Failures of mainline railway sleepers and suggested remedies - review of current practice

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Review

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A B S T R A C T

Over the last two decades, the premature failures of traditional railway sleepers have significantly increased the track maintenance costs. The primary obstacle to minimising this problem is the lack of understanding of the mechanism of sleeper degradation. This paper discusses the different deterioration mechanisms for traditional timber, concrete and steel sleepers and the potential protective measures to minimise these problems. This paper exhaustively reviews the failure mechanisms of these three commonly used sleeper materials with suggested solutions. Fungal decay, end splitting and termite attacks has been identified as the principal causes of timber sleeper failures. On the other hand, concrete sleepers are vulnerable to rail-seat deterioration, cracking and damaging under different loading conditions and adverse environments. Steel's risk of corrosion and fatigue cracking makes it an inferior-quality material for sleeper. Solution approaches are recommended and provided in this paper in order to the best utilise these different railway sleeper materials. New materials are also introduced as effective alternative to replace the traditional railway sleepers.

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1. Introduction and motivation

The Australian railway transport industry may realise a potential savings of $A80 million per annum in its operating cost if further improvements could be made in its railway operation and maintenance [1]. The premature deterioration of railway sleepers has become of great concern over the last two decades even the sleeper perfectly supported by the underlying ballast. For many years, timber, concrete and steel, which have targeted life spans of 20, 50 and 50 years, respectively have been used as sleeper materials. However, under certain circumstances and in particular environments, these traditional sleepers have not satisfactorily met the performance requirements due to their unexpected early failures. It has been reported that over 12 million timber sleepers are replaced every year in the USA due to in-service damage resulting in splitting and excessive wearing at a cost of around 500 million dollars [2] while another report indicates that the cost of sleeper renewal is about 12% of the total maintenance-of-way cost, that is, approximately twice that of the rail renewal [3], which has forced researchers and railway industry to think of effective ways of minimising this problem.

The demand for sleepers has been increasing over time, as the railways plays a significant role in the transport systems. In 2006, the International Federation for Structural Concrete [4] conducted a worldwide survey of annual demands for traditional sleepers in rail networks and is presented in Table 1.

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This survey illustrates that concrete is the dominant material for sleepers in many countries except in the USA where there is a major demand for timber sleepers. It is estimated that, there are currently approximately three billion sleepers in the world’s railway networks. Over 400 million of these sleepers are made from concrete and 2–5% of them requires replacement every year due to their premature failure [5]. Similarly, Australia has one of the largest rail networks in the world where approximately 13% are made from steel [6]. A sleeper’s ability to resist cracking, oxidation, chemical degradation, delamination and wear damage for a specified period of time, under appropriate load conditions and specified environmental conditions, has become of great concern. Research and innovation are now focusing on the durability of sleepers as the lack of understanding of sleeper degradation mechanisms is a great concern [7]. This paper aims to present these failure mechanisms and provide suggestions for minimising them to provide useful information to engineers, designers as well as asset owners.

2. Failure of timber sleeper

Proper investigation of the causes of premature failures of sleepers to minimise the cost of track maintenance and to improve the track efficiency, is necessary. The Railway of Australia (ROA) [8] surveyed several states in Australia in order to understand the causes and modes of failure of timber sleepers. For this purpose, it examined 2200 timber sleepers in Queensland railway tracks and found different reasons for the sleeper damage including fungal decay, end splitting, termites, still sound, sapwood, shelling, rail cut, weathering, spike kill and knots (Fig. 1). Of those failure types, fungal decay (53%), end splitting (10%) and termite attacks (7%) were found to be the principal causes of timber sleeper failure.

2.1. Fungal decay

Fungal decay is the predominant mode of timber sleeper failure as timber is susceptible to bio-deterioration from many micro-organisms because timber is an organic material. A fungus can lie dormant in timber until it obtains at suitable environment containing moisture, oxygen and nutrients. Railway sleepers can absorb moisture, especially in rainy seasons, that makes fungi reactive and when they are in timber, can spread from one sleeper to another across non-nutritional surfaces that adversely affect a track’s structural integrity [9,10]. Fig. 2 presents the fungal decay of a timber sleeper in a railroad track.
2.2. End splitting

The failure of a timber sleeper due to splitting at its end is another common failure mode which arises when the sleeper is subjected to large transverse shear loading [6,11]. Also the rail is connected to each sleeper by a proper fastening system which includes a rail fastening clip, sleeper plate and screw-spike. During insertion of the screw-spike, a sleeper may split over time (Fig. 3).

