber concrete suitable in regions with differing environmental and mechanical stressors for the sleepers. The rubber helps with critical needs like crack resistance and chemical resistance, and the HPC (High Performance Concrete) helps with the areas where rubber is deficient [39]. This balance helps the sleepers perform in varying environments and mechanical conditions.

7. Behaviour of CR-HPC Sleepers Under Railway Loading

Fig 2. Operational Railway Track Showing Prestressed Concrete Sleepers Supporting Heavy Maintenance Equipment Loads

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The behaviour analysis of railway-loaded Crumb Rubber-High Performance Concrete (CR-HPC) sleepers has been conducted thoroughly, covering static, dynamic, and fatigue-based performances [34]. Prestressed sleepers experience load combinations of a number of factors: bending, impact, ballast reactions, and cyclic stresses, which are repetitive due to millions of wheel passes. Operationally, how CR-HPC responds to these challenges and the benefits in structural and enduring toughness are explained in the attached document.

1. Static Bending Strength

The IRST-39-85 standard describes the Mischievous Rail Moments as the primary tests used to determine the strength of the rail sleepers. These tests apply a pre-determined load to specified positions (the seating of the sleeper and the mid-span) and carry out the tests. A sleeper is determined to be compliant if, under the specified moments at the seating position, no visual cracks are formed, and at mid-span, there is a stable behaviour. Your document shows that the CR-HPC sleepers under the Mischievous Rail Moments and FR conditions show that the load they were responsible for carrying was achieved without any structural cracks [34]. This shows that the increased compressive strength caused by the CR addition is within the limits of prestressed sleeper applications. The increased flexibility that is a result of the rubber particles assists the sleeper in carrying a uniform distribution of the different stresses and still performing without brittle fractures. The sleeper can still perform under controlled bending.

2. Dynamic Impact Behaviour

Under high-speed railway conditions, sleepers have to deal with impact forces coming from wheel flats, rail joints and irregular loading. In your study, the experiments proved that CR-HPC, due to the rubber's elastic and energy-absorbing microstructure, improves impact resistance. Rubber particle microstructure reduces the impact energy and stress concentrations within the rail-seat zone. Rubber is viscoelastic; the microstructure absorbs impact energy, and within rubber, the stress gets dissipated. This is important because concrete sleepers fail due to catastrophic cracking at the rail-seats during repeated impact forces. CR-HPC reduces peak stresses and crack initiation, and mitigates ballast attrition, resulting in better service life [40].

3. Crack Control

Your uploaded text explains the accepted presence of manufacturing cracks and the conditions under which they are considered stable. Such cracks may serve as a crack propagation mechanism when in service loading, and when the concrete is not tough enough. The incorporation of CR improves the crack-bridging and crack-arresting mechanisms. Micro rubber particles are elastic, and therefore will divert and dissipate crack energy, and as a result, will not allow microcracks to become larger fractures [41]. Therefore, it can be stated that CR-HPC sleepers are more durable, have lower crack growth and better resistance to progressive deterioration.

4. Fatigue Life

Railway sleepers experience severe fatigue loading, often exceeding 1–2 million load cycles annually. Every year, railway sleepers have to handle fatigue loading, which can go over 1 to 2 million load cycles. Among all the qualities that CR-HPC possesses, the most valuable one is the fatigue performance [42]. It is the rubber that increases ductility and the energy absorption capacity that causes rubber to lower the internal stress concentration during load cycles. Your uploaded files, as well as other research, describe the phenomenon where CR-HPC improves flexural fatigue and can maintain load-carrying capacity for more cycles than conventional concrete. The sleepers' increased toughness means that they will have controlled deflection and less stiffness degradation over time during repeated loading, which is a desirable quality for heavy-haul and high-speed rail operations.

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8. Finite Element Modelling (FEM) of Sleepers

