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Ballast Stabilization with Polyurethane for Use in Desert Areas

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Abstract

Sand dune accumulation in the railways passing through desert areas leads to ballast softening and settlement, which is one of the major challenges in the ballast maintenance operation. In this regard, ballast infilling with polyurethane could be mentioned as a novel solution that has been less attentional in previous studies. In this matter, in present study using a domestic cost-effective polyurethane, the ballast stabilization has been accomplished and the relevant shear strength parameters have been investigated via a series of large-scale direct shear tests. Since the utilized polyurethane has composed of two different components, in the first stage, the best weight ratios of components have been investigated via a series of compression tests. In this matter, the ratio of 1.5 units polyol to 1 unit isocyanate has been adopted as the best composition. Then, the resulting polyurethane was injected into the ballast to perform large-scale direct shear tests. According to the measurement results, the maximum shear stress, the internal friction angle, and the cohesion coefficient increased by 109%, 9.5%, and 162.5% with respect to the non-stabilized ballast (NSB), respectively. In addition, the dilation angle decreased by 66.4% with the injection of polyurethane into the ballast. Hence, the results indicate increased shear strength and lateral track resistance in the presence of polyurethane, which can prevent lateral deflection and improve track safety. In other words, the mentioned polyurethane has improved the shear parameters of the ballast more significantly than other polyurethanes and has shown its performance in increasing the bearing capacity.

Keywords

ballasted tracks, shear strength, polyurethane, direct shear test, sandblasted tracks

1 Introduction

One of the main tasks of the ballast layer is to create lateral and longitudinal resistance of railway tracks [1]. The infiltration of sand material into the ballast surface is the most common cause of ballast contamination in desert areas. This is a major problem in some parts of the southern part of the United States, South American, Africa, Asia, and the Middle East, where many sandstorms occur in these areas [2–6]. Sand contamination causes track deterioration in sandy areas and impairments in track performance. Some of these disturbances entail covering superstructure, comprising fully-fouled ballast layer, blocking of the railway track (Fig. 1(a)), damaging the sleepers (Fig. 1(b)), communication disconnection, disturbance in the ballast drainage (Fig. 1(c)), corrosion of rails, and turnout (or switch) movement disruption [7, 8]. Most importantly, it significantly reduces the shear and vertical resistance of the ballast. Decreasing the shear strength causes the loss of lateral resistance of the track, more track roughness, more rail wear, and increased derailments, especially at crossings and turnouts.

Two general measures taken to solve the problems of sandy areas can be classified into non-structural and structural solutions. The examples for the first category we can note the use of Rocky checkerboard sand barrier, used for arid and semi-arid areas, and is mainly used to keep the sand far from the railway (Fig. 2(a)), or the Sand-blocking fences designed using the local wind pattern, the holes of which prevent the sand from moving towards the railway track (Fig. 2(b)). As another example, the Sand-deviating boards that change the direction of sand movement (Fig. 2(c)), a wind-weaken leaf with many pieces of leaf-shaped concrete that reduce wind speed (Fig. 2(d)) [8].

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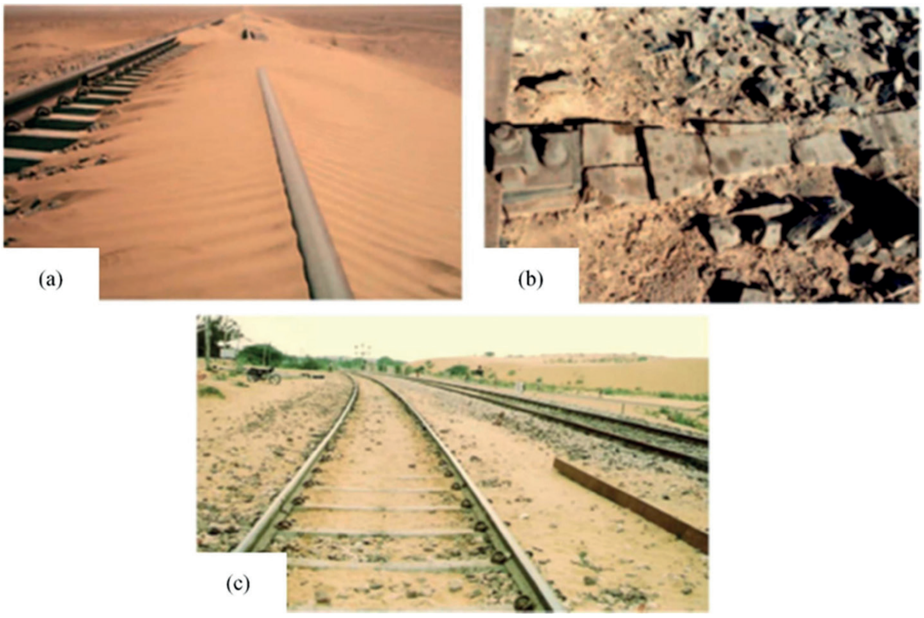


