Review on Geosynthetic Inclusions for the Enhancement of Ballasted Rail Tracks

S. Venuja, S. K. Navaratnarajah, C. S. Bandara, and J. A. S. C. Jayasinghe

Abstract Currently, there is an increasing demand for rail transport from a growing and urbanizing population worldwide as it is a resource-efficient transport system. Moreover, its popularity among people is due to safety, reliability and economic profit. The rail track system consists of rails, fastening systems, sleepers, ballast, sub-ballast and subgrade. Ballast is a highly angular coarse granular material which is the major load-bearing component as it transmits the stresses exerted by moving trains from sleepers to the subballast and subgrade at a reduced level. Ballast degradation is a major problem caused by the high dynamic and cyclic loads from faster and heavier trains as well as the impact loads due to wheel and rail irregularities and tracks at stiffness transition zones. It affects the track longevity together with the track geometry thereby a necessity of regular monitoring and maintenance. Ballast fouling is accompanied by ballast degradation as the broken ballast particles intrude into the voids of the ballast layer and obstruct the drainage. The popular method to reduce the excessive ballast deformation and degradation is the inclusion of geosynthetics such as geogrids, geotextiles, geocomposites, and geocells to the track foundation. This paper provides an extensive review of past studies on geosynthetics to reinforce the track foundation. In conclusion, this review presents the limitations of existing studies and provides recommendations for further studies.

Keywords Rail track · Ballast · Degradation · Ballast fouling · Geosynthetics

1 Introduction

The rail track system is divided into two parts: (i) Superstructure consisting of rail, fastening systems, ties or sleepers; (ii) Substructure consisting of ballast, sub-ballast or capping and compacted subgrade base or a concrete base. Ballast is divided into four subdivisions as crib, shoulder, top ballast, and bottom ballast. Short-term and

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long-term deformations of the ballasted rail tracks depend on the substructure components' characteristics. Ballast degradation is high under stiff subgrade conditions and heavy cyclic loads which affects the track stability and longevity [11, 15]. It also leads to increased maintenance costs, speed restrictions, track and vehicle component failures, stoppage and delays [4, 14].

One of the most widely used techniques in reducing ballast degradation is the inclusion of geosynthetic material to the track foundation. There are planar (geogrids, geotextiles, and geocomposites) and cellular layers (geocells) that are extensively adopted in the improvement of ballast performance. In this review paper, many past studies on geosynthetic enhancement of ballasted rail tracks were comprehensively reviewed.

2 Ballasted Rail Tracks

Conventional ballasted tracks and slab tracks are the two types of tracks extensively used nowadays as illustrated in Fig. 1. Even though the slab tracks have a longer lifespan compared to ballasted tracks, their initial construction and repair costs are much higher. Therefore the ballasted tracks are the most preferred [1]. In ballasted tracks, the ballast layer is the largest component in the substructure and it includes