2.3. Termite attacks

Termite attacks in timber sleepers have been identified as another significant cause of sleeper damage and it has been reported that the worldwide cost of repairing structures and preventing these attacks is approximately one billion dollars annually [12]. When a termite attacks timber, it consumes all the cellulose-containing materials and causes permanent damage [13]. Invasions of termites have been found in a cracked sleeper’s pocket even after it was treated with creosote (Fig. 4).

3. Failure of concrete sleeper

The many advantages of concrete technology led to its use for sleepers in the 1950s. Nowadays, approximately 500 million railway sleepers in the world’s railway networks are made from prestressed concrete and, every year, the demand for them constitutes more than 50% of total demand [4,5]. In Australia, the majority of modern railway sleepers are made from mono-block prestressed concrete which was first used in 1970 [15]. Over the last three decades, researchers in different parts of the world have been investigating the failures of concrete sleepers and looking for sustainable solutions. Dyk et al. [16] ranked the most common causes of concrete sleeper failures using the results obtained from their North American and worldwide surveys (Fig. 5). They indicated that the most critical cause of failure in concrete sleeper is rail-seat decay.
deterioration in the North America and the installation or tamping damage globally. However, these failure modes can vary from country to country as geometry and operation practices are different.

3.1. Rail-seat deterioration

The most common mode of failure for modern prestressed concrete sleepers in different parts of the world, particularly in western Canada and the northern United States, is the rail-seat deterioration. This failure is caused either by rail-seat
abrasion, hydro abrasive erosion, hydraulic pressure cracking, freeze thaw cracking or chemical deterioration [17] of which rail-seat abrasion is the most critical. Rail-seat abrasion occurs due to the relative movements between the rail pad and concrete rail seat which subsequently resulting in the gradual wearing away of the cement paste from the concrete by frictional forces as the abrasive fine particles and the water penetrates the rail-seat pad interface creating an ideal situation for abrasion. Zeman et al. [18] and Kernes et al. [19] have investigated the mechanism of rail-seat abrasion and found that, when the wheels transfer loads from the pad to sleepers through the rail, a shear force acts on the rail-pad interface. Once the shear force exceeds the static frictional force between the bottom of the pad and rail seat, slip occurs and the strain is transferred to the concrete. After a certain period when this strain overcomes the fatigue limit of concrete, deterioration starts and after many loading cycles, a significant amount of particles are torn from the rail-seat position which results in an uneven concrete surface underneath the sleeper pad. Several factors are responsible for the rail-seat abrasion, including the presence of water, heavy axle loads, the failure of fasteners, shoulders or sleeper pads, steep track gradients, and particularly track curves greater than two degrees [20,21]. Fig. 6 shows an abraded rail-seat area in a concrete sleeper. In 2010, the deterioration due to hydraulic-pressure cracking was investigated by Zeman et al. [22] and their results showed that a certain combination of dynamic rail-seat loads, sufficient moisture and sleeper-pad surface generates the high pressure responsible for rail-seat deterioration.

3.2. Centre-bound damage

The tensile fracture of a prestressed concrete sleeper may occur in a heavy-duty railway track. González-Nicieza et al. [24] investigated the failure analysis of a railway track used to transport heavy industrial freight with the aim of offering guidance to forensic engineers regarding the failure of railway track foundations. They observed vertical cracks on a damaged sleeper due to a tensile fracture in its upper central segment (Fig. 7a) which later propagated throughout its central segment and formed an ‘X’ shape before clearly fracturing (Fig. 7b).

A recent study by Rezaie et al. [25] found severe damage in a sleeper caused by longitudinal cracking which was observed even before the sleeper was mounted in a railway track (Fig. 8a). It originated from the rawlplug location due to the pre-tension forces which induce remarkable tensile stress around the rawlplug hole in the transverse direction. During its service

![Fig. 6. Failure of concrete sleeper due to rail-seat abrasion [23].](image)

![Fig. 7. Concrete sleeper damage due to tensile fracture [24].](image)

(a)  (b)
life, additional effects such as water freezing and the existence of fine rocks within its rawlplugs can lead to increases in the transverse tensile stress in a sleeper and cause longitudinal cracks to appear (Fig. 8b). Their simulation results also showed that the maximum tensile stress between the two rawlplugs in a fastening system is responsible for the longitudinal cracking. Similar conclusions were drawn by Ma et al. [26] who found that the high shearing tensile stress on the edge of the bolt hole is the main cause of longitudinal cracks in a sleeper.

