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Review Article

A Review of Composites Sleepers Used in the Railway Structure

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Abstract - *Composite railway sleepers made of recycled materials are gaining increased attention and momentum. The railway industry has used composite sleepers due to their increased mechanical strength and vibrational damping properties on the railway track system. The railway sleepers that have been widely used traditionally are timber, concrete, and steel. Timber sleepers have problems with fungal and termite attacks. Concrete sleepers tend to form cracks that lead to premature failure. Steel sleepers have a corrosion problem and cannot be used in modern trains running high speeds beyond 100km/hr. Composites sleepers have been adopted in the locomotive industry due to their durability and acceptable mechanical strength. This review paper discusses the properties of composite sleepers fabricated to accommodate modern trains that travel fast in the automotive industry. There is great potential for using composite sleepers in the locomotive industry because they can be biodegradable, making the disposal process extremely easy and environmentally friendly. Furthermore, composite railway sleepers are cheaper to manufacture and maintain. Further research is still needed to enhance composite sleepers' durability and mechanical properties, especially plastic sleepers, as they tend to succumb to creep, resulting in their deformation over time.*

Keywords - *Composites sleeper, Railway line, Mechanical properties, Concrete Sleepers.*

1. Introduction

Approximately 2 billion railway sleepers are distributed around the world's railway structure, with a steady demand for tens of millions of new sleepers per year [1]. The global railway industry is seeking an alternative railway sleeper material to replace traditional timber sleepers suffering from premature deterioration [2]. Recent developments in composite sleeper technologies have led to railway sleepers made from recycled materials. Using recycled polymeric material in composite materials has produced cheaper sleepers than concrete and steel ones. Plastic sleepers have gained limited popularity due to their susceptibility to ultraviolet (UV) radiation.

The radiation produced by the sun has sufficient energy to destroy and break the bond of molecules in the polymer structure, reducing its lifespan significantly [3],[4]. Composite sleepers have gained increased popularity. The life span of composite sleepers depends on the imposed loads, temperature and chemical elements in the air [5]. Composite sleepers are environmentally friendly and more sustainable than concrete sleepers because they are recyclable and durable [6]. Plastic sleepers recycle and reduce the pressure of emissions, leading to recycling plastic in an environmentally friendly way and reducing the cost of railway sleepers [1].

2. Polycarbonate and Polyethene Plastic Reinforced with Fibreglass Composite Sleeper

Composite sleepers are made of recycled polycarbonate and polyethene plastics with glass fibre reinforcement. Plastic sleepers reinforced with fibres have a greater strength-to-weight ratio than timber. Furthermore, these composite sleepers are more durable and have a longer service life [2].

However, the damping of impact loads, sound absorption, and lateral stability properties of waste plastic sleepers are similar to those of a timber sleeper. Polycarbonate and polyethene plastic reinforced with fibreglass are expected to have significantly more excellent weather resistance than lumber, cheaper primary material usage due to scrap plastic, and superior acoustic dampening capabilities than metal and concrete [4]. Table 1 shows th e mechanical properties of the railway sleepers made of recycled plastic developed in the United States of America [3].

The Rail waste project in Germany has been extruding alternative railway sleepers made from mixed plastic wastes, glass fibre wastes, and auxiliary agents with a thermoplastic polymer matrix since 2008. The sleeper has been shown to have a compressive, flexural and tensile strength of 43.9 MPa, 5 MPa and 4.94 MPa, respectively.

Fig. 1 Polycarbonate and polyethene plastic with fibreglass composite sleeper [3]

Table 1. Polycarbonate and polyethene plastic with fibreglass composite sleeper [5]

Polycarbonate and polyethene plastic with fibreglass composite sleeper Properties	Strength parameters
Compression strength	43.9 MPa
Tensile strength	4.94MPa
Flexural strength	5 MPa

Some challenges associated with using recycled plastic sleepers include low stiffness, low strength, and resistance ability to hold screws as well as voids within the sleeper. Furthermore, these sleepers have insufficient lateral resistance and permanent deformation due to creep and temperature variations [6]. When gaps emerge while manufacturing a plastic sleeper, transferring pressure from one area to another becomes difficult, resulting in stress concentration and localised failure before the sleeper's intended life. Furthermore, the composite sleeper may be prone to permanent deformation due to creep under sustained stresses [7]. The amount and duration of stress and the temperature at which the load is applied determine the creep rate. Creep causes stress relaxation, which causes the fastening system to loosen, especially on curved tracks, causing gauge holding to suffer [8].

