A Review on the Development of New Materials for Construction of Prestressed Concrete Railway Sleepers

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Abstract. Railways form the backbone of all economies, transporting goods, and passengers alike. Sleepers play a pivotal role in track performance and safety in rail transport. This paper discusses in brief about the materials that have been used in making sleepers in the early stages of railways. Extensive studies have been carried out on the static, dynamic and impact analysis of prestressed sleepers all around the globe. It has been shown that majority of the sleepers do not last till their expected design life resulting in massive replacement and repair cost. The primary reasons leading to the failure of sleepers have been summarised. This article also highlights the use of new materials developed recently for the construction of prestressed concrete sleepers to improve the performance and life of railway sleepers. Use of geopolymer concrete and steel fibre reinforced concrete, assist in the reduction of flexural cracking, whereas rubber concrete enhances the impact resistance of concrete by three folds. This paper presents a review of state of the art of new materials for railway sleepers.

1. Introduction
Railways as a mode of transportation have played a pivotal role in the development of all economies providing means for the transport of goods and passengers. Railways play a significant role in ensuring connectivity to different parts of a country at affordable costs to the common man. With the development of technology, there has been dramatic face-lift from where it all started to the present. In India, the railway track system components have undergone gradual evolution from the timber sleepers of pre-independence days to the prestressed concrete sleepers of the modern era being the most noticeable feature of a railway track. There is an ever-growing demand on the part of ordinary man and the industrialists for optimising the efficiency of the rail operation. Enhancing the load carrying capacity and improving the frequency of trips are essential in developing the rail service and making it viable eventually. Hence studies conducted on the failure of railway sleepers are reviewed to identify the significant forms of failures in prestressed concrete sleepers. Researchers all around the globe have focused on materials that could be used to nullify the causes of the failures. This paper concentrates on the review of some of the modern materials that can be employed in the manufacture of railway sleepers. Discussion on the pros and cons of traditional materials used in railway sleepers namely timber, cast-iron, steel, and reinforced concrete presents the picture of the evolution of sleepers.

Railway sleepers perform the role of holding the rail in proper gauge along with supporting the rail in an even manner all over rail length. They also help in maintaining the appropriate level at turnouts and crossovers and are essential in distributing the load transmitted through rails to the ballast underneath. In general, they perform a critical part in maintaining the overall stability of the railroad. Thus, their performance is key to overall efficiency and safety of the rail transport.
2. Traditional materials used for sleepers

The materials employed in the railway sleepers have been evolved over the last century. Many materials have been in use as per the prevailing conditions in different parts of the world. Some of the materials that have been traditionally used for railway sleepers are listed below.

2.1. Timber.

Timber sleepers have been used in railways for a long time and have been reliable and efficient. The most significant advantage obtained in the use of wooden sleepers is that they can be adapted to suit most of the railway tracks. This benefit attained by using timber sleepers is by easiness with which they can be handled when compared to other rigid sleepers. Problems arising at the site can be solved in-house without expert help from outside.

Timber sleepers are easily affected by mechanical wear and tear and natural decay leading to failure. Timber sleepers predominantly fail under fungal attack and decay. Termite attack also damages a significant number of sleepers. As the railway sleepers handle transverse shear loads of high magnitudes, the timbers split at the ends rendering them useless. Use of wood also leads to deforestation and hence the environmental impact is very high. Besides the use of chemically impregnated timber also pose disposal risks. These adverse effects have resulted in the use of other materials.

2.2 Cast-Iron.

Cast iron sleepers have a service life of five to six decades. They can be remoulded and have a significantly high scrap value. Apart from providing a significant bearing area, they are stronger at the seat of rails.

Despite having these advantages, as the case with most cast-iron elements, they get corroded at a faster rate and hence are not recommended for coastal areas. Cast iron sleepers get damaged during derailment and thus have high replacement costs. Along with the requirement of many fastening elements, they cannot also absorb shocks. Adding to these, the high initial costs, the cast iron sleepers are economically unviable.

2.3 Steel Sleeper.

Steel sleepers serve the railways for a couple of decades. Much unlike timber, the steel sleepers are free from decay and are not attacked by vermin. The use of steel sleepers establishes a better and simple connection between rail and sleeper. Apart from providing a superior lateral rigidity, steel sleepers also have a high scrap value. Because of the superior quality when compared to cast iron sleepers, more attention is not required after laying. Their resistance to creep also gives them an extra edge. Due to the factors mentioned above, they are suitable for high speeds and higher loads in comparison with cast iron.