3.3. Derailment

Defects in sleepers, which occur mainly during the operational stage because of manpower faults and existing imperceptible defects in tracks, are considered the ultimate failure as they can cause derailments and render the relevant track inoperable. In 2012, Zakeri and Rezvani [27] observed derailment failures in concrete B70 sleepers in Iranian railways (Fig. 9). The sleepers that are damaged due to derailment need to be replaced which increases the track maintenance costs. The primary causes of derailment failures they identified are due to manpower fault and existing impermissible defects in track.

3.4. High-impact loading

The bending cracks in a concrete sleeper are often detected at its mid-span and eventually reduce the sleeper’s flexural stiffness. Many railway organisations have observed cracks in concrete sleepers during field inspections, with the primary cause identified as an infrequent but high-magnitude wheel load of short duration, as reported by Murray et al. in 1998 [28, 29]. They indicated that this is normally produced by either wheel or rail abnormalities, such as flat wheels and dipped rails, for example, an approximately 400 kN force per rail seat could be generated in 1–10 ms due to ‘wheel flats’. Existing design guidelines for a prestressed concrete sleeper are based on only static and quasi-static loading conditions and do not take into account high-magnitude impact loads [30]. A field investigation into passenger lines as well as coal/mine transport in the Wollongong railway’s suburban network confirmed that a crack in a sleeper occurred because of the effect of impact

Fig. 8. Longitudinal cracking due to tensile stress between rawlplugs [25].

Fig. 9. Derailment failure of concrete sleepers [27].
loading (Fig. 10). Recently, a collapsed sleeper was found in another rail track designed for a 30-ton axle load train providing services to the outer city and interstate passenger trains, freight bogies and heavy-haul coal wagons [33]. It was damaged in the rail-seat area and during the failure investigation, a dipped rail joint was found just in front of the sleeper’s location. The local track maintenance engineers estimated that there was a 15–25 mm gap in the rail joint at the time of failure which could produce a high-impact load on the sleeper. Fig. 11a illustrates the collapsed railway sleeper and Fig. 11b the joint conditions after the track was repaired. The experimental investigation performed by Kaewunruen and Remennikov [34] determined the ultimate impact capacity of a prestressed concrete sleeper under impact loading which failed due to splitting (Fig. 12a). A similar failure pattern was found during a field investigation which demonstrated the domination of impact loading on sleeper failure (Fig. 12b).

(a) cracks at centre of sleeper  
(b) cracks near location of sleepers’ rail seats

Fig. 10. Cracks in concrete sleepers due to impact loading [31,32].

(a) collapsed sleeper  
(b) sleeper after track maintenance

Fig. 11. Impact damage to sleeper due to rail irregularities [33].

(a) experimental failure mode  
(b) field investigation

Fig. 12. Splitting failure of concrete sleeper caused by impact loading [34].
3.5. Delayed ettringite formation (DEF)

Soil, groundwater and sometimes aggregates may contain sulfates of sodium, potassium, magnesium and calcium which, when present in a solution, react with the tricalcium aluminate or calcium hydroxide components of the cement paste. Such reactions cause expansion which leads to cracking and, finally, deterioration of the concrete [35,36] as depicted in Fig. 13.

DEF caused by an internal sulphate attack can deteriorate concrete sleepers. The earliest observation of it was reported by Tepponen and Eriksson [38] who noted the damage that occurred in concrete sleeper in Finland within 10 years after its manufacture due to the formation of microcracks resulting from the heat treatment applied (75–80 °C for 2.5–4 h) during the pre-casting process. Also, Heinz and Ludwig [39] reported that the deterioration due to DEF does not occur at steam-curing temperatures below 75 °C even if the process takes 16 h. Hime's [40] investigation confirmed that the cracking of pre-stressed concrete sleepers due to DEF may come after they have been in service for several years (Fig. 14). According to him, in non-air-entrained concrete, the occurrence of DEF depends on the heat-curing temperature (above 60 °C) and the clinkers’ sulphate levels. Similarly, Sahu and Thaulow [41] in 2004, found that premature deterioration occurred in a Swedish concrete sleeper within 7 years of its manufacture due to DEF leading to concrete cracks. However, in their research, they mentioned that DEF is dependent not only on the heat of the concrete’s curing temperature but also on the composition (alkalis, C₂S, C₃A, SO₃ and MgO) and fineness of the cement, and may occur at temperatures lower than 60 °C if there are unfavourable combinations of these parameters.

