COMPOSITE RAILWAY SLEEPERS: NEW DEVELOPMENTS AND OPPORTUNITIES

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SUMMARY
Composite sleeper is becoming a suitable alternative for replacing the existing concrete, steel and particularly timber sleeper in both mainline and heavy haul rail network. Composite sleeper technologies are already available in the last 20 years but they have gained limited acceptance by the railway industry. For better understanding of the reasons for their slow uptake in the market, a comparative study was conducted among the existing composite sleepers. Firstly, this paper accumulated information on the performance of commercially available composite sleepers. Secondly, issues on the application and developments of composite sleepers are identified. Thirdly, the ongoing research on the composite sleeper is presented for keeping update the sleeper researchers, engineers and end users. The potential of sandwich composite for overcoming the current limitations of composite sleeper is briefly discussed. Finally, this paper provided suggestions and recommended solutions to increase the market opportunities of composite sleepers.

INTRODUCTION
Timber, steel and concrete are the primary materials used to manufacture railway sleepers; which are vulnerable to mechanical, biological and chemical degradation (1). The problems of timber rotting, splitting and being infested with insects, as well as its scarcity, became a new challenge which led to the use steel and concrete. 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 to be used in sleepers. On the other hand, prestressed concrete sleepers, which offer greater durability than timber and steel, suffer from heavy weight, high initial cost, low impact resistance, susceptibility to chemical attack and consequently have failed to satisfactorily meet demands (2).

The global composites market is rapidly increasing and it is anticipated to reach approximately $35.1 billion by 2019, with a compound annual growth rate (CAGR) of 6.6%. Several companies have been developed composite railway sleepers; but their acceptance by the railway industry is quite low despite the benefits of using composite product. This paper presented the true reasons behind their slow uptake and provided some guidelines to increase the market opportunities.

AVAILABLE COMPOSITE SLEEPERS
Several companies and research institutions have developed composite sleepers in different countries. These sleepers are made from a variety of materials: recycled plastic, FRP, natural rubber, sandwich composites and so on. Brief descriptions of the available composite sleepers are discussed in the following subsections.

1. FFU Synthetic Sleeper
In 1978, the Japanese company Sekisui Chemical Co. Ltd. developed a synthetic wood called ESLON Neo Lumber FFU (Fibre-reinforced Foamed Urethane) for the manufacture of railway sleepers in which thermosetting rigid urethane resin foam is reinforced with long glass fibres. As the
characteristic properties of the synthetic material FFU can be classified as being between those of wood and plastic, it possesses the advantages of both materials (3) and, unlike traditional timber sleepers, does not need to be impregnated with environmentally harmful chemicals. The key features are: light weight; good resistance to water absorption; heat and corrosion; easy drill ability; and more than 50 years of design life. An investigation of the acoustic and dynamic characteristics of a FFU turnout sleeper showed that its performance is equivalent to that of a timber sleeper (4). To date, this sleeper has been installed (Fig. 1) in more than 925 kms of track (approximately 1.5 million sleepers) with its main application in turnouts, open steel girder structures and tunnels (5). Apart from in Japan, Sekisui FFU sleepers have been installed in Germany, Austria and, recently, in Australia. Their applicability is also now investigated for a long span rail bridge in Chongqing city, China (6).

### 2. TieTek Sleeper

The US company TieTek LLC in Houston, developed a composite railway sleeper from recycled plastic bottles and bags, scrapped vehicle tyres, waste fibreglass and structural mineral fillers. It was composed of 85% recycled materials and designed to replace traditional timber sleepers and, in 17 years, approximately 2 million were installed (Fig. 2) throughout the world. The benefits of this sleeper: lower noise and vibration levels; better lateral stability; and a longer life span (40 years) than a timber sleeper; good resistance to rail-seat abrasion; spike pull; damage by moisture; insects and fungi; and low electrical conductivity (7, 8). Due to a number of quality control issues (9); TieTek ceased production in early 2010.

### 3. Axion EcoTrax Sleeper

‘Axion’, a US green technology company, now manufactures composite sleepers made from 100% recycled consumer plastic (such as plastic coffee cups, plastic bags, milk jugs and laundry detergent bottles) and industrial plastic waste under the brand name ‘EcoTrax’ (10). In 1994 this manufacturing technology was developed by the Polywood Plastic Composite Company. In 2007, its processing function, was taken over by Axion (7). Since its introduction, a variety of sleepers have been produced for different applications (Fig. 3) including: switches; road crossing; bridges; passenger; and heavy duty track. Compared with the traditional timber sleepers; this sleeper is more impervious to rot, fungus, insects and moisture, provides better resistance to plate wear and has a longer life span (50 years) (11). This sleeper technology is now being introduced in Europe, Australia, New Zealand, Canada and Southeast Asia (10).
4. IntegriCo Sleeper

IntegriCo Composites Inc. developed an unique processing technology for manufacturing composite sleepers from landfill-bound 100% recycled plastic materials (Fig. 4) and produces different types of sleepers depending on the required application. The different type of railroad applications are: Class I, Commuter, Industrial, and Mining. Benefits of this product include: good resistance to moisture; insects; plate-cut; and caustic environment; and an expected life span (50 years). Since 2005, IntegriCo has installed more than 1 million composite sleepers in North America and is currently introducing them in Mexico, Canada and India (12).