2.1. Urethane Foam and Fibreglass Composite

Composite sleepers made of foam urethane resin and fibreglass can be machined and fastened using conventional woodworking tools, as shown in Figure 2. This sleeper has greater compression strength and gives better resistance to the removal of screw spikes compared to a timber sleeper. Furthermore, the sleeper shows stiffness similar to timber sleepers. However, this kind of sleeper gained limited space in the railway industry due to its high cost [9]. In 1978, the Japanese company Sekisui Chemical Co. Ltd. created ESLON Neo Lumber FFU (Fibre Reinforced Foamed Urethane), a synthetic wood made of thermosetting stiff urethane resin foam reinforced with long glass fibres for the construction of railway sleepers. FFU is a composite with mechanical properties that fall between wood and plastic. Unlike typical wooden sleepers, the FFU sleeper does not require using environmentally destructive chemicals for preservation [11]. Table shows the mechanical properties of the urethane foam sleeper reinforced with glass fibre. The primary qualities of the composites are their light weight, good resistance to water absorption, heat and corrosion, ease of drilling, and a design life of more than 50 years. An analysis of the acoustic and dynamic properties of an FFU sleeper revealed that it performs similarly to a timber sleeper [12]. This sleeper has been put in about 925 km of track (roughly 1.5 million sleepers), with its principal applications in turnouts, open steel girder constructions, and tunnels [10]. Sekisui FFU sleepers have been placed in Germany, Austria, and, most recently, Australia, in addition to Japan. Their suitability is currently being researched for a long-span rail bridge in Chongqing, China [13], [14].

2.2. Recycled Plastic Bottles and Fibreglass Sleeper

TieTek LLC, in Houston, Texas, created a composite railway sleeper from recycled plastic bottles and bags, scrapped vehicle tyres, waste fiberglass, and structural mineral fillers, as shown in Figure 3. It was made from 85% recycled materials and was designed to replace traditional timber sleepers; after 17 years, it had been put in over 2 million locations worldwide. The advantages of this sleeper included less noise and vibration, more lateral stability, and a longer lifespan (40 years).

Fig. 2 Urethane foam and glass fibre [10]

Table 2. Properties of urethane foam and glass fibre and strength parameters [10]

Properties of urethane foam and glass fibre	Strength parameters
Density (kg/m^3)	670-820
Modulus of Elasticity (MPa)	8100
Modulus of Rupture (MPa)	142
Rail-Seat Compression (MPa)	58
Screw Pullout Force (kN)	65
Electrical Impedance (wet), (Ω)	140x10^6
Impact bending strength (MPa)	41

Fig. 3 Recycled plastic bottles and fibreglass sleeper [15]

Fig. 4 Industrial plastic waste sleeper [17]

Table 4. Recycled plastic bottles and fibreglass sleeper [16]

Properties of composite sleeper	Strength parameters
Density (kg/m^3)	1153
Modulus of Elasticity (MPa)	greater than 1724
Modulus of Rupture (MPa)	greater than 18.60
Compressive MOE, (MPa)	269.00
Rail-Seat Compression (MPa)	16.50
Screw Pullout Force (kN)	35.60
Thermal Expansion,(cm/cm/^{0}C)	1.35x10^{-4}
Electrical Impedance (wet), (Ω)	500x10^6
Flammability	205.00