3.6. Alkali–aggregate reaction (AAR)

The difference between sulphate and alkali attacks is that the reactive substance in the former is cement while, in the latter, it is aggregates [37]. Although the main source of alkalis in concrete is portland cement, sometimes, an additional one is unwashed sand containing sodium chloride while admixtures (super-plasticisers) and mixing water are also

![Fig. 13. Effect of sulphate attack [37].](image1)

![Fig. 14. Cracking of prestressed concrete sleeper due to DEF [40].](image2)
considered internal sources [36]. Silica-containing aggregates (e.g., chert, quartzite, opal, strained quartz crystals) could be affected by hydroxyl ions in alkaline cement solutions which may lead to destructive expansion (Fig. 15) as follows:

- Reactive silica + Alkali → Alkali–silica gel
- SiO₂ + Ca(OH)₂ + H₂O → CaH₂SiO₄·2H₂O (Alkali–silica gel)
- Alkali–silica gel + water = expansion, which is responsible for cracking

Shayan and Quick [42] investigated the causes of parallel longitudinal cracking on the top surfaces and map cracking at the ends of prestressed concrete sleepers by examining both cracked and uncracked sleepers which showed that the alkali–aggregate reaction is responsible for sleeper failures. This was also identified by another investigation in China [43] which studied an affected concrete sleeper in the Shanghai region and through its Scanning Electron Microscope/Energy Dispersive X-ray (SEM/EDAX) analysis they found the presence of potentially reactive silica in the concrete sleeper that promoted cracking. Fig. 16 presents the failure of a sleeper due to AAR.

3.7. Acid attack in concrete

Concrete containing portland cement is not resistant to attack by strong acids [36,45,46] and the most vulnerable cement hydrate is Ca(OH)₂ which converts to calcium salts when it comes into contact with an acid [35,37]. Also, calcium silicate

Fig. 15. Effect of AAR [37].

Fig. 16. Cracking in concrete sleeper due to AAR [44].
hydrate (C–S–H) and calcium aluminate hydrate can be attacked by acids [36,37] and due to this reaction, the structure of the hardened cement is destroyed (Fig. 17).

Industries and vehicles emit huge amounts of sulphur dioxide and nitrogen oxide into the atmosphere which are the primary causes of acid rain. This falls not only in areas of high industrial activity and transportation loads but also a long way away as a result of wind action and may harm concrete railway sleepers.

3.8. Bar corrosion

The deterioration of a concrete sleeper as a result of an adverse environment was studied by Mohammadzadeh and Vahabi [47] who focused on the impact of the penetration of chloride ion on the reliability index of a B70 prestressed concrete sleeper. Although most studies of sleeper failure have concentrated on damage at the rail-seat location, their research concluded that the mid-span of the sleeper is more vulnerable than its rail seat and the failure is more likely to happen at this position.

Fig. 17. Effect of acid attack [37].

Fig. 18. Failure of concrete sleeper as result of bar corrosion [47].
point. A large amount of fine-graded soil was found in the area of the sleeper examined and the relative humidity was measured as 30% which is a suitable environment for soils to be spread over sleepers by the wind. Over time, moisture and rain can provide favourable conditions for bar corrosion in concrete, and their observations indicate that the presence of chloride ions which ingress into the concrete and break down the protective iron oxide film is the main factor for the failure of a sleeper from bar corrosion (Fig. 18).

3.9. Ice forming in sleeper

Failures of concrete sleepers in a slab track system were studied by Zi et al. [48] who found that 0.22% of sleepers (approximately 1 sleeper in every 300 m of rail track), were damaged in the Kyengbu railway in Korea which was designed for high-speed train transport. According to their field observations, a crack was initiated from the bottom of a sleeper near the fastening bolt and formed a conical shape (Fig. 19). From the results of their experimental and numerical investigations, they concluded that failures occur due to freezing of the water leaking into sleepers which creates an ice pressure of 40 MPa that corresponds to 72–88 kN depending on the area of applied pressure.

4. Failures of steel sleepers

A very few studies of steel sleeper failure have been conducted. However, several researchers reported that the steel's risk of corrosion, high electrical conductivity, fatigue cracking in the rail-seat region and the difficulty of packing it with ballast has made it an inferior material for sleepers. Thus, a proper investigation into the reasons for its failure is essential.