However, steel sleepers also pose their share of disadvantages. Use of steel sleepers in salty regions make them susceptible to corrosion. Their inability to suit all sections of rails and the limitation of being used only with stones as ballast, act as a dampener reducing their use. The steel sleepers are also likely to get severely damaged in the event of a derailment. In such cases their replacement is unavoidable makes them economically unattractive.

2.4 Concrete sleeper.

With an expected service life of about half a century, concrete sleepers are the most durable of all the sleepers mentioned above. By their heavyweight, they can provide exceptional lateral stability to the tracks. Apart from being corrosion resistant when compared to other materials, concrete sleepers show high efficiency in controlling creep. Their ability to resist termite attack and their suitability with almost all kinds of soil make them widely accepted. Though the initial cost of manufacture of these sleepers is high, its recovery in half a century of its service life more than compensates for the high cost.
The rigid nature of the concrete sleepers makes them difficult to handle. Their inability to be as adept to the varying degree of use in comparison with timber sleeper, pose some problems. As compared to wood, concrete sleepers are rigid. Ordinary concrete sleepers have shown their inability to withstand the cyclic nature of loads acting on them during their service life.

2.5 Prestressed Concrete Sleepers.
The railways across the globe have been facing the challenge of improving their efficiency. As part of their struggle to improve the load carrying capacity and frequency of trips for trains, the use of high-speed lines has gained widespread acceptance. The use of these high-speed tracks has warranted the use of prestressed concrete sleepers. The prestressed concrete sleepers, when compared with the sleepers mentioned above live longer and result in cheaper maintenance costs. The prestressed concrete sleepers can withstand static and cyclic loads that act on them.

3. Major failures in prestressed concrete sleepers
Extensive studies done globally on the failure of the prestressed concrete sleepers have been reviewed. The primary causes of failure of prestressed concrete sleepers have been identified from the review of the literature and are explained below.

3.1 Rail Seat Deterioration.
In modern prestressed concrete sleepers, rail seat deterioration is the most repeated type of failure encountered. There are many reasons due to which rail seat deterioration takes place, and among them, seat-abrasion is the most feasible mode of rail seat deterioration [1]. Relative movement between the pads and rail seat face of concrete results in wearing of the concrete from the surface. The loads from the wheels are transferred to the pad which in turn transfer them to the rail. These loads are then taken up by the sleepers. During this process, a shear force acts on the interface between the rail and pad. When this force exceeds the static friction at the interface, slip takes place; concrete takes up the strain that is transferred. When this strain in concrete crosses its fatigue limit, it results in deterioration and eventually after considerable loading cycles, the concrete particles tear off from the rail seat location [2]. Greve et al. found that adding up of damages caused by crushing in the face of high repetitive loads initiate rail seat deterioration [3]. Fig.1 shows a schematic diagram for the rail seat deterioration.

![Figure 1. Schematic diagram for rail seat deterioration](image)

3.2 Centre-bound damage and longitudinal cracks.
Heavy duty railway tracks are the need of the hour owing to the ever-increasing demand for improving the efficiency of the rail operations. Sleepers develop tensile fracture while experiencing the high magnitude and high-frequency loads acting during the train movement. Severe damage to sleepers has been reported by Rezaie et al. owing to longitudinal cracking. The origin of the cracks was traced back
to the rawlplug location with the tensile stress developed due to the pretension forces around the same area being the main reason for its development. These stresses will eventually result in the development of longitudinal cracks because of increase in the tensile stress around the area [4]. Fig.2 shows the development of tensile cracks at the centre of the sleepers.

![Figure 2. Tensile cracks at the centre of sleepers.](image)

3.3 Derailment and Impact loading.
Derailment of trains occurs in the operational stage due to manual error or some defects in tracks that escaped detection. Many lives have been lost in India in the recent past due to the derailment of trains. Apart from the irrecoverable loss of life, derailment leaves the track in an inoperable condition. The massive force encountered by railway sleepers in the event of a derailment usually damages them beyond repair. Due to this irreparable harm, the sleepers need to be replaced, significantly affecting the economy of railway operations.

High magnitude wheel loads are acting for a short time duration act over railway sleepers whenever the trains move over them. These infrequent loads have a dynamic impact effect and can result in cracks [5]. This type of loading is the result of flat wheels and dipped rails. These factors may impart a force of 400kN on one rail seat for a period of fewer than ten milliseconds. In the present international scenario, most guidelines deal with only static and dynamic loads without much regard for the impact loads. Kaewunruen and Remenikov have carried out studies on the impact behaviour of prestressed concrete sleepers. They carried-out field investigation in a coal-mine transport facility to determine the ultimate impact energy that the sleepers can absorb before they failed by splitting [6].