Finite Element Modelling (FEM) has emerged as a primary analytical tool for studying the structural behaviour of railway sleepers under various load types, including static, impact and cyclic loadings. Modern sleeper materials, especially the crumb rubber modified high-performance concrete (CR-HPC), exhibit complex and continued, non-linear behaviours that are difficult to capture through experimental testing. Consequently, evaluating stress distribution, crack formation and deflection, as well as predicting long-term performance trends using FEM, proves to be a time-efficient modelling approach. The modelling process starts with the construction of an accurate geometric model of the sleeper that incorporates critical engineering features like the rail-seat shoulders, pre-tensioning zones, ballast-contact bottom surfaces, and the rail-fixation zones [43]. These geometric characteristics are crucial as a sleeper undergoes non-uniform bending, shear, and concentrated local loads at the rail-seat. The literature studies highlighted that oversimplified geometries underestimate the peak stresses, whereas geometries that are fully detailed predict the critical locations of crack formation with a high degree of accuracy (e.g., rail-seat and mid-span). After constructing the sleeper geometry, the sleeper is divided into a large number of finite elements to demonstrate the complex stress field phenomenology. Additionally, the models are designed so that a finer mesh is applied to all the high-stress areas (e.g. rail-seat and tendon anchorage areas), whereas a coarser mesh is applied to the areas with uniform stress distribution. This mesh gradation optimises computing resources while still being able to give correct predictions. In relation to the CR-HPC, concrete, and steel reinforcement, the stress-strain relationships are used to assign the FEM material properties [44]. A concrete is typically designed by using a fully nonlinear approach, which enables one to model and simulate the pre- and post-cracking stages by capturing the process of compressive crushing and tensile cracking. The crumb rubber-modified HPC can be modelled as having lower elastic moduli and an increased strain capacity, some added damping, and modified tensile behaviour to realistically represent the bridging of cracks [45]. The prestressing tendons can be modelled as high-strength steel with pre-stress losses due to the application of external loads. This is primarily why the FEM is able to duplicate realistic composite actions with the concrete and the steel. The boundary conditions replicate the ballast and sleeper interactions, which can be modelled using a combination of distributed springs, elastic supports, and contact surfaces that simulate the partial embedding of the sleeper and are configured to allow free rotation and translation of the various components. The application of loads is consistent with the loading patterns that are normally used in railways and includes rail seat cyclical loads, static flexural loads, and point impact loads. The parameters that define these loads are also designed in accordance with the railway construction codes. One significant factor that needs to be considered for FEM studies is model validation (or lack thereof). This is achieved by comparing the numerical results with the experimental results obtained from static bending, impact, or fatigue tests, and these are compared with the results of deflection, crack initiation, stress distribution, and maximum load applied [46]. Many peer-reviewed multi-studies document a steady and strong relation to the predictions obtained from FEM for the actual performance of sleepers in the laboratory, and this is particularly the case for CR-HPC. FEM also supports the suitable designation of rubberised mixes for high-impact applications as it captures the delayed cracking and greater post-peak behaviour as well as the enhanced energy absorption. Overall, FEM helps to fully comprehend CR-HPC sleepers with respect to a given range of loading conditions. This also helps inform the engineers to vary the proportions of materials, the design of the reinforcements, the configuration of the sleepers, and the design of the joints to promote long-term durability without the need for extensive, large-scale field tests. This attribute of FEM has made it a primary tool for design and research in the 21st century for the innovative design and research of sustainable and resilient railway sleepers.

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9. Sustainability Assessment

Aspects of sustainability drive the development of modern railway infrastructure. This includes the search for materials that minimise impact and have maximum structural integrity. The use of crumb rubber in High-Performance Concrete (HPC) is an example that addresses several of the environmental issues and operational and economic challenges for 'greener sleepers'. The reduction of landfill waste is one of the numerous advantages. Every year, millions of old vehicle tyres become an environmental hazard due to landfilling and open burning. Diverting crumb rubber from landfills into structurally sound HPC provides an effective waste stream for road base applications to support resource recovery and waste minimisation. Regarding litter footprint, the CR-HPC decreases the use of quarried natural aggregates and lowers the embodied energy and carbon footprint associated with the processes of extracting, crushing, and transporting aggregates. The use of silica fume, fly ash, and slag with HPC helps further reduce CO_2 emissions from cement production [47]. CR-HPC sleepers possess an improved service life over other competitors due to enhanced toughness, crack control, and fatigue resistance. This decreases the number of replacements needed over the life span of a railway track, which lowers material use, maintenance and transportation emissions. Economically, the utilisation of recycled rubber can lower material costs, particularly in regions where rubber waste is abundant and disposal is costly. Although HPC itself may be more expensive than conventional concrete, the extension of service life and reduction in periodic maintenance can significantly offset initial costs, delivering a favourable life-cycle cost profile. Moreover, adopting CR-HPC aligns with circular economy principles, transforming waste materials into durable infrastructure components and encouraging the development of recycling-based industrial ecosystems. From a broader sustainability perspective, CR-HPC sleepers support long-term resilience by reducing ballast degradation, limiting track geometry defects, and offering superior damping of vibrations, which in turn improves safety and reduces noise pollution in urban rail corridors. Overall, CR-HPC provides a multipronged sustainability advantage—environmental, economic, and operational—positioning it as a strong candidate for next-generation sustainable railway sleeper solutions [48].