4.1. Corrosion in steel

Steel sleepers suffer from corrosion in the areas where the supporting soil or ballast is rich in salty elements. The risk of corrosion is much higher than rail although both are made from steel as a sleeper establishes intimate contact with the

Fig. 19. Conical crack due to ice forming in slab track [48].

Fig. 20. Corrosion in steel sleeper [50].
ballast and subgrade materials. Sleepers may come into contact with different salts from soil, groundwater or aggregates which can react with steel, leading to sleeper failure due to corrosion (Fig. 20). Also, other reasons, including metallic slag-based ballast, a continually moist environment and the existence of corrosive materials, can enhance corrosion in a steel sleeper [49].

4.2. Fatigue cracking

Fatigue failure occurs in a railway sleeper because of the repeated stress imposed by cyclic loading and the rail-seat location is subjected to heavy shear that is vulnerable to fatigue cracking. When a train is running over rails, as a sleeper experiences both longitudinal and transverse stresses, a diagonal stress originates its rail-seat location which is usually on its top surface but can also occur in the reverse direction depending on the train’s movement and, over time results in fatigue cracking [51].

5. Approaches to minimise sleeper failure

Several studies aimed at minimising the problems of railway sleepers have been conducted and some of them already implemented. Some researchers have focused on taking special care of traditional sleepers while others have introduced relatively new materials. In this section the most appropriate method and best practice in reducing sleeper failure in service and in the maintenance work are discussed to provide guidelines for scientific researchers and practicing engineers.

5.1. Timber sleeper

The traditional timber sleepers could be saved from premature deterioration if some special treatments were performed. Thus, several researchers have suggested methods to prevent timber sleeper failure which are presented in the next sections.

5.1.1. Fungal decay and termite attacks

Timber protection methods for controlling fungus and termite attacks in timber structures are quite similar [52] and, over time, several have been studied with impregnation with synthetic chemicals and biological protection techniques the most common. Usually, toxic chemicals which can destroy harmful organisms in timber were used for more than two hundred years because of their relatively low cost. However, environmental agencies have now become concerned about the application of chemical preservatives in timber sleepers and their proper disposal when the sleepers are removed [53]. Recently, Verma et al. [52] and Susi et al. [54] have been emphasising the use of biological wood protection methods in order to address public concerns and conform with new environmental regulations regarding the use of chemicals. These methods involve placing micro-organisms in materials which prevent attacks by species but do not affect the materials’ properties. Experimental investigation by Susi et al. [54] found that, biological control of timber degradation can be as effective as chemical protection and has the additional benefit of environmental safety. Fig. 21 is a diagrammatic representation of termite control measures in timber structures.

5.1.2. Controlling end splitting

Splitting at the end of a timber sleeper separates one part of the timber from the other, and plates can be fixed at its ends to minimise separation [10,55]. However this technique only works when the splitting width and length is small, usually no more than 20 mm and 250 mm, respectively. For unseasoned and seasoned sleepers, the accepted limits for the splitting width are 3 mm and 6 mm and, for length 100 mm and the width of the sleeper respectively. Therefore, sleepers which are beyond their acceptance limits but not more than 20 mm in width and 250 mm in length could be saved by providing end-plates. Fig. 22 illustrates salvageable (Fig. 22a) and non-salvageable (Fig. 22b) situations of a timber sleeper.

![Fig. 21. Termite control measures in timber structures [52].](image)
5.2. Concrete sleeper

Rail-seat deterioration and concrete cracking were considered as the most critical failure modes for concrete sleeper and several methods to minimise and prevent these types of failure are discussed in the following sections.

5.2.1. Preventing rail-seat abrasion

Many studies have focused on minimising or preventing rail-seat deterioration which is identified as the most critical problem for concrete railway sleepers in the North America. In 2003, Peters and Mattson [56] attempted to minimise abrasion using cast-in-place steel plates that covered the rail-seat area. The completion of their experimental program of fatigue testing, which ran for 10 million cycles at a rate of 2.5 cycles per second showed no rail-seat abrasion occurred (Fig. 23). However, this additional steel plate could significantly increase the manufacturing costs of sleepers and the water intrusion below it may deteriorate the concrete in the rail-seat area. This issue should be carefully considered when adopting this approach.