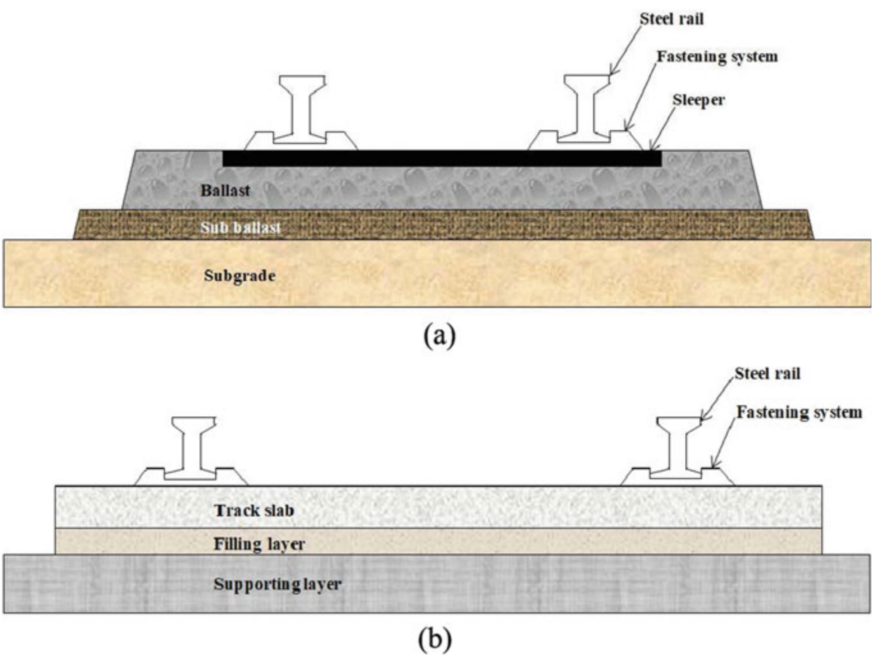

Fig. 1 Schematic diagram of **a** Ballasted rail track; **b** slab rail track

dolomite, rheolite, gneiss, basalt, granite, limestones, recycled slag and quartzite [4, 9]. Key functions of the ballast layer are but not limited serving as a bed to the rail tracks, maintains the gauge between sleepers thus alignment of the rails, providing track and substructure stability, drain out water quickly and barrier the growth of vegetation [2, 14]. Performance of the ballast depends on the strength and type of the parent rock, aggregate shape and size distribution, hardness and toughness, specific gravity and load cycles [9, 13, 19]. Anbazhagan et al. [2] critically analyzed the optimum ballast gradation which takes high shear strength (well-graded) and high permeability (uniformly graded) into consideration.

Ballast degradation is normally caused by particle breakage, abrasion, finer particles intrusion and contamination and, it reduces the shear strength and stiffness thereby high compressibility [15, 20]. The higher rate of ballast degradation and lateral spreading of the ballast occur due to repeated heavier and faster trains [16, 21]. The degradation of ballast depends on the load cycles, aggregate gradation, angularity and fracture strength of each particle and track confining pressure [9]. Ballast settlement can be either elastic which is an initial settlement due to the compaction of ballast or plastic where settlement is due to the densification and breakage of ballast particles.

Consequences of ballast degradation are track settlement and instability, poor track geometry, reduction in track longevity, poor drainage, necessity of regular monitoring and maintenance, involving cost and time consuming remedial actions such as stone blowing and ballast renewal [4, 11, 18]. Therefore, it affects safety, comfort, reliability, availability, speed and overall railway performance.

3 Geosynthetic Reinforcement

Generally, the major portion of the track maintenance cost is due to ballast degradation, poor drainage, track settlement and misalignment [17]. For nearly 30 years, geosynthetics are used for the improvement of railway tracks. Typically, geosynthetics are used as a separation layer between ballast and sub-ballast or subgrade layers in order to prevent ballast contamination through the intrusion of finer particles from the bottom layer. As shown in Fig. 2, there are various types of two dimensional or planar and three dimensional or cellular geosynthetics that are accessible based on the applications.

3.1 Past Experimental Studies

Railway tracks reinforced with geosynthetics were experimentally analyzed by many researchers (Biabani et al. [3], Fattah et al. [5], Horníček et al. [6], Indraratna et al. [8], Indraratna and Nimbalkar [10], Ngo et al. [18], Ngo and Indraratna [17] and Sweta and Hussaini [22]). The conventional design of railroad tracks concentrates more on