5. Fibre-reinforced Polymer (FRP) Sleeper

The ban on felling trees in India motivated Permali Wallace Pty. Ltd. to develop an alternative to a timber sleeper. An FRP composite ones using fibre reinforcement and a resin matrix. The key features are: light weight (54 kg); longer service life (40 to 50 years); good resistance to corrosion; high electrical insulation; lower life cycle cost; and innovative design. Since 1998, several have been installed in different locations in India for trial purposes (Fig. 5) (13).

6. I-Plas Sleeper

I-Plas, Halifax-based British manufacturing company has developed a new railway sleeper from 100% recycled composites obtained from both domestic and industrial wastes. These wastes include: plastic bags; drink bottles; and old car bumpers. The primary target is to replace timber sleepers with this eco-friendly product (Fig. 6) (14). Key benefits are: better performance against rotting; twisting; degradation; resistance to fire; low maintenance cost and 30-year service life (15). Some trial sleepers were installed as a replacement of deteriorated timber sleepers in slower lines and their performances in rail tracks are currently being investigated (16).

7. Tufflex Sleeper

In 2004, a South African company, introduced a composite sleeper made from a special mix of recycled polypropylene and high- and low-density polyethylene materials for an underground railway line and narrow gauge railway track in sugar plantation (Fig. 7). It is claimed to have a longer service life than timber and concrete sleepers when used in underground mines where high fluctuations of pH and high levels of water and humidity are challenging issues associated with using traditional sleeper materials. Recently, Tufflex Plastic installed sleepers in underground lines of the AngloGold Ashanti’ and Gold Fields’ mines in Africa and their in-service performances are now being investigated (17, 18).
8. Natural rubber composite Sleeper

The use of natural rubber in rubber-asphalt mixtures for road surfaces, bridge bearings, plates for vibration absorbers and blocks for the seismic protection of tall buildings inspired a group of researchers in Thailand to manufacture railway sleepers using it in 2005 (Fig. 8). They improved the mechanical properties of natural rubber using an ebonite system whereby the cross-link density of natural rubber was increased. They obtained better compressive modulus and hardness of the modified natural rubber than scrap rubber/tyres based TieTek composites which they considered their benchmark (19, 20).

9. KLP Sleeper

The ban of using harmful creosote oil to preserve timber sleepers motivated a company in The Netherlands to introduce 100% recycled plastic sleepers under the brand name KLP (Kunststof Lankhorst Product) for main track, switch and bridge applications (transoms). The manufacturer optimised the volumes of materials for its main track product which requires 35% less plastic than a traditionally shaped rectangular solid sleeper. This is a good initiative for minimising the cost of both the sleeper manufacture and transportation. The benefits of this plastic sleeper includes a long life (50 years), durability, ease of installation and environmental friendliness, and due to their innovative design, it is claimed to have a better lateral resistance. Since they were first developed in 2006, KLP sleepers have been installed in more than 20 turnout applications in the Netherlands and Germany (21). Recently, the French installed 1 km of rail track using them as a trial to evaluate the track’s performance (Fig. 9).

10. Mixed Plastic Waste (MPW) Sleeper

Since beginning in 2008, the Railwaste project in Germany has produced alternative railway sleepers from a combination of mixed plastic wastes, glass fibre wastes and auxiliary agents with a thermoplastic polymer matrix using an extrusion process. It is expected that this sleeper has much better weather resistance than timber, a lower consumption of primary materials due to the use of waste plastic and better acoustic damping properties than metal and concrete (22, 23). Also it has found many voids (Fig. 10) which are sometimes beneficial in terms of weight reduction but not good from structural point of view.
11. Wood Core Sleeper

In 2011, a plastic composite wood-core sleeper was introduced by the Texas based US company named Southwest RV and Marine. Its main design concept includes a polyethylene-based plastic mixture, which protects it from insect attack, moisture and UV degradation, with reinforcement provided by a rectangular wooden beam inside which carries the loads (Fig. 11) (24).