The properties of the sleeper are shown in Table 4. The recycled plastic bottle and fibreglass sleeper has numerous advantages over timber sleepers, such as good rail seat abrasion resistance, spike pull and moisture resistance. Furthermore, it also has insect and fungal resistance and low electrical conductivity [16]. TieTek discontinued production in 2010 due to various quality control [15]. These difficulties include the limited strength and stiffness of recycled plastic sleepers, which have been cited as significant roadblocks to their broad use on railway tracks. Most alternative sleeper technologies were created to replace current wood sleepers; however, their strength and rigidity are less than those of wooden sleepers. Hardwood timber sleepers have a modulus of 65 MPa, but recycled plastic sleepers have a modulus of rupture of approximately 20 MPa. Another reason for their limited adoption in the market is the expensive cost of most composite sleepers.

2.3. Industrial Plastic Waste Sleeper

Under the brand name 'EcoTrax,' 'Axion,' a US green technology business, currently produces composite sleepers manufactured from 100% recycled consumer plastic such as plastic coffee cups, bags, milk jugs, laundry detergent bottles and industrial plastic waste [17]. The Polywood Plastic Composite Company invented this production process in 1994, and Axion took over the company's processing function in 2007 [16].

Table 5. Properties of industrial plastic waste sleeper [18]

Properties of composite sleeper	Strength parameters
Density (kg/m^3)	849-897
Modulus of Elasticity (MPa)	1724
Modulus of Rupture (MPa)	20.60
Compressive MOE (MPa)	176.50
Rail-Seat Compression (MPa)	20.60
Screw Pullout Force (kN)	31.60
Thermal Expansion(cm/cm/^{0}C)	0.74X10^{-4}

Industrial waste sleepers shown in Figure 4 have been manufactured for several uses since their inception, including switches, road crossings, bridges, and passenger and heavy load tracks. The axion Eco Trax sleeper's properties are shown in Table . This sleeper has a longer life expectancy (50 years) and is more resistant to plate wear [18]. The sleeper technology is now available in Europe, Australia, New Zealand, Canada and Southeast Asia [19].

2.4. Polypropylene Sleeper

For an underground railway line and narrow gauge railway track in sugar plantations, a South African company produced a composite sleeper built from recycled polypropylene and high- and low-density polyethene components in 2004, as shown in Figure 5. When utilized in underground mines where strong pH variations, high water levels, and humidity pose challenges to traditional sleeper materials, it has been shown to have a longer service life than lumber and concrete sleepers. Tufflex Plastic recently installed sleepers in underground lines at AngloGold Ashanti and Gold Fields mines in Africa, and their in-service performance is currently being studied [20].

2.5. Natural Rubber Composite Sleeper

In 2005, a group of Thai researchers were inspired by using natural rubber in rubber-asphalt mixtures for road surfaces, bridge bearings, plates for vibration absorbers, and blocks for seismic protection of tall buildings to produce railway sleepers, as shown in Figure 6**Fig**.

Fig. 5 Underground sleeper [19]

Fig. 6 Natural rubber composite sleeper

They used an ebonite technique to improve the natural rubber's mechanical qualities by increasing its cross-link density. The researchers modified natural rubber, which had a higher compressive modulus and hardness than the TieTek composites made from scrap rubber/tyres, which they used as a benchmark. According to Ferdous et al. (2014) [21], the cost of a composite sleeper is about 5 to 10 times that of a regular timber sleeper. Due to their insufficient capacity for holding rail fastenings, some composite sleeper technologies struggle to maintain rail track gauges. However, the modified compound of natural rubber composite sleeper was reported to have a very rigid and inelastic performance in holding the spike for the fastening system.

2.6. Recycled Plastic Sleeper

The Dutch company KLP (Kunststof Lankhorst Product) developed 100% polyethylene recycled plastic sleepers reinforced with steel bars under the brand name KLP (Kunststof Lankhorst Product) for the main track, switch, and bridge applications when the use of toxic creosote oil to preserve timber sleepers were banned (transoms).