Fig. 1 Difficulties associated with railway tracks in desert areas: a) accumulation of sand over the track surface; b) sleeper deterioration; c track drainage malfunction [7, 8]

Fig. 2 a) Rocky checkerboard sand barrier; b) sand-blocking fence; c) sand-deviating board; d) wind-weaken leaf [8]

Alternatively, some structural modifications have also been applied to railway tracks so far. For instance, using a humped slab track, which by removing the ballast layer in the pavement, solves the problem of ballast layer stiffness caused by the movement of quicksand. Moreover, the rail seats of this superstructure were raised above the level of the slab, using reinforced concrete protrusions called bumps (Fig. 3(a)) [9]. The second solution is the use of slab tracks with elevated rail seats, in which the ballast layer is removed, thus preventing the accumulation of sand debris inside the slab track (Fig. 3(b)) [7]. Furthermore, as shown in Fig. 3(c), the installation of TurbFly systems alongside the rail turnouts is another effective method [10].

Utilizing the mentioned methods improved the environmental conditions surrounding the ballasted track, whereas no improvement was observed in the characteristics of

Fig. 3 a) sleepers with elevated rail seats; b) slab track system with elevated rail seats; c) TurbFly brushes installed next to the rail track [10]

ballast and stabilization it. Therefore, some methods should be considered to improve and treat the ballast and reduce the number of performed ballast maintenance operations. One of which is the use of polyurethane materials that are a type of polymer [11], composed of molecules with two or more isocyanate groups and polyol molecules with two or more hydroxyl groups and are produced as compact, soft (cushiony), semi-rigid (flexible), or rigid (stiff) foams [12]. PU chemistry was discovered in the 1930s by Bayer et al. [13] These materials were developed rapidly and became widespread worldwide due to their special mechanical properties [14]. Some polyurethane materials applied to improve ballast performance are rigid polyurethane foam (RPF) made by Bayer Material Science, Elastotrack made by BASF, and XiTRACK made by DOW [12, 15, 16].

Polyurethanes can be injected in the ballast track, especially in areas, including curves, bridges, tunnels, stations, and crossings [17], through the void between ballast aggregates to penetrate the ballast depth and by creating a bond between these aggregates, ballast performance improves. They can be used for injection in different ballast components (i.e., shoulder ballast, ballast bed, crib) and it can be efficient. These materials either bond at the points where the ballast aggregates are in contact with each other, in which case there will still be empty space between the ballast aggregates, or they fill the entire empty space between the ballast aggregates, in which case the penetration of sand and water in the track and ballast contamination is prevented, through creating an integrated structure in the ballast tracks [18–20]. Also, the level of the upper surface of the track is applied like a slab track with a mild slope to the outside so that the surface water and rainwater are directed to the water streams and the drainage problem of the track is solved.

Various studies have been performed about the polyurethane-reinforced ballast (PRB), one of which was the research of Woodward et al [21]. They showed that changing the ballasted track structure to a set of sand, Geotextile, XiTRACK-reinforced ballast, and non-stabilized ballast (NSB) caused a 36% reduction in track deflection in the treated zones, decline in track vibrations, and increase in track speed. In another study, Kennedy et al. [22] investigated the settlement of each track sample against the number of load cycles (up to 500,000 cycles). These authors found a 99% decrease in track permanent settlement in the presence of XiTRACK presenting the slab performance (made the track performance elastic). Moreover, this study reported a 53% improvement in path stiffness using ballast reinforcement with polymer Geocomposite, which was concluded through three-dimensional elastoplastic finite element analysis. In addition, Woodward et al. [23]. In a study found that by monitoring the track under a maximum of 500,000 load cycles, a 40%–50% elevation was achieved in track stiffness by reinforcing the ballast with polyurethane.

