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Polyurethane reinforced ballasted track: review, innovation and challenge

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Abstract:

During the development for railway, ballasted track is dominant structure and makes up more than 95% of the whole track modes. However, its shortage is considerable in high speed railway and heavy haul system. Regarding to the ballasted railway track's defects as particle breakage, settlement, and geometry irregularity which lead to enormous maintenance and cost, Polyurethane reinforced ballasted track has shown great application prospect. This reinforcement method can settle several problems, including stiffness adjustment, ballast flight prevention, and stability in specific zones, such as curve, tunnel line. This paper presents a comprehensive review of polyurethane research and application within ballasted track system. Besides, according to different usage, varies of bonding methods are also introduced in this paper. However, some challenges still exist such as maintenance and cost, potential solutions are put forward for further investigated and validated, consequently. Accordingly, an overall prospect of polyurethane reinforcement in railway system is presented.

Keyword: polyurethane, ballasted track, stability, maintenance, ballast flight

1. Introduction

During two centuries, railway has experienced great improvement since beginning. This transportation mode can occupy the higher percentage of railway network dedicated to both freight and passenger traffic. In recent years, especially after 1970s, railway industry shows great progress so that a large number of heavy-haul, high-speed and urban transit railway with different type of structures and new technologies was constructed through all over the world [1].

However, increasing the speed and load also produces higher stress and greater deformation, leading to track geometry changes. As a result, more frequent maintenance and cost will be needed. Consequently, higher demands were made on substructure which functions consist of bearing the force transferred from sleeper, keeping rail geometry and providing elasticity.

Nowadays, two main modes of substructures are used, including ballasted track and slab track. [1, 2]. Ballasted track is by far the most common track mode in railway system with a percentage of more than 95% [3]. Ballasted track is a granular layer which obey a certain particle size distribution. It has several advantages, including good-elasticity, low cost, easy to construct and maintain [1, 3-4]. On the other hand, with no confine pressure applied to ballast layer, some disadvantages also emerged, such as low geometry, ballast degradation, pumping effect and frequent maintenance [1-5].

Slab track is the latest in railway system compared to ballasted track, however, with several decades' development, this kind of mode has also significant effect for railway evolution, especially in high-speed railway. Slab track consists of concrete basement and slab. Sleepers are laid on a concrete base and, then concreted into slab, thus all parts of slab track system are working together as a whole. As a consequence, slab track has good workability and low maintenance frequency. On the contrary, the vibration and noise problems occurred due to the high stiffness. In addition, initial cost is large and maintenance is difficult [6-9].

However, slab track is an improvement in track system, it doesn't satisfy all kinds of track requirements. Therefore, the ballasted tracks which contribute to more than 95% of railway system are irreplaceable. To solve the geometry and durability of ballasted track, the many researches were carried out on reinforcement method.

The method to improve ballasted track bed performance commonly includes using rubber pads (or mats) and geogrids. Rail pads have the function which can increase ballast protection under higher dynamic overloads [10-12]. Under Sleeper Pads (USPs) can be used to decrease the settlement [13, 14], and Under Ballast Mat (UBM) can be used to damp vibrations and decrease stress of the ballast layer [15-16]. The usage of geogrid has a similar function, it can also reduce settlement and increasing capability [17, 18].

In addition, polyurethane reinforcement was put forward due to the concern which discussed above. After polyurethane bonding, some parts of ballasted track bed transfer from aggregate particles to a whole continuous structure, thus contributing more stability. With respect to different types of polyurethane and bonding method, polyurethane reinforcement can be applied in tunnel, bridge, station, transition zone and degraded ballast bed. Polyurethane reinforced ballasted track, which integrates the advantages of both ballast and slab track. Furthermore, this layer acts as an advanced track mode.

In China, 12570m polyurethane reinforced ballast tracks have been paved since 2009 to 2018 in 7 lines, In order to meet the stability requirement in special geological condition (such as geological fault zone), bridge and tunnel, as shown in Table1.

During the operation period, polyurethane reinforcement method performed, effectively, and through the operation history, a significant increase in the stability and less maintenance can be seen. Furthermore, 4 lines which are under construction also adopt polyurethane reinforcement, including 3 high-speed lines (Beijing-Zhangjiakou, Urumchi-Lianyungang, and Shangqiu-Hefei-Hangzhou), and 1 urban transit line (Urumchi）.

Table1 Polyurethane reinforced ballasted track in China (CARS)

Paving time	Opening time	Line	Type	Maintenance history
2009.10	2012.12	Beijing-Guangzhou	Bridge	Gauge adjustment 1 time in 2011. Gauge, Profile and alignment adjustment 1 time in 2015
2009.12	2010.03	Shanghai-Chengdu	Bridge	Profile adjustment 1 time in 2015.
2012.03	2012.06	Longyan-Zhangzhou	Bridge	Settlement after construction less than 3mm, 3 times UPS height adjustment in a small area.
2013.12	2014.12	Watang-Rizhao	Bridge	None
2014.01			Tunnel	
2014.11	2015.07	Datong-Xian	Subgrade	None
2015.05			Subgrade	
2016.07	2016.12	Shanghai-Kunming	Bridge	None
2018.06	2018.12	Jinan-Qingdao	Subgrade	None

Due to the advantages and wide usage, several groups research into the characteristics and behaviors of polyurethane reinforcement, including the polyurethane material, the function of polyurethane reinforcement, the spraying method and applications. By summarizing existing works and combining own views, this paper presents a comprehensive review and put forward the challenge/solution. What should be mentioned is that this paper firstly releases the research of China Academy of Railway Sciences (CARS) about polyurethane reinforcement.

2. Polyurethane Materials

2.1 Polyurethane

Polyurethane has a long history in other industries, but the usage in railway system is relatively short, it was first put forward by the research team of Heriot-Watt University, The XiTRACK® three-dimensional track reinforcement technique (Thompson D. and PK Woodward 2004) [19]. Another kind is improved from Elastocoast® which is produced from BASF's subsidiary Elastogran, focusing on

reinforcement of stone revetments (Hicks et al., 2008) [20]. Marcus S. Dersch and Erol Tutumluer (2010) [21] bring this material into the railway, thus put forward Elastotrack® as a method of polyurethane coating railroad ballast aggregate. China also focuses on polyurethane reinforcement method, such as CARS and Jing Guoqing [22,23].

The polyurethane mentioned above is an unfoamed material, performing stiff bonding. In addition, foamed polyurethane, which is an elastic material, is also used in railway. Andrew Keene (2012) carried out the research of rigid-polyurethane foam (RPF), thus creating unconnected monolithic formations of polyurethane-stabilized ballast (PSB) [24]. CARS also uses foamed polyurethane to reinforce ballasted track.

The Polyurethane material can be divided into two components, part A-Isocyanate and part B-Polyols which should be mixed 1:1 by volume before using. After mixing, polyurethane is a liquid and its viscous increases by time. The main chemical reactions including urea and urethane linkages generating, which chemical equations are as follows:

$$-NH_2 + -NCO \rightarrow -NHCONH - \text{(Urea linkage)} \tag{1}$$
$$-OH + -NCO \rightarrow -OCONH - \text{(Urethane linkage)} \tag{2}$$
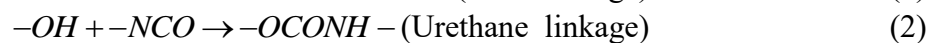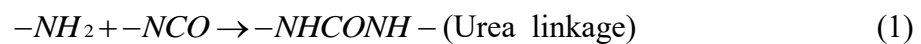
During hardening process, if there is water or foaming agent mixed in polyurethane, foam reaction will happen, the chemical equation is as follows:

$$-NCO + H_2O \rightarrow -NH_2 + CO_2 \tag{3}$$
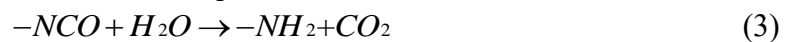
Polyurethane is commonly sprayed by spraying gun, shown as follows Fig.1 a). A whole polyurethane spraying system is developed by CARS, including spraying trolley as Fig.1 b), and drying trolley as Fig.1 c). With this system, more than 200m can be implemented per day. Besides, the amount and location can be precisely set.

a)   b)

c)