12. Glue Laminated Sandwich Sleeper

The behaviour of glue-laminated sandwich beams have been investigated by Manalo and Aravinthan (25) for replacing traditional timber sleepers in turnout application. The innovative sandwich beam concept (Fig. 12) showed far better mechanical properties than most of the available composite railway sleepers and is comparable with the existing timber turnout sleepers. This sleeper can provide sufficient resistance to hold the screw in position which is one of the most common problems of existing plastic composite product.

13. Hybrid Concrete Sleeper

The geopolymer concrete sleeper is now considered an alternative environmentally friendly railway sleeper as geopolymer concrete reduces landfill weights because it uses an industrial by-product called fly ash. Australia’s leading concrete sleeper supplier, Rocla, has been manufacturing geopolymer prestressed concrete sleepers for mainline rail tracks since 2002 (26). In 2010, Uehara (27) proposed a geopolymer concrete sleeper and conducted a series of tests on it, with the results stratifying the Japanese standard they used, JIS E 1202. In 2011, Palomo and Fernández-Jiménez (28) manufactured alkali-activated fly ash mono-block prestressed concrete sleepers for an industrial trial and their experimental results met the requirements of both the Spanish and European codes. Ferdous et al. (29) investigated the feasibility of a geopolymer concrete-filled pultruded composite sleeper (Fig. 13) and their initial results showed satisfactory performances compared with those of timber and existing composite sleepers. Recently in 2014, the durability of eco-friendly prestressed concrete sleeper made from steel slags have been investigated through field inspection and it is claimed as an alternative to conventional prestressed concrete sleeper with the additional advantage of low environmental impact (30).
Types of sleeper | Timber | FFU | TieTek | Axion | IntegriCo | Wood core laminated
--- | --- | --- | --- | --- | --- | ---
Density, (kg/m$^3$) | 1085 | 670-820 | 1153 | 849-897 | 1121 | 993
Modulus of Elasticity, (MPa) | 16000 | 8100 | >1724 | 1724 | 1655 | 1517 | 5190
Modulus of Rupture, (MPa) | 65 | 142 | >18.6 | 20.6 | 18.6 | 17.2 | 103
Compressive MOE, (MPa) | - | - | 269 | 176.5 | 262 | 241 | -
Rail-Seat Compression, (MPa) | 60 | 58 | 16.5 | 20.6 | 15.9 | 15.2 | -
Screw Pullout Force, (kN) | 40 | 65 | 35.6 | 31.6 | 73.4 | - | 63.8
Thermal Expansion,(cm/cm/°C) | - | - | 1.35×10^{-4} | 0.74×10^{-4} | 1.26×10^{-4} | 0.2×10^{-4} | -
Electrical Impedance (wet), (Ω) | - | - | 140×10^{6} | 500×10^{6} | - | - | -
Flammability | - | - | No@20s | - | - | - | -
Impact bending strength, (MPa) | - | 41 | - | - | - | - | -

Table 1: Comparison of the Performance of Composite Sleeper

PROBLEMS OF COMPOSITE SLEEPER

The limited strength and stiffness of recycled plastic sleeper has been considered the primary obstacles of their widespread application in railway track. Most of the alternative sleeper technologies are developed for replacing existing timber but their strength and stiffness are not compatible with timber. For example, hardwood timber sleeper has a modulus of rupture of 65 MPa while the recycled plastic sleeper exhibits only around 20 MPa. The prohibitive cost of the most composite sleeper is another reason identified for their slow uptake in the market. Van Erp and Mckay (33) indicated that the price of composite sleeper is approximately 5 to 10 times higher than that of a standard timber sleeper. Some of the composite sleeper technologies are struggling to maintain the rail track gauge due to their low capacity of holding rail fastenings. It has been reported that the modified compound of natural rubber composite sleeper showed very stiff and inelastic performance to hold the spike for fastening system (19). Over time the loosening of fastener makes the truck unstable due to stress relaxation when using composite sleepers (34). This has been considered the most likely reason for derailment failure of track system constructed with composite sleeper (32, 35).

Moreover, the formation of voids during manufacturing of plastic sleeper creates problems to transfer stresses from one part to others, generate stress concentration and lead to the local failure before their design life. Furthermore, under sustained loads, the composite sleeper may be subjected to permanent deformation due to creep (34, 36, 37). The rate of creep depends on the magnitude and duration of stress and temperature at which the load is applied. The effect of creep leads to stress relaxation and consequently the fastening system tends to loose particularly in the curve track that has an adverse effect on gauge holding (37). The lack of knowledge on the long term performances of composite sleeper technologies are also restricts their application in rail track.