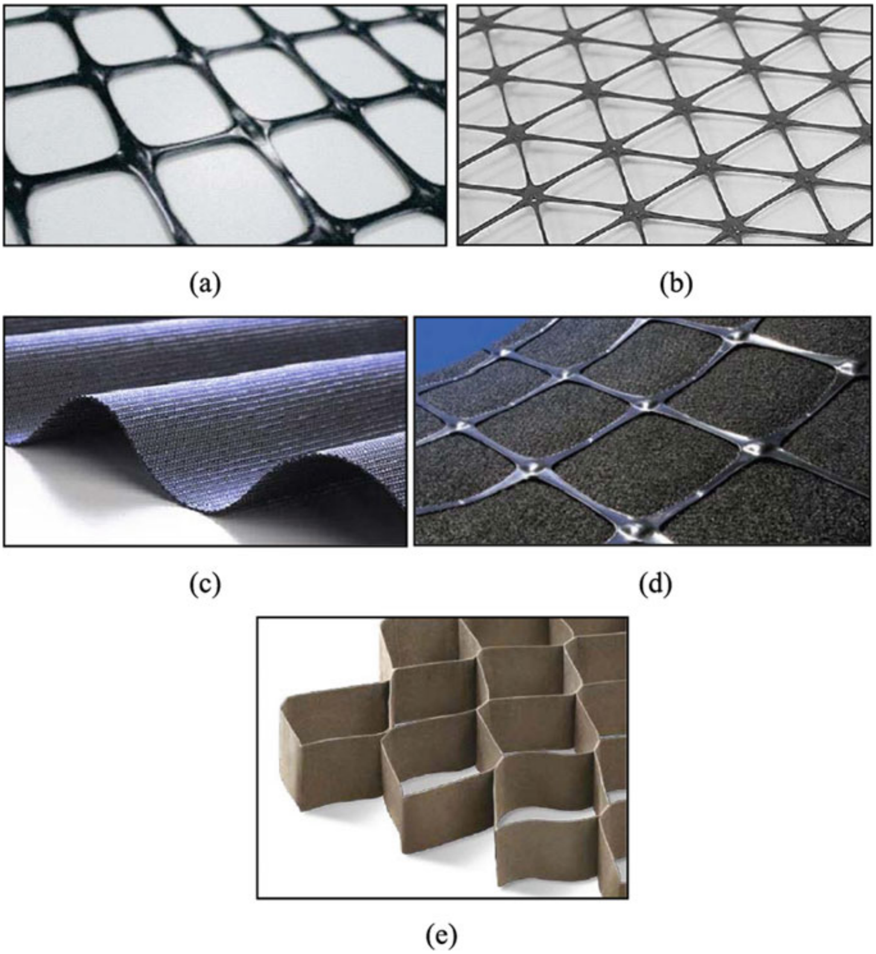

Fig. 2 Types of geosynthetics **a** Biaxial Geogrid; **b** triaxial Geogrid; **c** geotextile; **d** geocomposite; **e** geocell

the design of track superstructure while that pays little attention to the design of track substructure. It also considers quasi-static loading and too uniform particle sizes thus neglecting cyclic, impact loadings and particle sizes, shapes and subsequent particle breakage, respectively [10].

Large scale direct shear test is adaptable to analyze the behavior of ballast and geosynthetic [8, 17, 18] or sub-ballast and geosynthetic [3, 10, 22] or subgrade and geosynthetic interfaces [6] according to the location of the geosynthetic as indicated in Fig. 3. Ngo et al. [18] analyzed the interface behavior of ballast and geogrid using biaxial and triaxial geogrids with different aperture sizes where the geogrid was placed at the interface between the upper and lower shear boxes which are filled

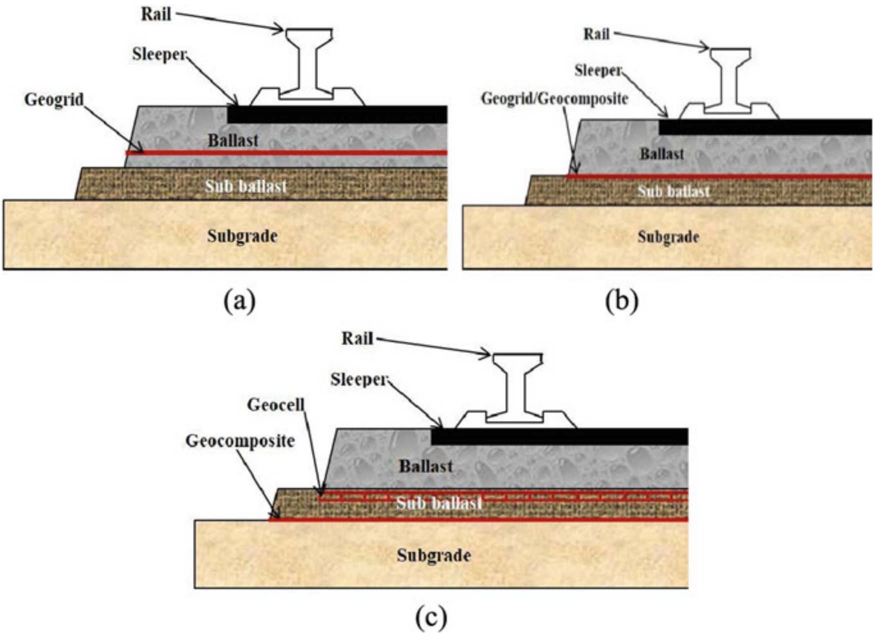

Fig. 3 Geosynthetic inclusion **a** Inside the ballast layer; **b** between ballast and sub-ballast layers; **c** combination