Fig.1 Spraying instruments:
a) spraying gun (Goldschmidt-Thermit-Group);
b) spraying trolley, c) drying trolley (CARS)

While spraying, polyurethane flows through the void of ballast particles, therefore, ballast particles bond at the contact point as follows Fig.2. With the chemical reaction, the strength rapidly increases within 15 to 30 minutes. To adjust the time range that to be shorter or longer catalyzer can be added. It should be noticed that after the first stage that strength increase, the entire hardening process will continue 7 days or even longer to 30 days.
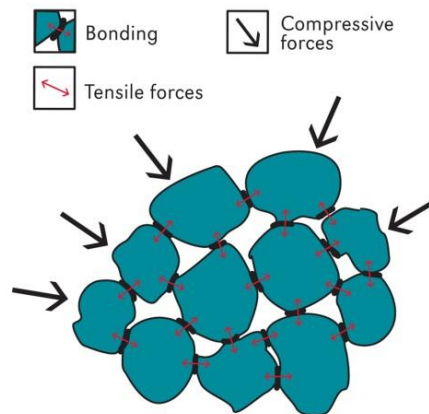

Fig.2 The mechanism ballast bonding (Goldschmidt-Thermit-Group)

The aging of polyurethane is tested by CAR. Fig.3 illustrates the tensile strength-aging curve, under hygrothermal condition (temperature 80℃ and humidity 95%). After 270 days, the tensile strength decreases to 80% of the initial data. Besides, the foamed polyurethane standard is published by CARS. The key characteristics is listed as follows Table2 [25].
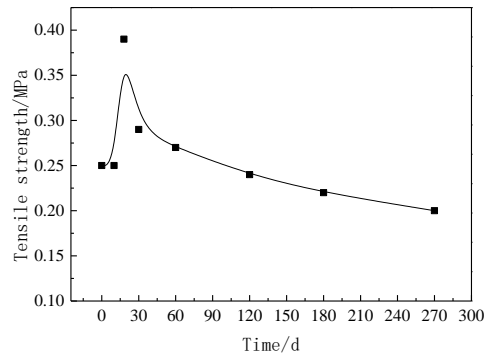
Fig. 3 Tensile strength in aging test (CARS)

Table2 Key parameters of foamed polyurethane by CARS

Items		Parameter
Free foaming density (kg/m^3)		≥130
Compressive strength (10% strain, kPa)		≥8
Tensile strength (MPa)		≥0.2
Elongation at break (%)		≥140
Tear strength (N/m)		≥400
Compressive permanent deformation (50%RH, 70℃, 22h)		≤10%
Dry-heat aging (110℃, 168h)	Retention rate of tensile strength	≥70%
	Retention rate of elongation at break	≥70%
Damp-heat aging (95%RH, 80℃, 168h)	Retention rate of tensile strength	≥70%
	Retention rate of elongation at break	≥70%
UV aging (168h)	Retention rate of tensile strength	≥70%
	Retention rate of elongation at break	≥70%
Low-temperature recovery capability (-20℃, 168h)	Retention rate of tensile strength	≥70%
	Retention rate of elongation at break	≥70%
Flame retardation	Average burning time (s)	≤30
	Average burning height	≤250
	Oxygen index	≥26%

In addition, some researchers also use other ballast bonding materials. In this aspect, it can be extended to various materials which characteristics are similar to polyurethane, such as ballast bonding resin (AgriTec® EWR-Winter, GREBOPOX®) [26] and bitumen [27-30].

2.2 Polyurethane-ballast

To qualify the characteristics of polyurethane-ballast, basic mechanic tests are needed. Marcus S. Dersch and Eros Tutumluer (2010) [21] conduct direct shear test on polyurethane-ballast cubic specimen with side dimensions of 305 mm and height of 203 mm. Results show that when the confined pressure is by 172KPa and 241KPa, the

ballast before polyurethane bonding has the lowest shear strength at 331 KPa and 400 KPa, respectively. As the strength of polyurethane increases along with time, the maximum strength, occurred on 14-day cured specimen, reached 726KPa. This data shows almost a doubling of the strength compared to the result of unbound specimen which tested at 241KPa. All results can be seen in Fig.4 as follows.
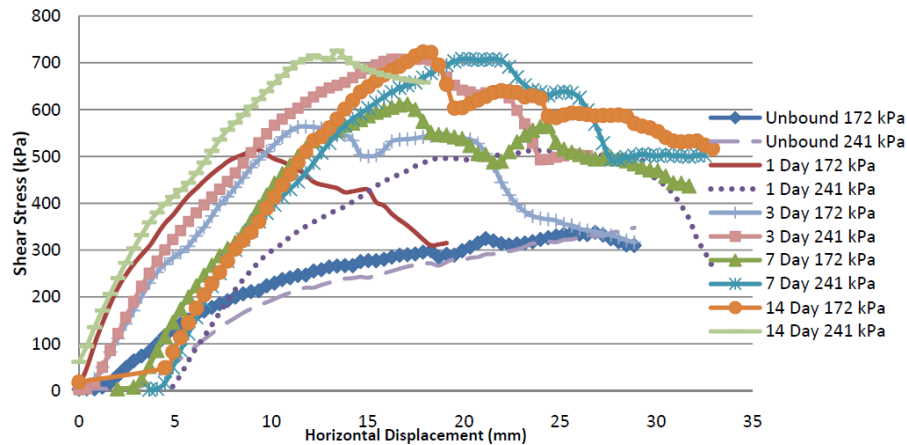

Fig. 4 Shear stress-horizontal displacement of direct shear tests (Marcus S. Dersch and Eros Tutumluer，2010)

Jing Guoqing prepared polyurethane-ballast cubic specimen with the side length of 300mm. In addition, compression tests were performed according to different polyurethane usage percentage (by volume). Results show that the axial force increase positively proportional to polyurethane usage percentage that lead to decrease the damage deformation. Without bonding, the compressive strength is by 0.073Mpa, and the elasticity modulus is about 1.039Mpa. After bonding with 2% polyurethane, the compressive strength is by 0.341Mpa, and the elasticity modulus is as 11.427Mpa. When it comes up to 4% polyurethane mixing ratio, the compressive strength and elasticity modulus are as 0.609Mpa and 41.695Mpa, respectively, as shown in Fig.5.
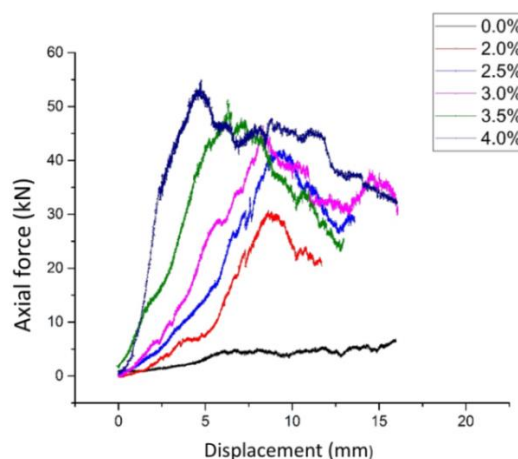

Fig.5 influence of the polyurethane usage (Jing Guoqing)

Jing Guoqing (2018) also did compression test considering two kind of polyurethane with tensile strength of 5.3Mpa and 14.2Mpa. This series of tests illustrated that the

strength increase according to curing days. For each test group, the maximum strength occurred on 7-day cured specimen. Fig.6 shows that the maximum compression stress is as 14.195kN (0.158Mpa) with displacement of 10mm, and 21.026kN (0.234Mpa) with displacement of 10mm, corresponding to the tensile strength as 5.3Mpa and 14.2Mpa of polyurethane, respectively [23].