POTENTIAL OF SANDWICH COMPOSITE

A sandwich composite panel is considered a material of choice because of its durability and superior structural performance under static, fatigue and impact loadings. It consists of strong fibre reinforcement through its thin layers being bonded to its lightweight thick core. Its flexural strength and stiffness are provided by its skin and its shear strength by its core. The flexural behaviour of a sandwich composite panel was
investigated by Manalo et al. (38) in both flat-wise (skin in the horizontal) and edge-wise (skin in the vertical) positions, with a sudden brittle failure of it observed in the former and a different failure mode seen in the latter in which the specimens provided higher ultimate strengths and their non-horizontal skins prevented sudden failure of the panel. Kulkarni et al. (39) investigated the fatigue crack growth and life prediction of foam-core sandwich composites under flexural loading. Stress levels of between 60 and 90% of their ultimate flexural strengths were applied in increments of 5% and at a frequency of 3 Hz until failure or up to 1 million cycles, whichever occurred first, and they found that their fatigue limits were around 60% of their ultimate flexural strengths. Impact loading can damage sandwich structures through delamination and fibre breakage in the skin, de-bonding of the skin and core interface, and/or core failure by either crushing or shear. Reductions in the tensile, compressive, shear and bending strengths of sandwich composites are expected when they are subjected to impact loading. However, compression-after-impact (CAI) has been considered the most important impact characterisation process because delamination damage is quite common in impacted skin. The CAI strength of a woven carbon/epoxy skin and PVC foam core sandwich composite panel was investigated by Schubel et al. (40) who found that there is a 60% reduction in compressive strength when a specimen is subjected to a large impact of 108 Joule.

Outdoors, a railway sleeper is not only subjected to wheel loads from vehicles but also environmental loads from UV radiation, high pH, high and low temperatures, moisture, etc. Unfortunately, to date, very little research has been conducted on the durability of sandwich composite structures. The effect of UV radiation on E-glass fibre-reinforced epoxy/GFRP composite laminates has been investigated through CAI testing (41), with their residual compressive buckling strengths obtained 47.1 and 56.1% after 48 hours of UV radiation under two different environmental conditions. Stone et al. (42) evaluated the flexural performances of GFRP skin-based honeycomb sandwich panels immersed in a 15% sodium chloride solution for 42 days at 60 °C. They drilled small holes through the width of a specimen in order to create the worst-case scenario of the entire core being flooded. Their results from four-point bending tests showed that its ultimate normalised load is only 10% lower than those of unaffected samples but they found no reduction in its stiffness properties. Wu et al. (43) investigated the effect of freeze-thaw cycling on the flexural strength, storage modulus and loss factor of a sandwich composite skin manufactured from a glass fibre and vinyl ester resin. Their results showed a very insignificant effect on the mechanical properties of the FRP skin for freeze-thaw cycling between 4.4 and −17.8 °C for 1250 hours and 625 cycles in dry air, distilled water and salt water conditions. The ingestion of moisture into a honeycomb core sandwich structure was studied by Cise and Lakes (44) who concluded that, although this sandwich panel can absorb some level of moisture, to prevent moisture ingestion, recommended using a protective cover over the structure if it is exposed to a moist environment.

**DISCUSSION**

The major challenges in using composite railway sleepers are their limited strength and stiffness which is not compatible with timber in most cases and their high prices compared to standard sleeper materials. To address those issues, a significant research needs to be performed either on the existing composite sleepers or a new composite sleeper from another material. To increase the strength and stiffness of recycled plastic sleepers, it is suggested to use fibre reinforcements. However, a significant amount of research is required to develop the techniques how the fibres will work with thermoplastic polymer. On the other hand, the cost of composite sleeper technologies can be reduced by optimising the use of materials. When the train passes over the rail, the wheel loads are generally distributed at the rail seat region. Therefore, rail seat region is the most critical section and other parts of sleeper do not require the same strength. The material cost is significant in case of composite and any reduction of the volume of materials can contribute to the cost minimisation.

**CONCLUSIONS**

A number of composite sleeper technologies have been developed in different parts of the world but their uptake in the market is extremely slow. The primary obstacles of their widespread application are their low strength and stiffness, high price, low capacity of holding screw, formation of voids into the body of sleeper, and permanent deformation due to creep and temperature variations. Moreover, the long term performances and durability of composite sleeper are not fully investigated yet. The introduction of long fibre reinforcements will improve the strength and stiffness of recycled plastic sleepers. Similarly, the optimal use of materials and improve manufacturing techniques will help minimise the overall costs. The potentiality of using sandwich composite panel for manufacturing composite sleeper is anticipated to provide an efficient structural element.

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