4. Standard tests for railway sleepers in India
In the Indian scenario, T-39-85 issued by RDSO (Research Design and Standard Organisation) [7] govern the quality of materials used in the manufacture of pre-tensioned prestressed concrete sleepers. It specifies a cement content of 350 kg to 480 kg for M 55 grade concrete mix and 350 kg to 500 kg for M 60 grade concrete mix. The minimum release strength specified is 40 MPa. The manufacturers are also obliged to abide by the testing standards specified for the purchase of sleepers. Every sleeper should be able to withstand a maximum test load of 50 tonnes in the increment of loading at 5 tonnes/min starting from 5 tonnes. The maximum load of 50 tonnes has to be maintained for 5 minutes. A vertical dynamic load range of 39.2 kN to 196.2 kN with a frequency range of 5 Hertz need to be withstood without damage to the sleepers to pass the dynamic load test. The sleepers should also absorb an impact load developed by a 500-kg wheel falling at the height of 750 mm over two drops at two locations. Similar guidelines are available in different parts of the world. The acceptance criteria for the sleepers after subjecting them to static, dynamic and fatigue tests in Britain are guided by EN 13230-2:2009 [8].
5. The necessity for New Materials
Railway sleepers employed over the world are facing extraordinary performance challenges. Even the rigid and high quality prestressed concrete sleepers do not stand up to the modern performance demands. Studies all around the world indicate that in many areas prestressed concrete sleepers do not complete their intended service life of five decades. The main factors for sleeper failure are the high magnitude impact and dynamic loads acting on the sleepers. In places where the use of modified timber sleepers persist, their rotting and decay are still a menace. Corrosion and uneasiness of handling have thrown steel and cast-iron sleepers out of favour from the rail operators. These have resulted in a considerable increase in the replacement and maintenance cost of railway tracks. So, the evolution of the sleeper material to meet the modern demands of high performance with low maintenance has become the need of the hour. This requirement necessitates scientific investigations on the potential replacements to existing materials.

6. Potential materials that can be used for sleepers
The primary focus of studies conducted on railway sleepers in recent years has been on the development of new materials that give comparable or better results in comparison with conventional sleepers. Following sections discuss some of the new materials that can be used for the manufacture of sleepers.

6.1 Polymer composite Sleepers.
Composites made of polymers have superior corrosion and chemical resistance, better durability characteristics and high specific strength. They can be considered eco-friendly as they can be recycled, reducing the dumping of plastics in landfills. They also help to reduce deforestation. Studies on glue-laminated sandwich beams indicate that they can be suitable for turnout sleeper due to their strength and stiffness. When these sandwich beams are provided with fibre wraps, there is an increase in shear strength of about 7%. Manalo and Aravinthan reported using their studies that sandwich beams possess properties which are more than comparable with that of fibre composite materials specified by AREMA (The American Railway Engineering and Maintenance-of-Way Association). The Youngs modulus and bending strength of the tested laminated panels were about 4.5 times greater than the standard material, and the shear strength possessed was more than twice the requirement in AREMA[9].

Table 1. Property comparison of FFU with Australian hardwood (Kaewunruen et al. (2013))

| Properties                  | FFU  | Australian hardwood |
|-----------------------------|------|---------------------|
| Life expectancy             | 50 years | 10 years            |
| Bending strength (MPa)      | 142  | 65                  |
| Hardness (MPa)              | 28   | 10                  |
| Shear strength (MPa)        | 10   | 6.1                 |
| Water Absorption (mg/cm²)   | 3.3  | 137                 |
| Impact Strength (MPa)       | 41   | -                   |

Fibre reinforced foam urethane (FFU) made with long glass fibre show better thermal resistance when compared with the conventional polymer. Sleepers made of fibre reinforced foam urethane exhibit high compressive and tensile strength. Recycled plastic materials and fibre composite, have high strength, are more durable. Their weight is comparable to timber sleepers, and they exhibit similar properties to their wooden counterparts about absorption of impact loads and assignment of lateral stability. Insitu track performance of FFU sleepers was carried out by Kaewunruen et al., and they reported that the on-track service of FFU is at par with that of timber sleepers and they exhibit higher life expectancy than the traditional material. The FFU bearers, when compared to regular hardwood, exhibit double the flexural strength. With a comparable compression strength and 1.5 times
higher shear strength, the FFU bearers provide superior hardness to their timber counterparts. Table 1 presents a comparison of strength properties of FFU with Australian hardwood[10].