a)   b)
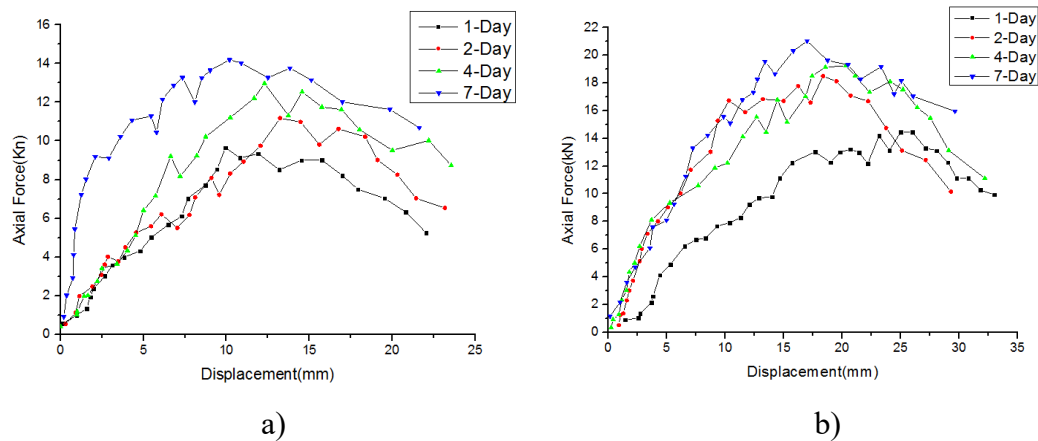
Fig.6 force-displacement curve of compression test
a) 5.3Mpa polyurethane, b) 14.2Mpa polyurethane (Jing Guoqing, 2017)

For a specific kind of polyurethane, it can be seen that when the strength of polyurethane increased by days, the damage deformation decreased, consequently. It is the same trend compared with Jing Guoqing's research when compression stress increased by the increase of the usage of the polyurethane ratio. But for the compression between different polyurethane, it cannot be determined easily, it's corresponding to the polyurethane strength and stiffness.

Furthermore, uniaxial compression tests, considering different content of polyurethane, were carried out by Su Hyung Lee (2017) [31], in this research, cylinder specimen was used. The strain-stress graphs are illustrated in Fig.7. Similar to previous researches, when the polyurethane usage percentage increased, the initial stiffness and strength increased, consequently. Moreover, the abruption is caused by breakage of bonding that can be seen due to the less polyurethane usage (70 kg/m^3).

At the beginning of the curve, there were two linear regions which can be classified into Linear-I, Linear-II, and Curved regions, as indicated in Fig. 7(b). The Linear-I region would be related to the initial compaction of the polyurethane mixed ballast. Subsequently, after slightly more compaction by the initial loading, the specimen would show more resistance to the applied load. Accordingly, the Linear-II region would show a steeper slope. In the Curved region, the bond between the aggregates and polyurethane and/or polyurethane itself would start to break; also, the interlocking of ballast aggregates would begin to weaken.
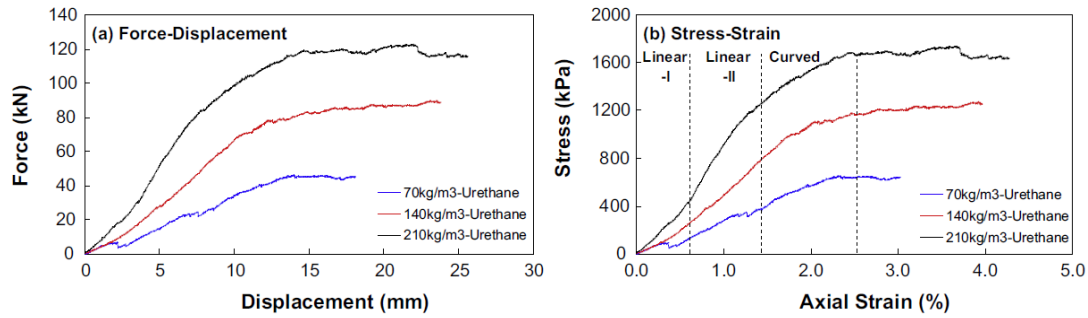
Fig.7 Uniaxial test results for polyurethane-mixed ballast (Su Hyung Lee,2017)

The slope of the linear region indicated the stiffness. The Linear-I region had a lower stiffness than did Linear-II. The slope changed at an approximate strain of 0.5%. The polyurethane content of 70 kg/m^3 showed drops at around 0.4 and 1.2%, and appeared to behave linearly up to the strain of 2%; thus, three linear regions divided by two dropped points (i.e., 0.4, 1.2% strain) were fitted by a linear function. Fig. 8(b) plots the three regions' linear fitting results. It can be seen that the first block has a slope different from those of the other two, and that whereas the latter two blocks would behave similarly to each other. The first block would behave differently from them. This is supported by the observation of the different polyurethane contents (140, 240 kg/m3). Fig. 8(c) and (d) show that the slope of the Linear-I region differs from that of the Linear-II region, which is divided by a strain of approximately 0.5%. This strain level could be considered to be the strain limit of the linear relationship in the ballast-only tests. In this regard, one can imagine that the initial behavior of polyurethane-mixed ballast is associated with that of ballast-only. That is to say, under an initial small strain, the ballast materials would play a role; but then, as the strain increases, the role of polyurethane would become much more important. Under a small strain (i.e., less than 0.5%), the initial densification would have an effect on the initial behavior.
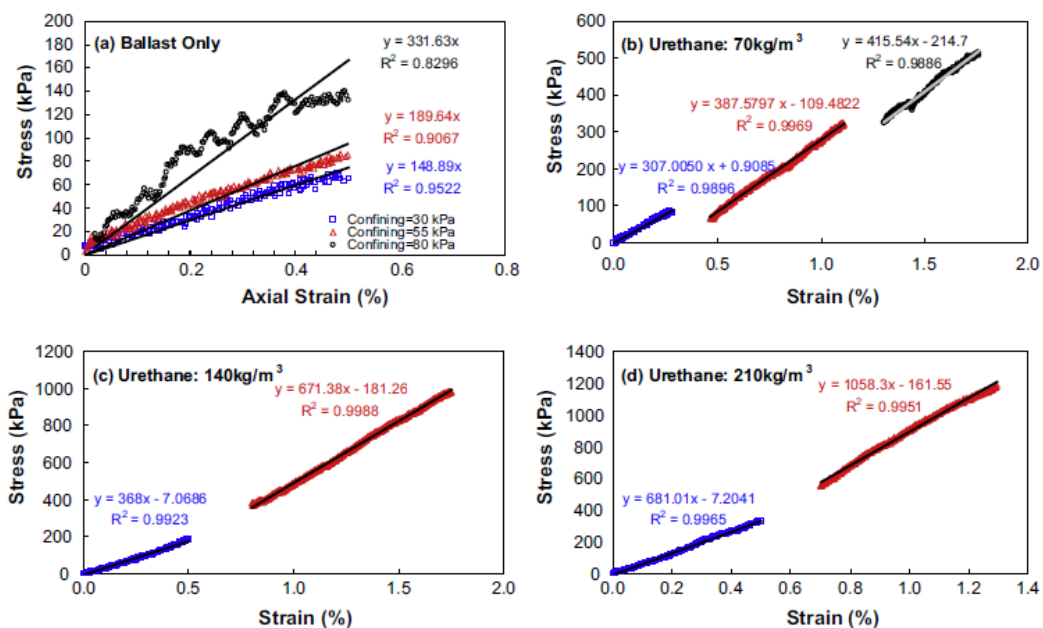
Fig.8 Stiffness by linear fitting
(a) Ballast-only, (b) Polyurethane 70 kg/m^3, (c) Polyurethane 140 kg/m^3, (d)
Polyurethane 210 kg/m^3 (Su Hyung Lee,2017)

The deformation moduli (initial linear slope, i.e., stiffness) are plotted with different polyurethane contents, in Fig. 9. Considering the confining pressure in the field, two different stiffness values were used in order to suggest stiffness of polyurethane-mixed ballast according to the content. The first case shown in Fig. 9(a) assumes no stiffness under no confining pressure. The second case shown in Fig. 9(b) assumes confining pressure of 30 kPa is close to field condition. However, one can believe that the actual condition is between these two cases.
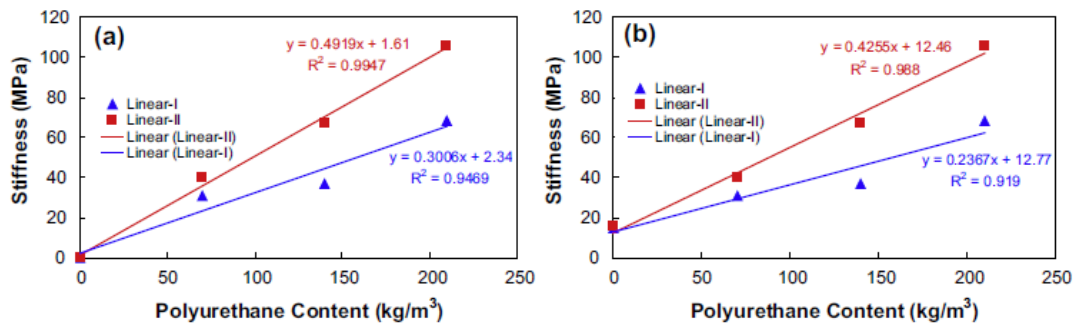

Fig.9 Deformation moduli according to polyurethane contents (Su Hyung Lee, 2017)

Based on this research, a predict relation between deformation modulus and polyurethane contents is put forward as follows Eq. (4) and (5).