Another approach for preventing abrasion was studied by Peters [57] in which the researcher applied an epoxy coating over the rail-seat region. However, it is not a very convincing option as it is labour intensive, requires track closures during the application and curing of the epoxy, and there is a possibility that the epoxy will wear away over time. Alternative preventive measures considered by researchers include: the addition of fly ash and silica fume to the concrete in the rail-seat [58]; the introduction of steel fibre-reinforced grout in the rail-seat region during manufacturing [56,59]; the application of multi-layer abrasion-resistant pad assembly [56]; and placing metallic aggregates in the rail-seat area [60]. In 2002, Atis [61] showed that concrete with a high-volume of fly ash has better abrasion-resistant properties and suggested using it in areas where highly abrasion-resistant concrete is required. The concept of improving concrete materials in the rail-seat area aims to restrict the cracking and concrete’s permeability that allows water to intrude through a cracked channel into the void structure of the cement paste underneath the sleeper pad. However, although upgrading the concrete materials in the rail-seat region can increase the compressive and tensile strengths of the concrete, its effectiveness against abrasion is unwarranted and better alternative solutions should also be considered [20,58].
5.2.2. Controlling longitudinal crack

The high shearing tensile stress around the rawlplug/bolt hole is identified as the main cause of longitudinal cracking and, to minimise it, Ma et al. [26] suggested redistributing it by the use of a special expansive concrete in the inner and ordinary concrete in the outer parts of the bolt-hole area which will produce a radial nested stress on the interface between the two parts through expansion of the inner part and, finally, achieve a significant reduction of the shearing tensile stress. Another method for controlling longitudinal cracks suggested by Rezaie et al. [25] is to place transverse reinforcing bars in a sleeper, especially around the rawlplug hole to strengthen the sleeper transversely and sustain more inducing pressure which can change the directions of the cracks and cracking planes.

5.3. Steel sleeper

A very limited study has been conducted so far to minimise the problems of steel sleeper. Some studies provide suggestions for controlling steel corrosion, among them the Australian Rail Track Corporation (ARTC) has suggested avoiding the use of steel sleepers in locations where the ballast is made from slag, there is high salinity, such as coastal regions, continually moist areas and areas with corrosive materials, such as coal, minerals, mud, clay and dirt [49]. Hernandez et al. [50] found that the presence of salt has the very detrimental effect on steel of accelerating corrosion which supports the ARTC recommendation to avoid placing steel sleepers in areas of high salinity. In its report, the ARTC also suggested that placing zinc (Zn) coating over steel is a useful method to create a protective layer that prevents corrosion. The Transit Cooperative Research Program (TCRP) stated that the use of metallic slags as ballast can enhance corrosion in steel and is not recommended for use in railroad tracks with steel sleepers [62].

6. New materials for railway sleepers

The many advantages of geopolymer concrete and composite materials have recently motivated researchers and railway industry to consider using them in sleeper construction, as highlighted in this section.

6.1. Geopolymer concrete sleeper

Many studies have shown that ordinary cement concrete sleepers can deteriorate because of alkali–silica reactions [42,43,63]. It has been claimed that fly ash-based geopolymer concrete is beneficial for reducing this reaction due to the chemical reaction between alkalis and the amorphous component in the fly ash which produces cementitious binders that increase the density of the concrete, decrease its permeability and reduce the mobility of its aggressive agent. Therefore, there is a lower possibility of an alkali–silica reaction because there are insufficient alkalis available to react with the reactive silica [64]. Kupwade-Patil and Allouche [65] reported that fly ash-based geopolymer concrete is significantly less vulnerable to an alkali–silica reaction than cement-based concrete, and García-Lodeiro et al. [66] drew similar conclusions, observing that the expansive character of the gel depends largely on the calcium oxide (CaO) content. Alkali-activated fly ash cement has a very high alkaline (Na) content but is low in calcium (Ca) while fly ash itself contains alkalis but, as only one-sixth of them are potentially reactive [36], if an alkali–silica reaction takes place, it will have a much less expansive character than that normally produced in cement.

Some recent investigations [40–42,67] have indicated the failure of concrete sleepers due to DEF which is a special case of sulphate attack. In cement concrete, sulphate ions may react with calcium hydroxide to form gypsum or with calcium aluminate hydrate to form calcium sulfoaluminate or ettringite both of which result in expansion, cracking and spalling in the concrete [36]. Fly ash-based geopolymer concrete has an excellent resistance to sulphate attack as it has no significant calcium aluminate hydrate reactant [68].