6.2 Geopolymer sleepers.
Davidovits coined the term geopolymer to name a set of amorphous minerals that act as binders[11]. Geopolymers rely on polycondensation reaction between alumina and silica for strength gain. Strength attainment up to 80 Mpa in 24 hours is an advantage that cannot be discarded in the modern world. In a controlled environment, the exact chemical combination can be mastered with some deliberation to achieve properties that new sleepers demand. Geopolymer requires reaction between a cementitious binder, aggregates, and an alkaline activator solution (AAS) for efficient strength attainment. The molarity of the AAS govern the properties of the mix. Partial or complete replacement of cement with the supplementary cementitious binders like ground granulated blast furnace slag or fly ash has been tried.

Geopolymer has a wide variety of applications in precast industry. The properties of geopolymer concrete mostly depend on the constituents used. However, most of the mechanical properties of geopolymer concrete are at par with the conventional concrete. Shojaei et al. have studied the use of geopolymer concrete in railway sleepers. Ground granulated blast furnace slag was used as the binder, and a mixture of sodium hydroxide and sodium silicate acted as an activator. They reported that 6M solution provided the best results while considering the compressive strength. They concluded that the use of geopolymer concrete satisfies the standards existing in railway codes [12]. Deivabalan and Tamilamuthan conducted static tests on low calcium fly ash based geopolymer railway sleepers and prestressed concrete railway sleepers. An insight into the static and flexural tests that were done on sleepers indicate that geopolymer concrete gave better results than conventional concrete [13]. However, more studies have to be carried out on the impact resistance of the sleepers.

6.3 Fibre reinforced concrete. Fibres of different types have been used in concrete for decades. Among the fibres most sought after one is steel fibre. Researchers have been pursuing various forms of fibre to improve the properties of ordinary concrete. The addition of steel fibres only marginally increases the compressive strength of concrete, but the split tensile strength can be increased to just a shade under 40%. 8% increase in the modulus of elasticity along with the ability of fibres to bridge the gap when cracks start to develop, lead to enhanced strength properties [14].

Sadeghi et al. have carried out studies to gauge the efficacy and practicability of using steel fibres to enhance the characteristics of sleepers such as load-bearing ability and toughness. The results of the study have pointed out that application of hybrid fibres in sleepers enhances the tonnage and improves the energy absorption consequently improving the service life of the sleepers. It was also noted that the dynamic characteristics namely natural frequency, damping ratio and mode shapes of modern sleepers are mostly same when compared to conventional ones [15]. However, there are indications of these sleepers being cost-effective for high speed as compared to regular sleepers tracks owing to the enhancement in mechanical properties.

Parvez et al. studied the improvement in fatigue performance of prestressed concrete sleepers when steel fibres are added to them. They added 0.25% and 0.5% of total volume and reported that fibre sleepers exhibited 15% enhancement in static capacity than those without fibres. The surface strain of concrete showed reduction due to the action of fibres. Steel fibres in concrete improved the crack resistance of concrete. The maximum and average width of cracks were reduced due to the presence of fibres as steel fibred bridged the macrocracks developed. The study points out that a minimum amount of fibres is essential for improved performance and a fibre fraction of 0.5% provides an extended fatigue life for concrete sleepers [16].

6.4 Self-compacting concrete(SCC).
Self-compacting concrete was evolved in Japan due to the necessity of finding a material that could be used in heavily reinforced sections. Ever since then it has found a broad range of applications. Property studies carried out using self-compacting concrete indicate that most of the properties are comparable or better than ordinary concrete. A Skilled workforce is essential for the production and
handling of self-compacting concrete. The use of self-compacting concrete improves the bond between prestressing strands of smaller diameter and concrete. However, once the technique is mastered the use of self-compacting concrete can prove to be useful since the workability of the mix remains good. This form of concrete provides ample finishing, and a significant saving on labour cost can be achieved.

Ranjbar et al. studied the use of palm oil fuel ash as replacement of cement for up to 20% by weight of cementitious materials. They concluded that the acid resistance and sulphate resistance of SCC underwent improvement along with the drying shrinkage property without much change in the compressive strength [17]. Studies conducted by Altoubat et al. indicate that fly-ash and blast furnace slag provide enhanced crack resistance and relaxation pattern of self-compacting concrete [18,19]. Singh et al. also stated that use of slag concrete enhances the durability characteristics of SCC. The essence of these studies points out that SCC can be efficiently utilized in the manufacture of prestressed concrete sleepers [20].