$E_{mixture}=0.3149\omega_{urethane}$ for Strain < 0:5%

$E_{mixture}=0.5018\omega_{urethane}$ for Strain > 0:5%   (4)

$E_{mixture}=0.2367\omega_{urethane}+12.77$ for Strain < 0:5%

$E_{mixture}=0.4255\omega_{urethane}+12.46$ for Strain>0:5%   (5)

Where:

$E_{mixture}$ = deformation modulus (MPa) of polyurethane-mixed ballast and

$\omega_{urethane}$= polyurethane contents (kg/m^3).

As mentioned above, polyurethane in railway system have two main kinds, besides the test of unfoamed material, Andrew Keene (2012) using RPF (rigid-polyurethane foam) prepared polyurethane-ballast beams (i.e. PSB, polyurethane-stabilized ballast) and performed compression and flexure tests. Results show, comparing flexural test results, when the average RPF density is 200kg/m^3, the average PSB flexural modulus (274 MPa) is greater than the average RPF flexural modulus (124MPa). However, the average PSB flexural strength of 938 kPa is less than the average RPF flexural

strength 3652KPa. Greater flexural stiffness of PSB compared to RPF can be attributed to the stiffness of the ballast particles. The lower flexural strength of PSB relative to RPF can be attributed to weakness in the bonding interface between the ballast particles and RPF [24,33-33].
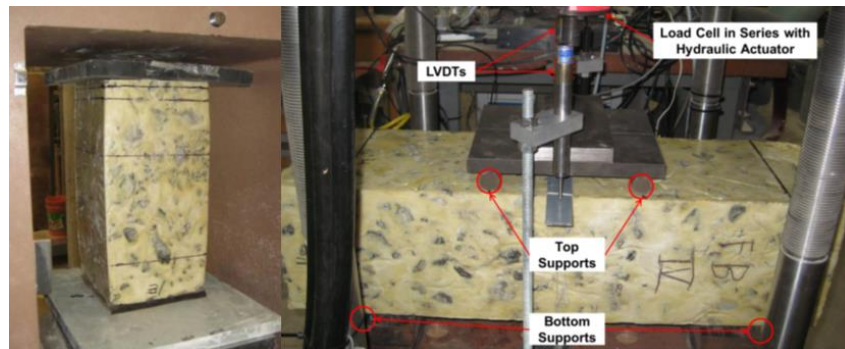

Fig.10 Compression and flexure tests (Andrew Keene, 2012)

Overall, polyurethane reinforcement increases the strength and modulus (stiffness) of ballast, and the stability grows with the polyurethane strength, curing days and content.

3. Bonding method and Application

Polyurethane reinforcement can solve several problems in the following aspects，Lakušić, S (2010) summarized some of the functions, as follows Fig.11 [34].
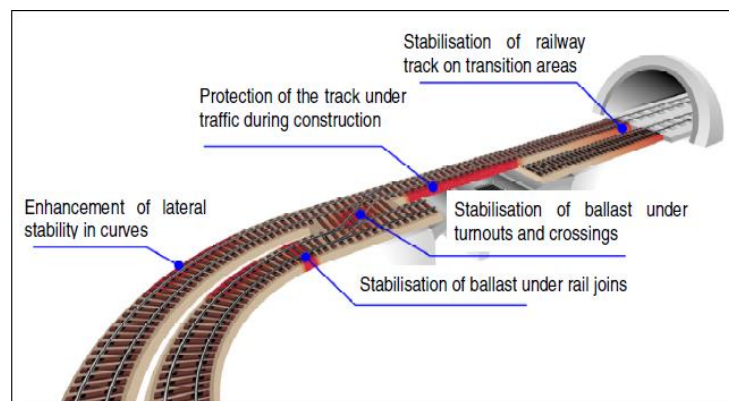

Fig.11 The main functions of polyurethane reinforcement (Lakušić, S, 2010)

Polyurethane bonding optimizes the contact characteristics between ballast and sleeper. For unformed polyurethane which as a stiff boding material, mainly works to improve track stability and durability. the entire functions include ballast flight prevention, enhancement of lateral resistance in curve, tunnels, and station, the stability of ballast under rail joint, turnout bridge and crossings, and adjustment of stiffness in transition zones. Foamed polyurethane as an elastic material, mainly works to improve track force and energy performance considering dynamic load. In addition, polyurethane bonding method according to different research varies from full-section bonding, surface bonding, specific section bonding (by unfoamed

polyurethane) and internal bonding (by foamed polyurethane).

3.1 Ballast flight prevention

When train passes the ballast track at a high-speed (especially above 300km/h) the great difference of air pressure will apply to the surface of ballasted layer. Under the air pressure and vibration, ballast have the possibility to fly, and hit the train or rails, thus affect the safety of train operation [35-38]. Polyurethane can bond the ballast and make its surface fixed. Particle, especially with small size or density, cannot move under air pressure and vibration, thus preventing ballast flight. Ding Dong (2017) demonstrated ballast settlement using polyurethane bonding. A half-structure 1:1 mode is tested in wind tunnel. Results show, after bonding, ballast displacement did not occur when wind speed adding to 30m/s, corresponding to 350km/h train passing [39].

In this prospect, full-section bonding is a method in which all ballast of the track bed are bonded, thus ballast displacement will be restricted. In addition, this method can maximize the track resistance compared to other bonding methods, because all the ballast are bonded as an entire structure. Xiao Hong (2017) illustrated that, after full-section bonding, the lateral resistance can reach to 55.5kN corresponding to 1 mm displacement [40]. In this research, a simulation model based on DEM is set up and analyzed. Results show, after full section bonding, the number of sleeper-ballast contact point is 870, the compression force point is 355 which contributing 72.5% of lateral resistance. Moreover, the tension force pointis 515, contributing 40.8% of total lateral resistance.

However, full-section bonding method largely increases lateral resistance, it should be noticed that this method causes some vital disadvantages, such as large material consumption that creates great initial cost, and wide spraying range leading to maintenance unavailability.

Furthermore, Jing Guoqing (2018) used full-section surface bonding in order to prevent ballast flight, considering maintenance availability, spraying at the surface till the depth of 60mm, as shown in Fig.12. This method is aiming to settle the ballast flight problem so that ballast particles on the surface cannot move due to the bonding method. At the same time, it can increase the lateral resistance by 17%, which is enough to keep track stability. Test showed that full-section surface bonding does not influence the tamping maintenance because of the lower bonding depth [23].
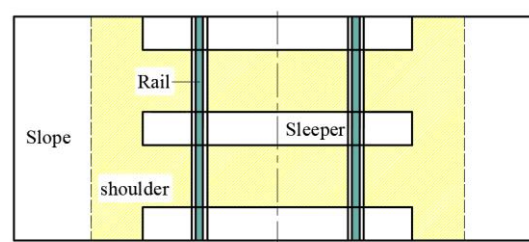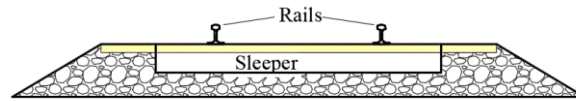
Fig. 12 Full-section surface bonding (Jing Guoqing, 2018)

3.2 Stiffness adjustment (transition zone)

Vehicle transition from a section of ballasted track with higher elasticity to a section of slab track with significantly less elasticity result in vibration amplification effect, which is destructive to the track system. Polyurethane bonding changes contacts between ballast particles. Before bonding, particles contact can be described in occlusal force, friction and pressure. Track elasticity is provided by particle slight movement due to void existence and free-contact. After bonding, those free-contacts are fixed thus ballast working together with the stiffness of the unfoamed polyurethane, the track stiffness is positively related to bonding depth and width increase. Therefore, using different bonding depth and width can make the stiffness gradually changes, consequently, the vibration effect can be decreased, details are shown as follows Fig.13 [34].