The resistances of geopolymer and ordinary cement concrete in acidic media were well studied by Bakharev [69] in 2005, with the results confirming that the former exhibits superior performance in terms of resisting acid attack. Although experiments by Song et al. [70] proved that, after a sulphuric acid attack, a geopolymer concrete matrix remains identical to that of an unaffected matrix. Wallah et al. [68] concluded that geopolymer concrete may be affected by acid depending on the concentration of the acidic solution. These superior performances of fly ash-based geopolymer concrete over traditional cement-based concrete have motivated concrete researchers to apply them in railway sleepers.

Rocla, the Australia’s leading concrete sleeper supplier, has adopted the conventional prestressing process to develop geopolymer prestressed concrete sleepers for the mainline railway tracks since 2002. They have proven through inspections that presented geopolymer concrete sleeper perform well without presenting any problems (Fig. 24). [46,71].

In 2007, Palomo et al. [5] investigated the use of alkali-activated fly ash concrete in railway sleepers and suggested that it could be a suitable material for them, although their study did not provide adequate information regarding performance. In 2010, Uehara [72] proposed an environmentally friendly geopolymer prestressed concrete sleeper, manufactured using fly ash as the binder in the concrete (Fig. 25), which satisfied the static performance requirements of the standard they used, JIS E 1202. Palomo and Fernández-Jiménez [73] manufactured alkali-activated fly ash mono-block prestressed concrete sleepers for an industrial trial in 2011 and their experimental results met the requirements of both the Spanish and European codes.
Ferdous et al. [74] investigated a geopolymer concrete-filled pultruded composite beam as a replacement for a timber sleeper (Fig. 26). Their study found that the composite beam satisfies the minimum flexural requirements for composite railway sleepers as stated in the AREMA standards and shows satisfactory performance when compared with those of existing railway sleepers.

6.2. Composites as materials for sleeper

TieTek developed new composite sleepers using recycled plastic, old tyres, waste fibreglass and structural mineral fillers which it claimed have beneficial properties over timber sleepers because they resist rail-seat abrasion and spike pull, and are

![Fig. 24. Geopolymer concrete sleeper in mainline tracks [71].](image)

![Fig. 25. Ordinary and geopolymer prestressed concrete sleepers [72].](image)

![Fig. 26. Geopolymer concrete-filled pultruded composite sleeper [74].](image)
not damaged by moisture, insects or fungi [75,76]. However, they cost about twice as much as concrete sleepers [77]. Fibre-reinforced Foamed Urethane (FFU) synthetic sleepers made from hard polyurethane foam and glass fibres, with physical properties similar to those of timber sleepers and designed for more than 60 years of service, have been used in Japan while RailCorp is the first company in Australia to have used them as trial turnout sleepers (Fig. 27). According to the manufacturer, FFU does not need to be impregnated with environmentally harmful chemical which is essential for timber sleeper to protect them from biological degradation [78]. Moreover, they claim their sleeper is durable enough to provide resistance against the damaging effect of acids, alkalines and saltwater [79]. The use of these sleepers is increasing in situations in which maintenance and replacement are difficult [15].

In 2002, recycled plastic composite sleepers manufactured from recycled plastic bottles combined with glass fibre reinforcement were introduced in the USA as replacements for timber sleepers. Although the manufacturer claims that they are able to solve many drawbacks of timber sleepers, their performances in real tracks are only now being investigated [76]. Chow [80] conducted a series of tests on the static bending properties, compressive modulus of elasticity, surface hardness and three spike-resistant properties of IntegriCo composite sleepers made from composite plastics and oak with their test results satisfying the minimum requirements of the AREMA standard. This sleeper claims longer service life, immune to insect infestation, good resistance against fungus attack, and greater prevention of rail plate cutting which reflects their superior performance over timber sleeper [81]. Another research study, in which the team investigated an alternative sleeper material made from glass fibre composite skins and modified phenolic foam, was conducted at the University of Southern Queensland [82,83]. Their experimental investigation on composite sandwich beam in edgewise position showed higher shear capacity which can prevent the undesired failure due to end splitting. As the composite material has good resistance against corrosion, these proposed sleepers have the ability to overcome corrosion problems. In fact, the Queensland Rail has

<table>
<thead>
<tr>
<th>Sleeper</th>
<th>Failure mode</th>
<th>Causes of failure</th>
<th>Country</th>
<th>Study</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>Decay</td>
<td>Fungus attack</td>
<td>Australia</td>
<td>1991</td>
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Table 2
Summary form of sleeper failures and causes throughout world.
installed the first 50 sleepers made from laminated sandwich beams in the maintenance of their existing railway lines to determine the in-service performance of this new sleeper material. However, the composite sleeper discussed here is addresses some solutions of the specific problems of traditional sleeper and more investigation is required to check the other application issues particularly, their performance against impact and fatigue.