They stated that the evaluation of road stiffness by another measuring technique and on another soil, demonstrated that, this parameter rises in the presence of polyurethane. For this reason, they stated that the track stiffness is independent from the soil type and the measurement technique. Furthermore Jing et al. [24] performed a series of laboratory tests in which they introduced three zones of ballast for polyurethane injection and examined the effect of using polyurethane in these zones on the lateral ballast resistance. According to the results, by reinforcing the shoulder, crip, and both the shoulder and crip ballast by polyurethane with bonding depth of 200 mm from the top surface, lateral resistance force increased 100%, 86% and 142%, respectively. Moreover Jing et al. [25] stated in a literature review that reinforcing the entire ballast surface by polyurethane with bonding depth of 60 mm from the top surface can prevent ballast flight and it can increase the lateral resistance of the ballast by 17%. Jing et al. [16] also stated in another review paper that according to a FEM simulation, reinforcing a ballasted railway bridge with polyurethane reduced stress on the crown of the arch by approximately 30%. In another study, Woodward et al. [26] injected polyurethane into the shoulder ballast and created an equivalent polyurethane wall to rapidly improve the lateral passive resistance of the railway track. The results showed a significant increase in the lateral passive resistance, especially in switch and crossings.

In addition to stiffness and lateral resistance, another critical parameter in the ballasted tracks is their shear behavior. The direct shear test is used to evaluate the maximum shear stress of granular materials. The standard direct shear apparatus is not designed based on the grain size of the ballast. Consequently, various researchers attempted over the years to enhance the performance of this apparatus as much as possible to be utilized on ballast material by altering the apparatus dimensions [5]. Boler [27] performed direct shear tests on polyurethane coated ballasts using Elastotrack technology and concluded that the friction angle and cohesion coefficient in polyurethane-coated granite ballasts (with curing period of 1 day) decreased from 40.7° to 29.3° and increased from 0.097 MPa to 0.201 MPa, compared to granite ballast without polyurethane, respectively. Research of Dersch et al. [28] in this field showed the highest shear strength between non-stabilized and polyurethane-coated ballast specimens for the 14-day treated sample among 1,3,7, and 14-day curing periods and under normal stresses of 0.17 and 0.24 MPa. It is equal to 0.73 MPa, which is almost twice the shear strength of the non-stabilized sample under normal stress of 0.24 MPa.

As a summary of the above studies, the sand dune accumulation in railways has caused significant problems for the ballast maintenance in the desert areas. The proposed solutions for these problems have mostly been employed to prevent the sand penetration into the ballast railway tracks, although these just have balanced the penetration rate, extended intervals between the maintenance operations, and have not improved ballast properties. Notably, these operations themselves, however, cause damage to the ballast. Therefore, in the present study, as a novel and lesser studied solution, the polyurethane injection in the ballast railways is proposed to fill the space between ballast grains to completely prevent the sand penetration in one hand, and on the other hand, to improve ballast properties and make it maintenance free by creating an integrated and sustainable structure. For this purpose, the truck's air filter polyurethane (TAFP), economic and domestic, was injected into the ballast in this study.

It should be noted that there is no easy access to the polyurethane materials used in most countries, and due to their nature, their properties are different from each other. However, the TAFP unlike other polyurethane materials used in the ballast track, is easily available and used as a raw material for air filters of trucks. This polyurethane with its unique properties has been used in the present study for injection with the aim of improving the shear parameters of ballast track, and then compared to other polyurethane materials used in the railway industry for the first time and its results were presented.