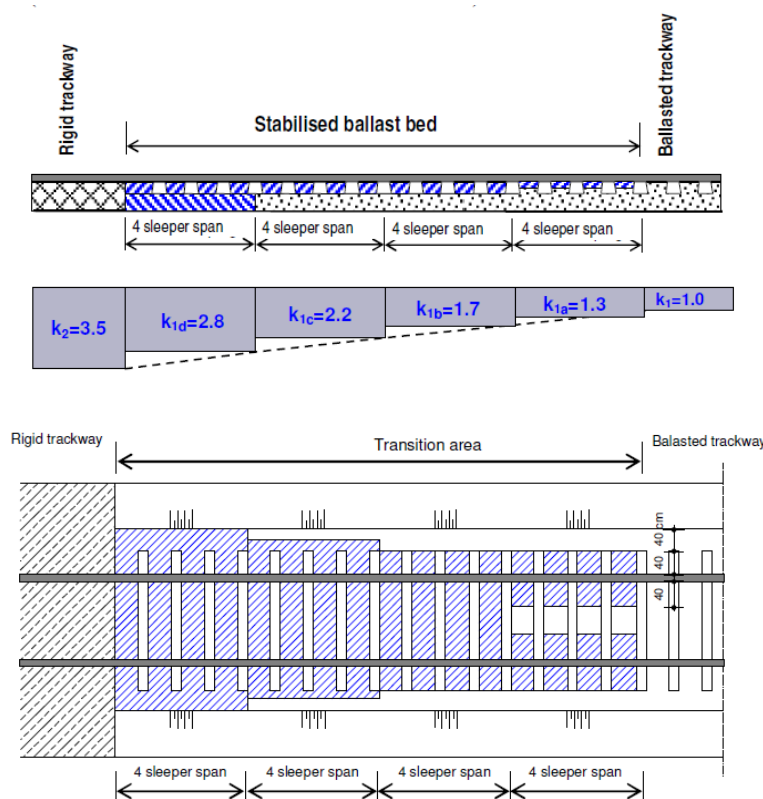Fig.13 Spraying in gradually changing depth at transition zone (Lakušić, S, 2010)

Along with the increase in stiffness, vibration seems to be a problem. CARS tested the vibration acceleration level after the gradual changing bonding method. Results show that the characteristic of vibration of polyurethane reinforced ballasted track is better than slab track, especially in low frequency. Besides, 16.4dB reduction can be found
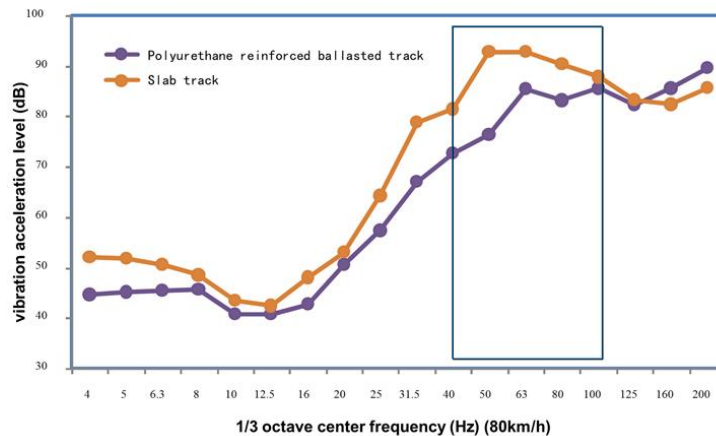
around 50Hz. As shown in Fig.14.

Fig.14 Vibration acceleration (CARS)

3.3 Track stability

The stability of the ballasted track, in some conditions, is not enough to keep safety, moreover, increasing track resistance, force and energy performance are importance. The particular safety problem always occurred in critical area, such astunnels and station line, where ballast depth or width is lower due to the structural approach limit; curve, turnouts and crossing, where track bed bear higher lateral force; bridge and joint, where track faces more frequency vibration. In these sections, elastic and plastic movements of the track substructure can lead to voiding issues within the ballast and hence superstructure movements along with high degree of vibration, which increases the track damage and hence the likelihood of excessive maintenance and/or safety issues rapidly developing.

P K Woodward（2011）[41] used specific section bonding method in station line, spraying polyurethane at the shoulder of track bed, forming a continuous beam (Fig.15 a), thus stabilized the ballasted track. Jing Guoqing (2017) reinforced by spraying at the end of sleeper and crib, increasing the lateral resistance (Fig.15 b) [22].

a)   b)
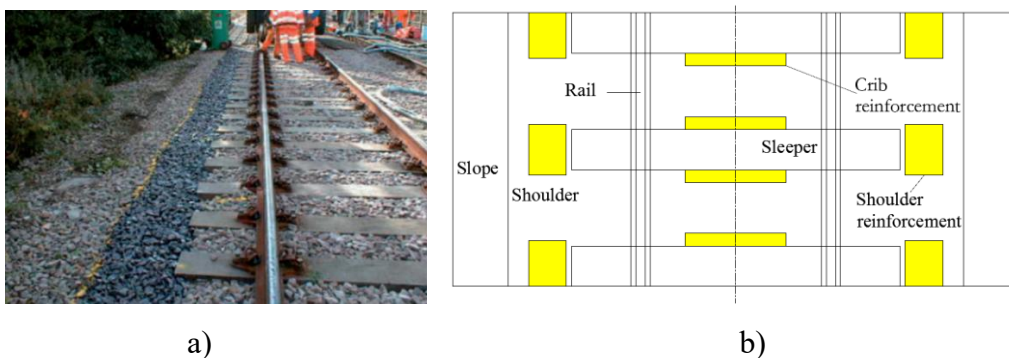
Fig. 15 Specific section bonding
a) By P K Woodward, 2011, b) By Jing Guoqing, 2017

Jing Guoqing (2017) tested the lateral resistance (Fig. 16) with the polyurethane bonding method mentioned above. Results show that after section reinforcement the lateral resistance can be increased from 100% to 184%, depending on different methods (abovementioned: crib, sleeper-end and comprehensive reinforcement) [22] (Table 3).

a)   b)

Fig. 16 Lateral resistance test

a) Counterforce device, b) Displacement supervising (Jing Guoqing, 2017)

Table 3 Lateral resistance after specific section bonding (Jing Guoqing, 2017)

Reinforcement method		Lateral resistance(kN)	Ratio
Without polyurethane		7.05	-
Shoulder reinforcement	200mm	14.09	100%
	300mm	16.07	128%
Crib reinforcement	200mm	13.09	86%
	300mm	14.09	100%
Synthetical reinforcement	200mm	17.08	142%
	300mm	20.02	184%

In the same way with Jing Guoqing (2017), the research of A.A. Kruglikov (2016) also bonding the ballast at sleeper end. Result shows about 168% increase after continuous shoulder reinforcement [42] (Table 4).

Table4 Lateral resistance after specific section bonding (A.A. Kruglikov, 2016)

Ballast prism features	Shift, mm	Applied force, kN
a GeoComposite thinkness is 33mm	23	40.2
b Ballast is not strengthened	24	15.0
c Ballast is not strengthened, no ballast prism shoulder	20	13.5

Reinforcement of the bridge and the tunnel line can be seen in Fig.17 [43, 44].