6.5 Rubber Concrete. The addition of rubber in concrete as replacement of aggregates (both fine and coarse) have been on for 40 years. Rubber has been used as partial replacement of fine aggregate or coarse aggregate. Shredded and crumb form of rubber are the usually used forms of rubber. The workability of fresh concrete is considerably affected by the addition of rubber with higher workability for larger size rubber particles coming under the sizes of fine aggregates [21].

The use of rubber in concrete forces a decrease in compressive strength and split tensile strength of concrete. However, pre-treatment of crumb rubber with adhesives led to more bonding of rubber with the concrete matrix and counter the reduction in strength properties [22]. The disposal of tyre rubber waste is an added advantage when we also consider improvement in impact resistance [23]. Over the years, the technique of replacing aggregates with rubber has evolved due to extensive studies in this field. The reduction in compressive strength gets predominant when the size of rubber particles increase. Table 2 and Table 3 provide a comparison of mechanical properties of rubber concrete and depicts the trend in the properties of concrete due to the addition of rubber particles.

Table 2. Mechanical properties of rubber concrete as reported by Topcu [24]

| Topcu (1995)        |       |       |       |       |
|---------------------|-------|-------|-------|-------|
| Volume Replacement of fine aggregates (%) | 0     | 15    | 30    | 45    |
| Unit Weight(Kg/dm³) | 2.30  | 2.22  | 2.14  | 2.01  |
| Cylinder compressive strength(MPa)  | 23.48 | 24.22 | 19.70 | 14.77 |
| Cube compressive strength(MPa)      | 29.50 | 18.80 | 16.90 | 12.90 |
| Split tensile strength              | 3.21  | 2.17  | 1.53  | 1.13  |
| Volume Replacement of coarse aggregates (%) | 0     | 15    | 30    | 45    |
| Cylinder compressive strength(MPa)  | 23.50 | 16.18 | 12.62 | 9.90  |
| Cube compressive strength(MPa)      | 29.50 | 14.60 | 8.91  | 12.20 |
| Split tensile strength              | 3.32  | 1.50  | 1.06  | 0.82  |

Table 3. Mechanical properties of rubber concrete as reported by Khaloo et al.[25]

| Khaloo et al.(2008)       |       |       |       |       |
|---------------------------|-------|-------|-------|-------|
| Volume Replacement of fine aggregates (%) | 0     | 25    | 50    | 75    | 100  |
| Cylinder compressive strength(MPa) | 30.77 | 6.36  | 1.22  | 0.81  | 0.55 |
| Volume Replacement of coarse aggregates (%) | 0     | 25    | 50    | 75    | 100  |
| Cylinder compressive strength(MPa) | 30.77 | 6.52  | 1.49  | 0.65  | 0.37 |

Experimental studies on railway sleepers were carried out by Hameed and Shashikala [26] with the substitution of 15% by the volume fraction of fine aggregate by crumb rubber. The study using
scaled down models points out a reduction in the moduli and compressive strength, and an increase in the fatigue failure load as well as impact resistance. They reported an increase of 60% in impact resistance of crumb rubber sleepers when compared to conventional prestressed concrete sleepers.

7. Conclusions
Advantages and disadvantages of materials historically used in the manufacture of railway sleepers were discussed in this paper. In Indian scenario, most of the sleepers in use are made of prestressed concrete. A review of studies on the failures of prestressed concrete sleepers shows that important modes of the failures are rail seat deterioration, centre-bound damage and longitudinal cracks and derailment and impact loading. This paper also discusses the modern materials that can be used in the manufacture of railway sleeper that can account for the impact loads. Polymer composite sleepers have improved properties when compared to wooden sleepers. Properties of FFU sleepers are found to be superior to the standard hardwood bearers. Studies on the static and dynamic behaviour of geopolymer sleepers are found to be comparable to conventional prestressed concrete sleepers. However extensive studies are essential to estimate the behaviour of geopolymer sleeper material before they are put in service. Fibre reinforced sleepers provide better performance than conventional sleepers. Use of self-compacting concrete can improve the bond between concrete and steel and provides an excellent finish without much labour. Rubber concrete sleepers perform three times as better as normal prestressed concrete sleepers when their impact performance are compared. Use of these modern materials individually or in combination with one another can provide us with an alternative product with improved efficiency.

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