Moreover, the effect of TAFP injection on the internal friction angle, cohesion coefficient, dilatancy angle, shear modulus, shear strength (maximum shear stress), and shear behavior was evaluated by direct shear tests under the normal stresses of 0.05, 0.1, and 0.15 MPa and its results were presented. It should be noted that, large-scale direct shear apparatus was used to perform the above tests due to closer test conditions to the existing real and field conditions and its higher accuracy [5]. To find the acceptable mixture of polyol and isocyanate for making the required polyurethane, first, small polymer samples with diverse weight ratios were made from the two mentioned components, and some of them were removed due to their non-functionality. Next, cubic polymer samples were made with the remaining ratios and some of them were selected based on compression test results. Finally, polyurethane-reinforced ballast (PRB) cylindrical specimens with selected ratios from the previous step were subjected to compression tests to select the final and acceptable ratio (Fig. 4).

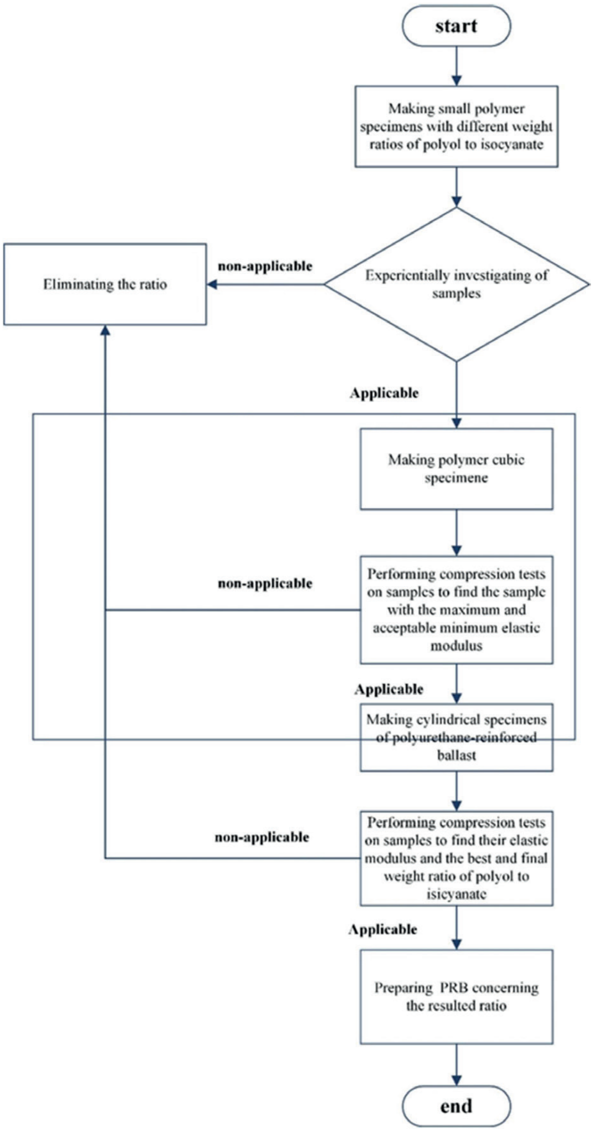


Fig. 4 Flowchart of finding the best weight ratios of polyol to isocyanate

2 Materials and methods

2.1 Ballast specifications

In this study, the andesitic ballast of Shahriar mine was selected by group 1 granulation from Code 301, the granulation curve of which is shown in Fig. 5 [29]. Table 1 shows the results of the UCS tests for the ballast mother rock of Shahriar mine based on ASTM D3148 [30–33]. Table 2 demonstrates the findings of ballast physical and mechanical properties according to the relevant standards [34–38].

2.2 Polyurethane specifications

The selected TAFP is composed of two components called K-FLEX 5534 (polyol) and Kabonate-420K (isocyanate), mixed in a certain weight ratio according to the target property. From the environmental point of view, each of the two independent components is harmful to the environment, but after combining with each other, this problem is solved, and the resulting polyurethane is compatible with nature. Table 3 [39] summarizes the specifications of the polyurethane used in this study.