<table>
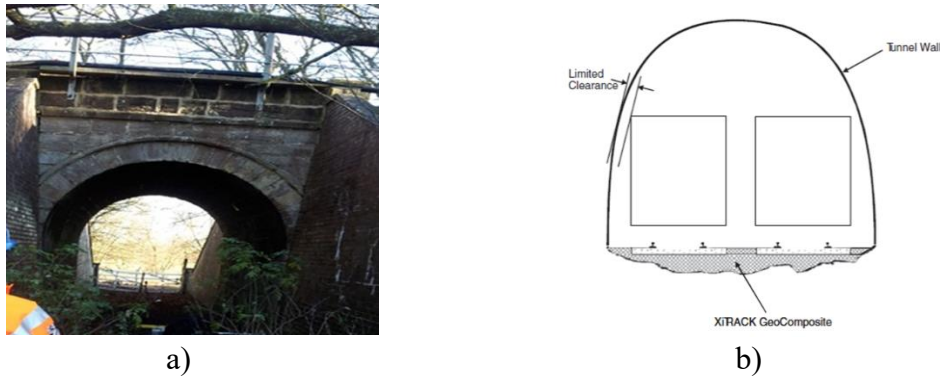<tr><td>a)</td><td>b)</td></tr>
</table>

Fig. 17 Tack stability:
a) Bridge line (Sadiq Thomas, 2015); b) Tunnel (P K Woodward, 2012)

Sadiq Thomas (2015) studied the XiTRACK reinforced ballasted track on bridge line by FEM simulation, results show that the maximum displacement contours without the polymer is 2.1 mm, in contrast, adding a polymer raft with the dimensions as 8m × 3m, at a depth of 300 mm below the sleeper bottom, reduced the contour displacements to 1.8 mm. Besides, polyurethane reinforcement reduced the stress on the crown of the arch from 35 kPa at a load of 150 kN to 25 kPa (i.e. a reduction of approximately 30%). As shown in Fig. 18 [43].

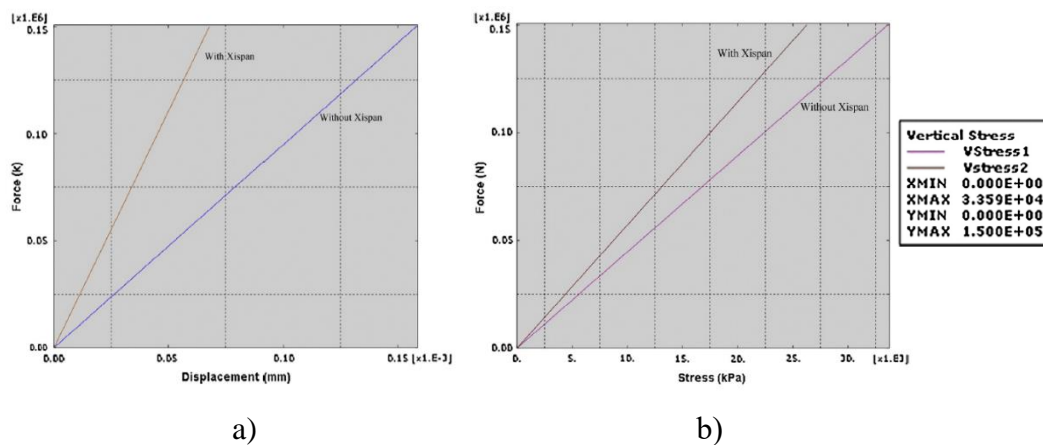a)   b)

Fig. 18 Displacement and vertical stress performance with and without polyurethane above the arch. a) Plot of displacement distribution b) Plot of vertical stress

Xing Ling (2018), using energy method, analyzed the characteristics of polyurethane-ballast based on the field tests and DEM simulations. Results show that there are 4 main forms of energy, including elastic strain energy, viscous strain energy, friction energy and dashpot energy. The elastic strain energy decreased at power rate under the quasi-static load, while the remaining forms of energy decayed exponentially. Four kinds of energy showed exponential attenuation under the trainload. The friction energy and elastic strain energy had a higher proportion on the bottom of sleeper. The viscous strain energy and dashpot energy had a higher proportion on the side of sleeper [45] (Fig. 19).
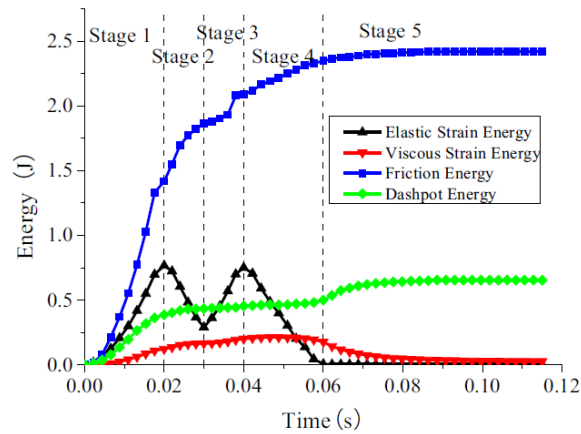
Fig.19 Energy change diagram (Xing Ling, 2018)

Andrew Keene (2013) use RPF (Rigid-Polyurethane Foam) reinforcement method with internal injection as Fig.20 [32]. The internal injection needs three-step construction including the removing ballast above the height of the sleeper bottom, then polyurethane spraying and ballast backfill.

Fig. 20 Internal injection (Andrew Keene, 2013)

This method also is used by CARS in China railway construction using large spraying machine in fig.1 (b), and it is already applied in Shanghai to Kunming high-speed railway construction as a method of ballasted track reinforcement on large-span bridge. Lateral and longitudinal resistance is tested, as follows Fig. 21.

Fig. 21 Lateral and longitudinal resistance tests (CARS, 2017)

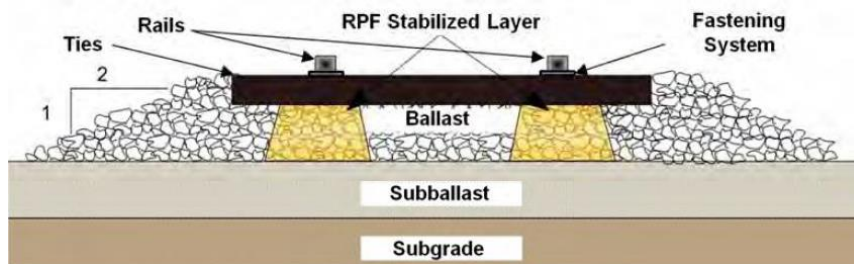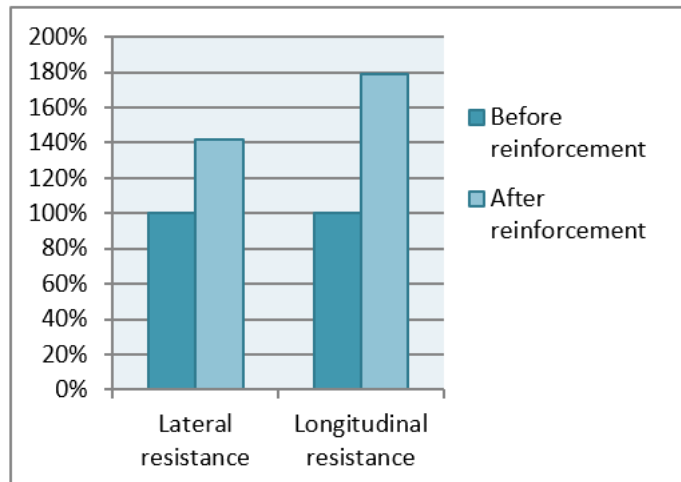In addition, Andrew Keene (2013) conducted cyclic triaxial tests and simulation of the track response based on FEM using RPF foam. Polyurethane-stabilized ballast (PSB) showed a significant reduction in accumulation of plastic strain during cyclic triaxial tests but also displayed a somewhat lower resilient modulus than the host ballast modeling [33] (Fig. 22).
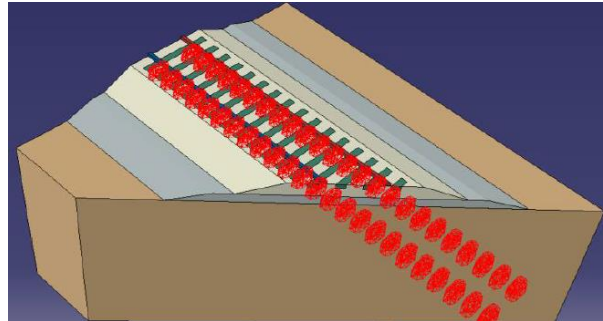
Fig.22 FEM simulation (Andrew Keene, 2013)

CARS tested the accumulated deformation influenced by train passage, results show that after polyurethane reinforcement, the deformation largely decreased, as follows Fig. 23. After foamed polyurethane reinforcement, the accumulation deformation of high-speed and heavy haul railway shows similar trend. Whereas, before reinforcement, the data of heavy haul was much bigger. As a result, polyurethane increases the transportation capability and prolongs the life of ballasted track.