Fig. 7 Recycle plastic sleeper [17]

Table 6. Mechanical properties of recycled plastic sleeper [22]

Properties of composite sleeper	Strength parameters
Density (kg/m^3)	870
Modulus of Elasticity (MPa)	800
Poisson's ratio	0.4

KLP sleepers have been deployed in more than 20 turnout situations in the Netherlands and Germany since they were initially developed in 2006 [17]. The French recently erected a 1 km of rail track to evaluate the railway's performance, as shown in Figure 7**Fig**. The manufacturer optimized the volume of materials for its primary track product, which uses 35% less plastic than a solid rectangular sleeper in the typical shape. This is a good approach for reducing sleeper manufacturing and transportation costs. Table shows the properties of recycled plastic sleepers. The advantages of this plastic sleeper include an increased life span of approximately 50 years, durability, ease of installation, and environmental friendliness. The properties of the recycled plastic sleeper are shown in Table 6. These plastic railway sleepers help to reduce vibration and noise significantly. Because of the plastic's ductility combined with the steel's strength, the plastic sleepers provide good damping capabilities and optimum stiffness.

2.7.Wood Core Sleeper

Southwest RV and Marine, a Texas-based US firm, produced a plastic composite wood-core sleeper in 2011. Its fundamental design concept consists of a polyethene-based plastic mixture that protects it from insect assault, moisture, and UV degradation and rectangular reinforcement. Inside is a wooden beam that is load bearing, as shown in Figure 8**Fig** [23]. A wood core sleeper is a timber sleeper laminated with plastic materials to avoid termite attack and excessive water absorption. Table shows the mechanical properties of the wood core sleeper. The properties of wood cores are comparable with the properties of plastic and timber sleepers. The rail seat compression is 15.2 MPa, comparable with a recycled plastic sleeper.

Table 7. Properties of wood core sleeper [23]

Properties of composite sleeper	Strength parameters
Density (kg/m^3)	993
Modulus of Elasticity (MPa)	1517
Modulus of Rupture (MPa)	17.20
Compressive MOE, (MPa)	241
Rail-Seat Compression (MPa)	15.20
Thermal Expansion (cm/cm/^{0}C)	0.2X10^{-4}

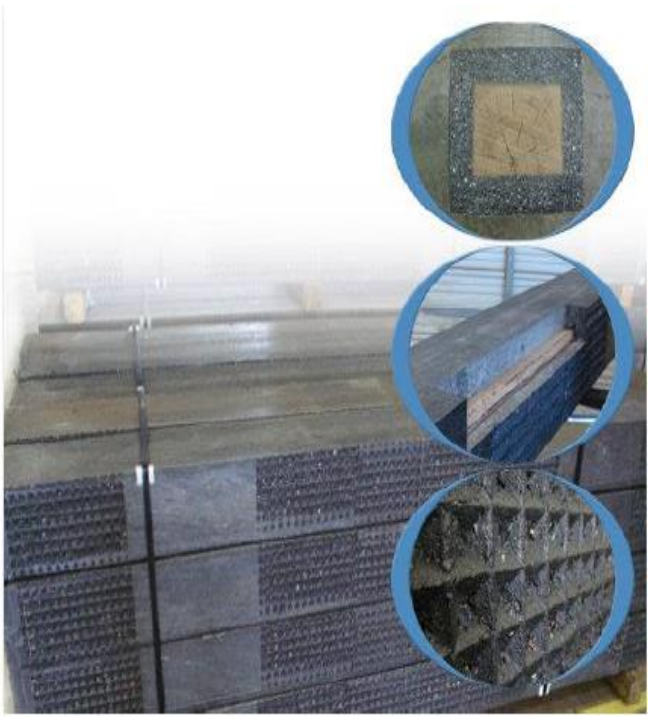

Fig. 8 Wood core sleeper [23]

2.8. Glue Laminated Sandwich Sleeper

The sandwich beam is produced by attaching layers of the fibre-reinforced sandwich in a horizontal and edges (straight). A study by Allan (2011) [24] evaluated the behaviors of glue-laminated sandwich beams as a replacement for standard timber sleepers in turnout applications.