10. Research Gaps Identified

Despite considerable progress in understanding the behaviour of Crumb Rubber–High Performance Concrete (CR-HPC) for railway sleeper applications, several critical research gaps persist that limit full-scale implementation. Although great strides have been made in understanding the behaviour of Crumb Rubber-High Performance Concrete (CR-HPC) for railway sleeper applications, a few critical research gaps remain and preclude full-scale implementation. First, while most studies have documented retractions in compressive strength for increased CR content, there is a severe lack of consensus regarding the optimal range for CR replacements for sleeper-grade HPC. Most studies reviewed focus on small batches and, while there are structural applications, most do not focus on sleeper-specific mixes subject to severe bending, impact, and fatigue. Consequently, there remains no aggregate mix design methodology. Next, while there is some understanding of the behaviour of the interfacial transition zone (ITZ) in pre-stressed conditions, there is insufficient understanding of the impacts of pre-treatment methods (NaOH washing and cement slurry coating) on the ITZ under the aforementioned loads of a railway sleeper, moisture conditions, and ballast abrasion. While these methods have been documented to improve the ITZ, there is a lack of long-term micro-structural studies to support these claims. Third, there is very da little analysis of the fatigue behaviour of CR- HPC sleepers. While some existing research claims improved energy absorption and overall sleep toughness, there are very few to no large-scale studies or studies examining the function of railways under heavy-haul or high-speed conditions, and there is a very noticeable absence of studies or

large-scale data on million-cycle fatigue. Most importantly, the effects of dynamic wheel-rail contact, prestressing, and CR content on fatigue life are not fully understood.

Most FEM studies that employ ANSYS and ABAQUS to model sleeper performance ignore the rubber's non-linear behaviour. There is a gap for complex constitutive models that capture the elastoplastic, viscoelastic and damping behaviours of CR-HPC, considering that concrete and rubber are the main components, in relation to realistic crack propagation and rail seat stress concentration. Sustainability studies are often restricted to waste utilisation and some form of carbon reduction. A more thorough approach is necessary, including life-cycle and life-cycle costing of CR-HPC sleepers in relation to design, production, service, recycling, and disposal phases. Such studies are necessary for large-scale implementation in national rail systems. The aforementioned gaps in research indicate the need for better experimental, analytical and fieldwork in the optimisation of CR-HPC for the next generation of railway sleepers.

11. Conclusion and Future Directions

This review shows that Crumb Rubber-High Performance Concrete (CR-HPC) is a viable and sustainable option for next-generation prestressed concrete railway sleepers. Rubber's unique ductility and microstructure of High-Performance Concrete (HPC) allow CR-HPC to outperform traditional concrete in a variety of railway load environments. CR-HPC, at optimal rubber content, consistently meets and enhances most of High-Performance Concrete's (HPC) key performance indicators: impact absorption and fatigue resistance. Within a limit of compressive strength, CR-HPC improves vibration damping and crack resistance. Overall, fatigue and compressive strength analysis indicate that CR-HPC's rubber content meets the demands of protective railway applications. In the modern application of railways, less long-term railway maintenance, enhanced resistance to freeze and thaw cycles, and improved resistance to chemical and mechanical cracking justify the use of CR-HPC.

Although the outcomes are promising, the review describes the preliminary scientific and pragmatic questions that need answering prior to the implementation of CR-HPC sleepers at an industrial scale. Specific long-term field performance data, deficiency in sleeper-specific mix design standards, and a lack of understanding of ITZ behaviour under prestressed ITZ conditions are some of the concrete cases. Rubber's nonlinear viscoelastic response is unable to be captured in the current mathematical models, which means analytical models will need to be developed. Rail authorities are unable to determine the full economic value and CR-HPC's environmental benefits because of the absence of comprehensive life cycle and sustainability studies. Future research should be directed at developing large-scale experimental fatigue studies under realistic track conditions, advanced FEM-experimental hybrid modelling and AI/machine learning optimisation frameworks for mix proportioning. Without the addition of hybrid reinforcement systems, surface treatments of rubber particles, nano-modified CR-HPC, and the reinforcement of rubber, improved surface treatments for rubber particles will be essential for strength and ductility enhancement. The global railway networks will be able to adopt CR-HPC sleepers in a widespread, cost-effective, and safe manner once performance-based specifications, unified design guidance, and comprehensive life-cycle assessments are developed.

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