with ballast, along the shearing direction. This research came up with the conclusions of (i) Triaxial geogrids (Fig. 2b) that are not that much efficient compared to biaxial geogrids (Fig. 2a) in enhancing the performance of granular ballast particles through mechanical interlocking. It is because of the smaller triangular apertures where ballast particles not get complete interlocking and get a slippery plane, (ii) Geogrids prevent the free movement of ballast particles through mechanical interlocking as illustrated in Fig. 4. On the other hand, Sweta and Hussaini [22] studied the effect of normal stress and shearing rate on the interface shear behavior of the ballast and sub-ballast interface with and without the inclusions of biaxial and triaxial geogrids with various aperture sizes and shapes. The equivalent aperture sizes of rectangular geogrids are the square root of the aperture area where for triangular geogrid is the diameter of the largest inscribed circle inside the aperture. The outcomes of this study are (i) geogrid inclusion at the ballast and sub-ballast interface that reduces the extent of dilation for different normal stresses and shearing rates, (ii) the increase in the normal stress as well as in the shearing rate that reduces the shear strength, the friction, and dilation angle at the ballast and sub-ballast interfaces for both geogrid-reinforced and unreinforced conditions. This is because of the ballast breakage and quicker sliding of the ballast particles, respectively. Further, Biabani et al. [3] investigated the effect of normal stress, rate of shearing, relative density and open area on the interface behavior of sub-ballast reinforced with different types of geocells and geogrids. This study encountered the following closures: The aperture shape and size

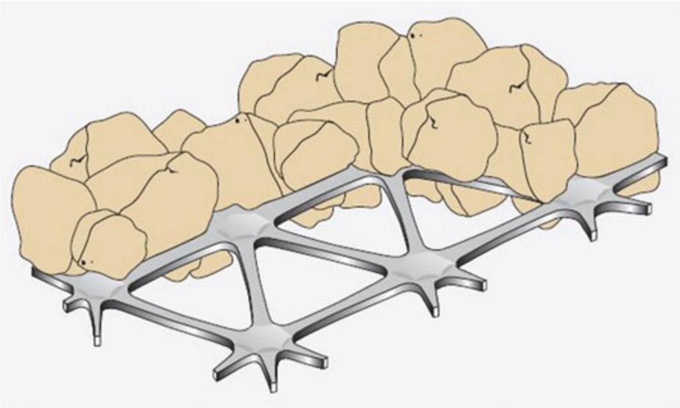

Fig. 4 Mechanical interlocking of ballast particles into apertures of triaxial geogrid

affect the performance of the granular material. Higher shearing rate leads to faster particle rearrangement and densification thereby decreases the interface coefficient. Frictional resistance reduces with the increase in the open area of the reinforcement. The triaxial geogrids provide more passive resistance than biaxial geogrids due to the effectiveness of transverse ribs thus maximum performance improvement was obtained for sub-ballast reinforced with triaxial geogrid. Geocells give much better lateral confinement than planar geo-inclusions as it provides maximum interface shear resistance.

Cyclic loading tests are used to analyze the degradation behavior of ballast under cyclic loads. Ngo et al. [18] studied vertical and lateral deformation of geogrid-reinforced and unreinforced ballast under 420 kPa cyclic stress and 15 Hz frequency up to 500,000 load cycles. There was a rapid settlement in the ballast observed at the initial load cycles due to the particle rearrangement and densification, and the settlement became marginal after a certain number of cycles.

Geogrids resist the lateral movement of ballast thus it can be used as a non-horizontal boundary. Geogrids reduce the ballast breakage through reducing the pressure at the ballast layer by interlocking the particles into the apertures. Further, the highest efficiency of geogrid reinforcement was obtained when the geogrid was placed at a 1/3 height of ballast layer thickness, from the interface of ballast and capping layers. But there are practical issues when the maintenance activities are taking place. Geogrids interfere with the removal of used ballast and placing of fresh ballast using machinery. Thus, it is advisable to place the geogrids at the ballast and capping layer interface considering the convenience during the track maintenance. Indraratna and Nimbalkar [10] investigated the degradation behavior of granular layers and their developments using planar and cellular geo-inclusions. The planar geosynthetic (geogrid, geotextile, and geocomposite) was placed at the ballast and sub-ballast interface. Ballast stabilized with geocomposite resulted in low vertical strain followed by geogrid and geotextile stabilization as well as more effective in reducing the ballast breakage. Cyclic loading test was also conducted for the sub-ballast reinforced with geocell. Geocell can be more effective at low confining pressures and at high frequencies by confining the infill soil into its pockets.