Fig. 23 Accumulated deformation- total passage curve (CARS)

3.4 Settlement

J. Kennedy (2013) analyzed permanent settlement after foamed polyurethane reinforcement by dynamic loading test. Results predicted settlement curve which highlights the significant reduction in track settlement (99% over 500,000 cycles or 18.5MGT) that can be achieved using polymer reinforcement of the ballasted track [46] (Fig. 24).
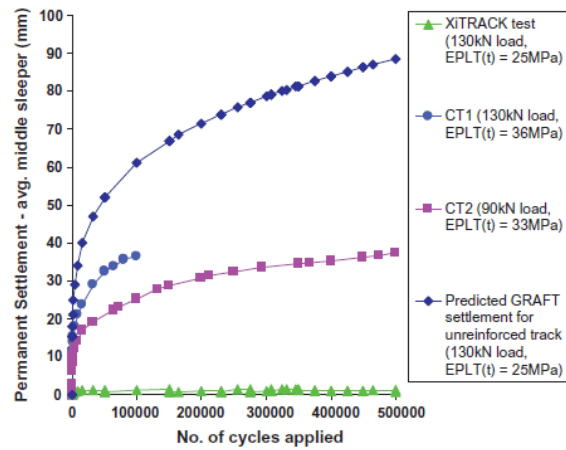
a)   b)

Fig.24 Dynamic load test
a) GRAFT (Heriot-watt University), b) Settlement test result (J. Kennedy, 2013)

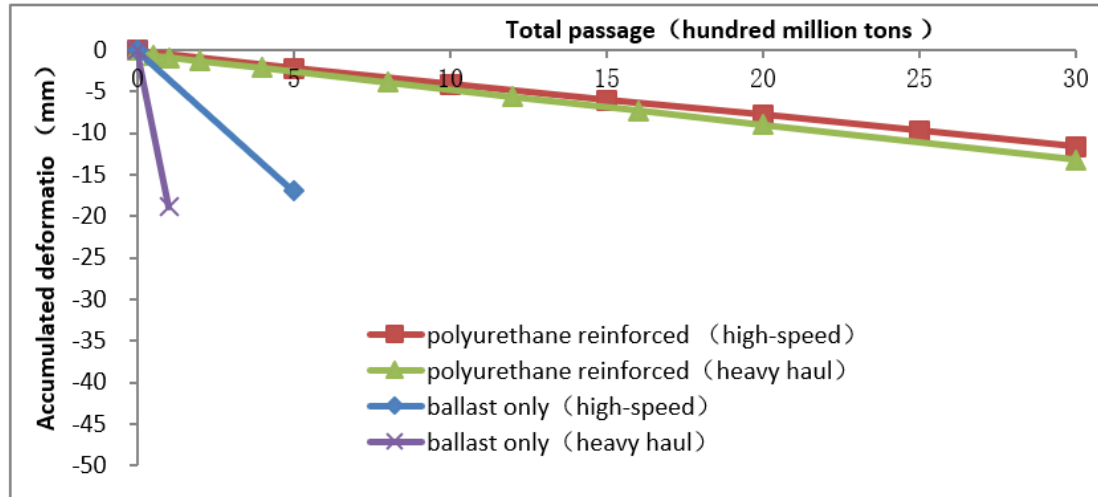P K Woodward (2014) also using GRAFT which showed a marked increase in track stiffness when the polymer was applied. It is likely that the improvement was around 40% for the particular polymer, loading level and ballast depth applied [47].

3.5 Others
The usage of polyurethane in railway not just confined to ballasted track, but also in other application such as Neoballast made by sticking rubber particles on the cover of ballast by polyurethane. This environmental friendly innovation can reduce ballast degradation, compared to the normal ballast, about 15% decrease in LAA can be observed. As a consequence, ballast lifespan is extended. In addition, rubber which is an elastic material, improving noise and vibration performance of the track [48] (Fig. 25).

Fig.25 Neoballast (by COSMA, MAPEI, UPC, ADIF, 2015)

4. Summary of present research

Table5 Summary of present researches

Organization	Author	Year	Keyword	Method
Unfoamed polyurethane reinforcement				
Heriot-watt university (HWU)	P K Woodward [41,44,47,49,51]	2007-2014	Xi Track three-dimensional track reinforcement, bridge, station and tunnel line, crossing and turnouts, shoulder reinforcement, track response, settlement	FEM simulations, box tests (GRAFT), Application analysis
	Sadiq Thomas [43]	2015	Xi track, masonry arch bridge reinforcement	FEM simulations
University of Zagreb	Stjepan Lakuši [34]	2010	Reinforcement function, Stiffness adjustment	Application analysis
University of Illinois at Urbana-Champaign (UIUC)	Dersch S. Marcus [21]	2010	Elastotrack (from BASF), shear strength, aggregate breakage and degradation	Direct shear tests, powdering tests
China Railway 23th Bureau Group CO,. LTD	Yang Jianming [50]	2011	Stiffness adjustment in transition zone	Support stiffness test
Beijing Oriental Yuhong Waterproof Technology Co.Ltd	Li Hongying [23]	2013	Chemical and solidification characteristics	Laboratory tests
Massachusetts Institute of Technology (MIT)	Sakdirat Kaewunruen [52]	2014	Dynamic responses, bridge end	In-situ vibration suppression
China Academy of Railway Sciences (CARS)	Industrial standard [25]	2014	Technical requirements, test method, inspection criterion, construction, package and transportation.	Based on tests and operation
	Wang Hong [53]	2015	Transition adjustment, bonding effect	Application analysis
	Qie Luchao	2017	Maintenance method, deformation, stiffness, lateral resistance, deterioration, bridge line, spraying machine(train),	Full-scale cyclic loading tests, lateral and longitudinal resistance tests, in-situ stiffness tests
Beijing Jiaotong university (BJTU)	Jing Guoqing [22, 23]	2015-2017	specific section bonding, surface bonding, tamping availability, ballast flight prevention, compression strength	Lateral resistance tests, uniaxial compression tests
	Xiao Hong [40]	2017	full-section bonding	Lateral resistance tests and DEM simulations

	Xing Ling [45]	2018	energy method	Field tests, DEM simulations
Rostov State Transport University	A.A. Kruglikov [42]	2017	Shoulder reinforcement	Lateral resistance
Korea Railroad Research Institute	Su Hyung Lee [31]	2017	Strength, stiffness, estimated equations	Large-scale triaxial test
Foamed polyurethane reinforcement				
University of Wisconsin–Madison (UW-Madison)	Andrew Keene [24,32,33]	2012-2013	Rigid Polyurethane Foam (RPF) to, Internal injection, compression strength, plastic and elastic deformational Behavior	Compression tests, monotonic and cyclic flexure tests
University of Pretoria (UP)	R F du Plooy [54,55]	2016-2017	RPF, settlement, resilient modulus	Cyclic loading ballast box tests
Other use or material				
Goldschmidt-Thermit-Group	Company brochure [26]	2007	GREBOPOX®/ AgriTec® EWR-Winter (epoxy resin), ballast stabilization	Application analysis
COSMA, MAPEI, Universitat Politècnica de Catalunya (UPC), ADIF	Consortium report [48]	2015	Neo-Ballast, recycled rubber	Application analysis
The University of Nottingham	G. D'Angelo [27-29]	2016-2017	Bitumen reinforcement	Laboratory tests

5. Challenge and Solution

Through present research and application, polyurethane reinforced technique still has some challenges, mainly in cost, maintenance, drainage, and construction.

5.1 Cost

Polyurethane is a kind of expensive material so that the cost of full-section reinforcement can equal to the cost of ballast, nearly 150 thousand (EURO) per kilometer, and its high price restricts to polyurethane ballasted track application. However, spraying method innovations provided a new thought such as reinforcing the most variable part instead of whole section. For example, using specific section bonding by Jing Guoqing, the cost of polyurethane can be reduced more than 70%, comparing to full-section bonding. Besides, the specific bonding methods are flexible to select according to construction conditions, thus avoiding the disadvantages of polyurethane abuse, such as excess stiffness increase.

Secondly, one cost reduction method is prefabrication the polyurethane-ballast unit in factory, and transported to construction site. The method avoids employing the usage of special train for polyurethane ballasted track injection, which is quite expensive.