The novel sandwich beam concept shown in Figure 9 outperforms the most current composite railway sleepers in terms of mechanical qualities, as shown in Table 8, and is equivalent to existing timber turnout sleepers.

This sleeper has enough resistance to keep the screw in place, which is one of the most common issues with existing plastic composite products.

Table 8. Properties glue laminated sandwich sleeper [24]

Properties of composite sleeper	Strength parameters
Modulus of Elasticity (MPa)	5190
Modulus of Rupture (MPa)	103
Screw Pullout Force (kN)	63.80

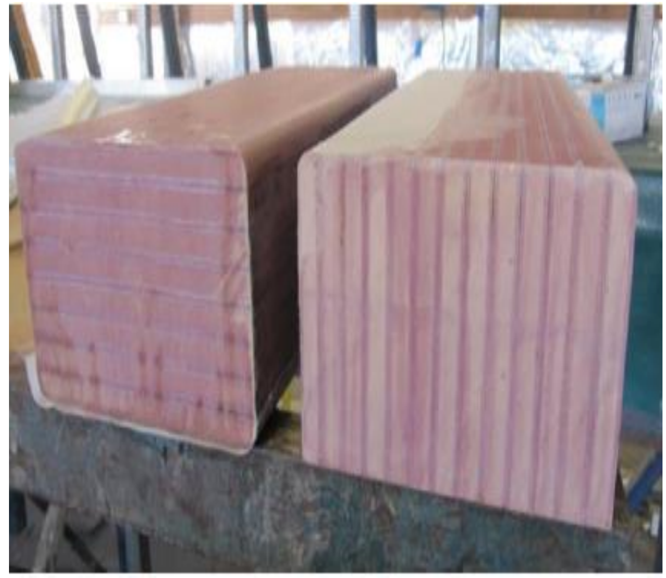

Fig. 9 Glue laminated sandwich sleeper [24]

Fig. 10 Malleable railway sleeper [24]

2.9. Malleable Railway Sleeper

IntegriCo Composites Inc. developed a unique processing technology for producing composite sleepers from landfill-bound 100 percent recycled plastic materials, as shown in Figure 10 and manufactures several types of sleepers based on the application. Class I, Commuter, Industrial, and Mining are the different types of railroad applications. This product has good moisture, insect, plate-cut, and acidic environment resistance and a long-projected life lifetime (50 years). The mechanical properties of the sleeper are shown in Table 9. IntegriCo has installed over 1 million composite sleepers in North America since 2005 and is now expanding into Mexico, Canada, and India. IntegriCo Company has installed over 1 million malleable composite sleepers in North America on railway lines since 2005 and is now expanding nationwide.

Table 9. Properties of Malleable railway sleeper [24]

Properties of composite sleeper	Strength parameters
Density (kg/m^3)	1121
Modulus of Elasticity (MPa)	1655
Modulus of Rupture (MPa)	18.60
Compressive MOE (MPa)	262
Rail-Seat Compression (MPa)	15.90
Screw Pullout Force (kN)	73.40
Thermal Expansion (cm/cm/^{0}C)	1.26X10^{-4}

2.10. Hybrid Concrete Sleeper

Because geo polymer concrete employs an industrial by-product called fly ash, it is currently regarded as an alternative environmentally friendly railway sleeper. Since 2002, Rocla, Australia's premier concrete sleeper manufacturer, has produced geo polymer pre-stressed concrete sleepers for mainline rail tracks [25]. Uehara (2010) [30] developed a geo polymer concrete sleeper in 2010 and put it through a series of tests, with the results stratifying the Japanese standard they employed, JIS E 1202. For an industrial trial, Jiménez produced alkali-activated fly ash mono-block pre-stressed concrete sleepers, and the testing findings met the Spanish and European requirements codes. Uehara [26] looked into the feasibility of a geo polymer concrete-filled pultruded composite sleeper, as shown in Figure 11. The author's findings were promising compared to timber and existing composite sleepers. The durability of an eco-friendly pre-stressed concrete sleeper manufactured from steel slags was recently tested through field inspection in 2014, and it is said to be a viable alternative to traditional pre-stressed concrete sleepers with the added benefit of low environmental impact [27]. Table 10 shows the mechanical properties of the hybrid concrete sleeper. Depending on the prescribed performance targets, different hybrid structural systems have been proposed in the literature [28]. Hybrid railway sleepers are made up of materials chosen for their inherent properties, such as strength, durability, cost, and aesthetics [28].