Indraratna et al. [8] examined the performance of a fully instrumented field track with various types and aperture sizes of geosynthetics and various subgrade conditions. Track sections constructed with both fresh and recycled (used) ballast were tested in this study. Outcomes of this research are: (i) geocomposite inclusion for fresh as well as recycled ballast reduced the vertical and lateral deformations of the track through interlocking the ballast particles into the apertures, (ii) lateral deformation of ballast was higher at the crest and it always occurs spreading the particles outwards, and (iii) geogrids were more effective for the soft subgrade condition in comparison with hard rock base. Horníček et al. [6] also conducted field tests such as static plate load tests and impact plate load tests for the period of 2.5 years on the real rail track reinforced with geocomposite between ballast and subgrade. It was observed that the rail seat level at reinforced track section has a higher load-bearing capacity than the unreinforced section and there was a reduction in rail deflection, therefore, improved riding comfort and lower wear of the track components. Further, the optimum aperture of the geogrid when inserted into the ballast is 1.2 times d_{50} [7, 12, 18]. Geocomposite acts as both reinforcement and separation layer when installing at the ballast and the sub-ballast interface. It prevents the movements of fines from sub-ballast layer into the voids in the ballast layer, such that it reduces the ballast fouling as well.

3.2 Past Numerical Studies

Discrete type elements are used in modeling the ballast layer as ballast is a coarse granular particle as shown in Fig. 5. Discrete Element Modeling (DEM) was introduced by Cundall and Strack in 1979. Ngo et al. [18] discussed some previously generated *DEM*s and their outcomes in detail. They simulated *DEM* with large scale direct shear test results to study the interface mechanism between geogrid and ballast using a micromechanical analysis. They validated their model in capturing the shear stress-strain behavior of both unreinforced and reinforced ballast by comparing the stress-strain curves obtained from laboratory tests and model analysis. They mentioned that the strain behavior of geogrids could be studied using *DEM* analysis, which could not be measured from experimental analysis due to the complexity of strain gauge installation. They also analyzed the significance of the coordination

Fig. 5 Ballast particles modeled using DEM

number and the contact force orientations on the shear strength behavior of granular materials.

Fattah et al. [5] used *PLAXIS 3D* software to conduct the numerical analysis of geogrid reinforced ballast. The previously available numerical analysis methods such as Composite Element Test, the *ABAQUS* model, ballast track settlement prediction model and aggregate imaging-based *DEM* were also discussed individually. Hardening soil, Mohr-Coulomb, Linear elastic and Elastic material models were used for clay, ballast, timber sleeper also steel rail and geogrid, respectively. This research concluded that the settlement behavior is depended on the aggregate shape, gradation, thickness and the initial density of the ballast layer.

4 Conclusions and Recommendations

Geosynthetic reinforcements are more beneficial for tracks on soft subgrades as it provides a marginal improvement in the ballast performance on hard base condition. The behavior of geosynthetic-stabilized ballast depends on normal stress, rate of shearing, type of geosynthetic (also aperture shape and size) and relative density. Recycled ballast could be used in the rail tracks with geosynthetic reinforcement thus reduce the necessity for the new ballast. Geocells provide more confinement than planar geo-inclusions and perform well at low confining and high-frequency conditions. Geocomposite provides ballast confinement and barrier the fine particles intrusion from the subgrade to the ballast layer. Optimum location of geogrid derived as 2/3 of the ballast thickness, depth from the bottom of the sleeper and the optimum aperture size of geogrid is 1.2 times of d_{50}.

There are many journal publications that examined the effect of geo-inclusions for only a few ballast gradations. It is not readily applicable to other countries that are using different ballast gradations. Therefore, it is recommended to analyze the effectiveness of geosynthetic enhancement with different ballast gradations as well as installing these geo inclusions at different positions of track foundation. Blasting of rock to obtain ballast material is a big concern nowadays due to the air and noise pollution, also a scarcity of parent rocks because of frequent quarrying. Therefore, studies could be conducted in analyzing the reuse of used ballast materials with geosynthetic reinforcements into the railway applications. It also leads to a reduction in land use of ballast disposal sites. Moreover, it is suggested to examine the benefits of a few layers of geosynthetic inclusions (more than one layer, also different types of geosynthetics) into the track substructure. Most of the past numerical studies considered only the elastic behavior of ballast. Thus a numerical model could be developed incorporating elasto-plastic behavior of ballast in *ABAQUS* software to validate using experimental outcomes. This will help to perform a parametric study to understand the rail track behavior by varying different gradations of ballast and different types of geosynthetics.

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