Last, recycled rubber crumb are used into the polyurethane ballasted track with aim to reduce the volume of polyurethane.

5.2 Maintenance

Maintenance availability or how to carry daily maintenance is a main problem of polyurethane reinforcement, due to the high bonding strength and wide spraying area, especially for full-section bonding. In contrast P K Woodward (2011), A.A. Kruglikov (2016), Jing Guoqing (2017,0218) proposed to use specific section reinforcement method which already shows its maintenance availability, as mentioned above [22,23,35,36].

Furthermore, some kinds of methods which can avoid or settle this problem are put forward. CARS developed a geometry adjust method, as shown in Fig.26. This maintenance method includes 4 processes. First, lift the rail and sleeper to a designed height, second, place the model and filling in ballast by ballast-blowing machine, third, pouring polyurethane, and last, dismantle the model after solidification. Along with the height adjustment of fasteners, geometry problems in operation can be settled.
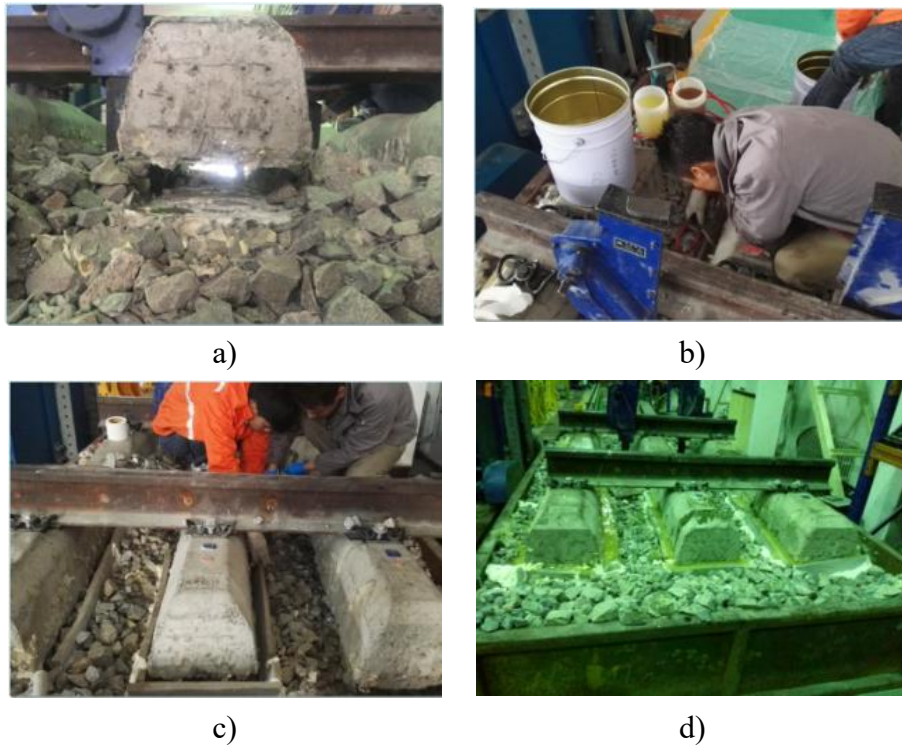
Fig.26 Geometry adjustment method
a) Lift the rail and sleeper to a designed height, b) Place the model and filling in ballast, c) Pour polyurethane, d) Dismantle the model after solidification

Moreover, the dismantlement in some occasions is needed, especially on how to treat polyurethane-ballast with no toxic substance waste. However, French researchers developed a kind of organic ballast polyurethane which can degrades with no poison residual under natural condition, most of ballast glue materials still made out of polyurethane.

Lastly, recycling of polyurethane ballasted track. The method used by CARS is cooperated with chemical industry, after removing polyurethane-ballast form track, polyurethane-ballast will be sent to the separation equipment, by which big block is crushed into small particles, then transporting those particles to cycling center (or mobile equipment), in this process, thermal degraded actions clean the polyurethane cover of ballast, and gas emissions can be treated by exist chemical method with no harmful waste. As shown in Fig.27 [56].
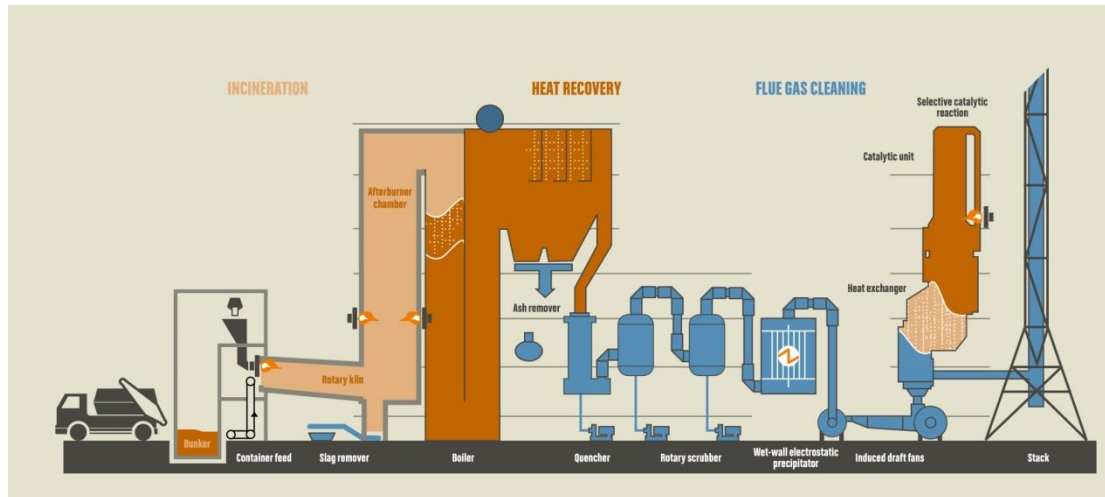
Fig. 27 Treatment method of polyurethane-ballast (CURRENTA)

5.3 Drainage

Another problem is drainage of ballasted track. Under dynamic loading, water related pumping effect which is vital to safety. For unfoamed polyurethane, the bonding function shown in Fig.2 can prove that this kind of reinforcement does not affect drainage. At the same time, Jing Guoqing (2012) tested the drainage property of polyurethane-ballast cubic specimen, and got the same result [3]. However, the spraying condition should be free of water strictly. As for foamed polyurethane, there is no research that illustrates its drainage property.

5.4 Construction

Finally, construction time restrict train operation, especially for maintenance. The hardness process of polyurethane needs approximately 15 to 30 minutes, although catalyzer can adjust to a shorter time, the spraying instruments do not allow due to the possibility of pipe get bonded. This means after spraying, speed of passage should be declined adopted with, thus affects operation. To solve this problem, prefabrication seems to be a good way. Ballasted track can be constructed by prefabricated polyurethane-ballast blocks and straightly changing those blocks can be a maintenance method.

6. Conclusion

Polyurethane reinforced ballasted track has shown great application prospect, becoming a new kind of track type and attracted researcher's attention. This paper concludes current outcomes, analyses the characteristic of polyurethane and polyurethane-ballast, and introduces the function/application of polyurethane reinforcement. Besides, challenges and possible solutions are put forward. Main

conclusions are as follows:

(1) Polyurethane used in railway system has two types, i.e. foamed and unfoamed materials, and both contain two components. When components of A and B mixed 1:1 by volume, chemical reaction occurred, thus bonding ballast particles.

(2) Polyurethane solidification is within 15-30 minutes, but it will take 7-day or longer to reach the final strength, whereas catalyzer can help speeding up this process.

(3) Polyurethane spraying methods including 4 kinds. full-section bonding can increase track stability with the maximum ratio between different methods, but without tamping ability. In contrast, specific section, surface and internal bonding solve or avoid tamping problem.

(4) polyurethane bonding optimize the contact characteristics between ballast and sleeper, the entire functions including the ballast flight prevention, enhancement of lateral resistance in curve, tunnels, and station, stability of ballast under rail joint, turnout, bridge and crossings, and adjustment of stiffness in transition zones.

(5) By far, challenges about cost, maintenance availability, drainage and construction restrict the application of the polyurethane reinforcement. However, some of those problems are settled, further researches are still needed to improve the polyurethane-ballasted track.

Acknowledgments

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