7. Discussions

Several causes of sleeper deterioration around the world over the last two decades are summarised in Table 2. This study found that the big problem inherent in timber sleepers is their susceptibility to mechanical and biological degradation, including decaying, splitting and insect infestation which leads to their failure. Mono-block prestressed concrete sleepers are the most commonly used sleepers throughout the world due to their greater durability in adverse environments and, in Australia, the majority of modern railway sleepers are of this type. However, the low impact resistance and susceptibility to chemical attack (DEF, AAR etc.) of mono-block prestressed concrete sleepers are major problems. On the other hand, the worrying aspect associated with steel sleeper is their fatigue cracking at the rail seat region, which leads to failure and their acceptance is decreasing due to the risks of corrosion and other chemical attacks. To protect the sleepers from those unfavourable circumstances researchers have investigated their mitigation techniques as tabulated in Table 3.

The remedial measures discussed above are effective to protect sleepers from its early deterioration, but the cost associated with it, is a great concern. However, research and development are now focussed on new materials for manufacturing sleeper, particularly composites which have the potential to solve many problems of traditional timber, concrete and steel sleeper.

8. Conclusions

The unexpected deterioration of traditional railway sleepers and the lack of understanding of their degradation mechanisms are the main drivers behind this research which aims to provide guidelines for structural designers, engineers, researchers as well as asset owners. Several causes of sleeper deterioration are identified and some best practices for minimising sleeper problems provided by different researchers and organizations are presented, from which the following conclusions are drawn.

- **Timber sleeper failure:** The most predominant and two other major modes of timber sleeper failure are fungal decay, end splitting and termite attacks. They are responsible for 53%, 10% and 7% respectively of the total premature failures. **Protective measures:** Impregnation with synthetic chemicals and biological treatment protects sleeper from fungal decay and termite attacks. Biological protection methods are now being promoted to lessen the impact of chemical protection on environment. The use of end-plates on the cracked ends is a common practice to control the end splitting of timber sleeper.

- **Concrete sleeper failure:** The two major modes of failure for concrete sleeper are rail-seat deterioration and longitudinal cracking. **Protective measures:** The rail-seat deterioration can be minimised by (a) using cast-in-place steel plates that cover the rail-seat area, (b) applying epoxy coating over the rail-seat region, (c) adding fly ash and silica fume to the concrete in the rail-seat, (d) introducing steel fibre-reinforced grout in the rail-seat region during manufacturing, and (e)
applying a multilayer abrasion-resistant pad assembly and metallic aggregates in the rail-seat area. The longitudinal cracking of a concrete sleeper can be controlled by introducing a special expansive concrete around the bolt-hole area while transverse reinforcing bars can be placed in it, especially around the bolt hole, to strengthen it transversely.

- **Steel sleeper failure**: Corrosion in steel sleepers is considered the principal cause of its early failures. The factors responsible for steel corrosion are (a) salts which can come into contact with sleepers from soil, groundwater and aggregates, (b) metallic slag-based ballast, (c) a constantly moist environment around sleepers, and (d) corrosive materials in the track. **Protective measures**: Steel sleepers are suggested not to be used in locations where (a) the ballast is made from slag, (b) there is high salinity, including in coastal regions, (c) the area is continually moist, or (d) there are corrosive materials, such as coal, minerals, mud, clay and dirt. If these situations cannot be prevented, zinc (Zn) coating should be applied to steel sleepers as a protective layer for precautionary measure.

- **New materials for sleepers**: The deterioration of concrete sleepers due to DEF and AAR could be minimised by replacing cement concrete with geopolymer concrete as the latter material exhibits excellent engineering properties which provide protection against chemical degradation. On the other hand, the composite properties of resistance to corrosion, high-impact loading and fatigue, as well as their durability, make them efficient sleeper materials. Continued efforts are still needed towards the better understanding of these new materials for their more economical exploitation in mainline railway sleepers.

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