Table 10. Hybrid concrete sleeper

Properties of composite sleeper	Strength parameters
Tensile strength (MPa)	24
Flexural strength (MPa)	22
Compressive strength(MPa)	171

Fig. 11 Hybrid concrete sleeper [26]

3. Conclusion

The concrete sleeper has higher compression strength than the composite sleeper. However, cracks that spread from rail seats to midspans are a challenge caused by heavy-loaded trains. Composite sleepers are gaining momentum in the locomotive industry due to their elasticity and ability to accommodate the fastest modern trains. The plastic composite sleepers are promoting sustainability and development goals in our environment. However, plastic sleepers soften when exposed to hot conditions and harden when cold, resulting in the deformation of sleeper structures. The demand for composite sleepers is going up, and there is a need to improve reliability, performance, and durability. Furthermore, composite sleepers that will resist termite attack, be resistant to UV radiation, have less moisture absorption, and can absorb shock loads from heavy-loaded trains are still needed.

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References

[1] Samuel Thompson et al., "Life Cycle Cost and Assessment of Alternative Railway Sleeper Materials," *Sustainability*, vol. 14, no. 14, pp. 1-18, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[2] Amanda Jacob, "Indian Composites Industry Set to Take Off," *Reinforced Plastics*, vol. 48, no. 3, pp. 34-39, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[3] A. Manalo et al., "A Review of Alternative Materials for Replacing Existing Timber Sleepers," *Composite Structures*, vol. 92, no. 3, pp. 603-611, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[4] G. Graebe, J. Woidasky, and J.V Fraunhofer, "Railway Sleepers from Mixed Plastic Waste-Railwaste Project Status Information," *Fraunhofer ICT*, 2010. [Google Scholar]

[5] P Indhiradevi et al., "A Comparative Study on Recycled Plastic Railway Sleeper with Concrete Sleeper," *IOP Conference Series: Materials Science and Engineering*, vol. 1145, Coimbatore, India, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Wahid Ferdous et al., "Geopolymer Concrete-Filled Pultruded Composite Beams - Concrete Mix Design and Application," *Cement and Concrete Composites*, vol. 58, pp. 1-13, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[7] Richard Lampo, Thomas Nosker, and Henry Sullivan, "Development, Testing and Applications of Recycled Plastic Composite Cross Ties," *U.S. Army Engineer Research and Development Center*, pp. 1-14, 2003. [Google Scholar]
[8] Thomas Nosker et al., "A Performance-Based Approach to the Development of a Recycled Plastic/Composite Crosstie," *Technical Papers of The Annual Technical Conference-Society of Plastics Engineers Incorporated*, *Society of Plastics Engineers Inc*, Atlanta, GA, USA, vol. 3, pp. 2911-2915, 1998. [Google Scholar] [Publisher Link]
[9] Pizhong Qiao, Julio F. Davalos, and Michael G. Zipfel, "Modeling and Optimal Design of Composite-Reinforced Wood Railroad Crosstie," *Composite Structures*, vol. 41, no. 1, pp. 87-96, 1998. [CrossRef] [Google Scholar] [Publisher Link]
[10] Günther Koller, "The Use of Sleepers Made of FFU Synthetic Wood in Europe," *Railway Technical Review*, vol. 2, pp. 28-32, 2009. [Google Scholar] [Publisher Link]
[11] Wahid Ferdous, and Allan Manalo, "Failures of Mainline Railway Sleepers and Suggest Remedies-Review of Current Practice," *Engineering Failure Analysis*, vol. 44, pp. 17-35, 2014. [CrossRef] [Google Scholar] [Publisher Link]
[12] S. Kaewunruen, "Acoustic and Dynamic Characteristics of a Complex Urban Turnout Using Fibre- Reinforced Foamed Urethane (FFU) Bearers," *Noise and Vibration Mitigation for Rail Transportation Systems: Proceedings of the 11th International Workshop on Railway Noise*, Uddevalla, pp. 377-384, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[13] E. Sarlin et al., "Vibration Damping Properties of Steel/Rubber/Composite Hybrid Structures," *Composite Structures*, vol. 94, no. 11, pp. 3327-3335, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[14] An-Shuang Liu, Delan Yin, and Guoxiang Liu, "A Study on the Application of Resin Composite Sleeper in the Design of Long-Span Rail Bridges," *Sustainable Transportation Systems: Plan, Design, Build, Manage, and Maintain*, pp. 523–531, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[15] William C. Vantuono, "TieTek LLC is Up for Grabs, Bids Are Due," *Railway Age*, 2010. [Google Scholar] [Publisher Link]
[16] Monica L. Louie, "Sustainable Solutions for Railroad Trackwork," *Urban Public Transportation system*," 2013. [CrossRef] [Google Scholar] [Publisher Link]
[17] Wahid Ferdouset al., "Static Behaviour of Glass Fibre Reinforced Novel Composite Sleepers for Mainline Railway Track," *Engineering Structures*, vol. 229, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[18] Eric Yu, *Modeling Strategic Relationships for Process Reengineering*, Social Modeling for Requirements Engineering, vol. 11, pp. 11-152, 2010. [CrossRef] [Google Scholar] [Publisher Link]
[19] Valerii I. Kondrashchenko, Guo Qing Jing, and Chuang Wang, "Wood-Polymer Composite for The Manufacture of Sleepers," *Materials Science Forum*, vol.945, pp. 509-514. [CrossRef] [Google Scholar] [Publisher Link]
[20] Jianfeng Wang et al., "Advances in Toughened Polymer Materials by Structured Rubber Particles," *Progress in Polymer Science*, vol. 98, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[21] Wahid Ferdous, "Composite Railway Sleepers – Recent Developments, Challenges and Future Prospects," *Composite Structures*, vol. 134, pp. 158-168, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[22] M. Siahkouhi et al., "An Experimental and Numerical Study on the Mechanical Behavior of Kunstst of Lankhorst Product (KLP) Sleepers," *Scientia Iranica*, vol. 28, no. 5, pp. 2568-2581, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[23] S. K. Das et al., "Composite railway sleeper," *Invertis Journal of Renewable Energy*, vol. 8, no. 4, pp. 197-201, 2018. [CrossRef] [Google Scholar] [Publisher Link]
[24] Allan Manalo, and Thiru Aravinthan, "Behavior of Full-Scale Railway Turnout Sleepers from Glue-Laminated Fiber Composite Sandwich Structures," *Journal of Composites for Construction*, vol. 16, no. 6, pp. 724-736, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[25] Terry Gourley, and Greg Johnson, *Developments in Geopolymer Precast Concrete*, Proceedings of the World Congress Geopolymer, 2005. [Google Scholar] [Publisher Link]
[26] Motoki Uehara, "New Concrete with Low Environmental Load Using the Geopolymer Method," *Quarterly Report of RTRI*, vol. 51, no. 1, pp. 1-7, 2010. [CrossRef] [Google Scholar] [Publisher Link]
[27] Taehoon Koh, and Seonkeun Hwang, "Field Evaluation and Durability Analysis of an Eco-Friendly Prestressed Concrete Sleeper," *Journal of Materials in Civil Engineering*, vol. 27, no. 7, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[28] Sakdirat Kaewunruen et al., "Enhancement of Dynamic Damping in Eco-Friendly Railway Concrete Sleepers Using Waste-Tyre Crumb Rubber," *Materials*, vol. 11, no. 7, pp. 1-20, 2018. [CrossRef] [Google Scholar] [Publisher Link]