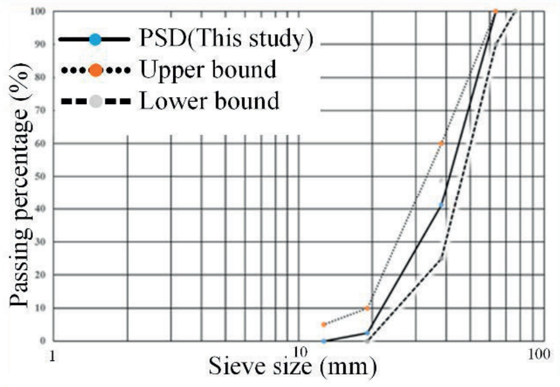


Fig. 5 Ballast gradation curve of group 1

Table 1 UCS test results of ballast specification mother rock [30]

Average dimensions of samples					The results of the Uniaxial compression test of the ballast samples		Elastic modulus and the Poisson ratio of ballast samples		
Ballast type	Relevant standard	Diameter (mm)	Height (mm)	Diameter/height	Relevant standard	Uniaxial resistance (MPa)	Relevant standard	Young modulus (MPa)	Poisson ratio
Shahriar	ASTM D4543 [32]	66.58	144.67	2.17	ASTM D2938 [33]	158.95	ASTM D3148 [31]	0.03	0.20

Table 2 Mechanical properties of ballast aggregates

Test name	Relevant standard	Standard limits	Results of the test
Test Method for Materials Finer than 75-µm (No. 200)	ASTM C117 [37]	≤ 1%	0.34%
Test Method for Clay Lumps and Friable Particles in Aggregates	ASTM C142 [38]	≤ 0.5%	0.17%
Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles apparatus	ASTM C535 [36]	≤ 30%	27%
Test Method for Relative Density (Specific Gravity)	ASTM C127 [35]	≥ 2.6%	2.83%
Test Method for Absorption of Coarse Aggregate	ASTM C127 [35]	≤ 1%	0.78%
Test Method for Bulk Density	ASTM C29 [34]	–	1570 (kg/m)

Table 3 Specifications of the TAFP components [39]

Polyol Name	K-FLEX 5534
Isocyanate Name	Kabonate-420K
Polyol density (kg/m^3)	1012.4
Isocyanate density (kg/m^3)	1176
Tank temperature (°C)	20–35
Cream time (S)	20–35
Free rise density (kg/m^3)	400000–420000

2.3 Polyol and isocyanate mixture design

The first part of this study was devoted to finding an appropriate and acceptable mixture of polyol to isocyanate to obtain an efficient and as cost-effective ratio as possible. To do this, in the first step, as shown in Fig. 6, distinct weight ratios of polyol to isocyanate, including 1:1, 1.5:1, 2:1, 2.5:1, 3:1, 4:1, 4.5:1, 5:1, 5.5:1, and 6:1, were made and experientially investigated to select the weight ratios required for the next step.

In the second step, Cubic polymer specimens with dimensions of 20 × 20 × 20 mm were made to achieve the optimal weight ratio. (Fig. 7), and compression tests were performed on all of them based on ASTM-D575 [40].

Finally, PRB cylindrical specimens were made with ratios obtained from the previous step to achieve the final weight ratio for ballast injection. For making these specimens, the molds were P.V.C with a diameter of 100 mm and a height of 200 mm, and the ballast was the grade of group 1 of Code 301 (Fig. 8). Next, cylindrical samples were subjected to compression test according to ASTM C39 [41], after 24 hours of injection.

3 Direct Shear Tests

3.1 Test setup

The large-scale shear box machine in the school of Railways Engineering of Iran University of Science and Technology designed for ballast materials consisting of two boxes was used in this study. The lower box has the dimensions of 540 × 440 × 180 mm, and the upper box is 440 × 440 × 180 mm (Fig. 9) [5].

To make an NSB sample, by considering the bulk density of samples and the shear box dimensions, 122 kg of ballast samples were prepared and poured in two layers in each box and compacting each layer 25 times by a 7.8 kg metal hammer to achieve the reference density (Fig. 10) [42].

To make a PRB specimen, ballast was poured into the shear box similar to the method of making NSB. Then polyurethane consisting of 1.5 units of polyol and 1 unit

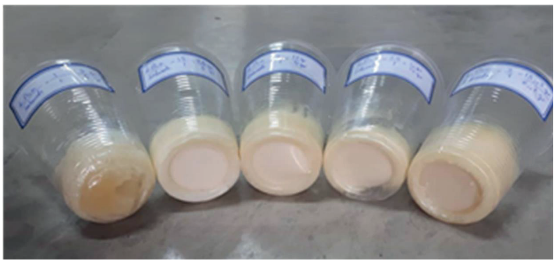


Fig. 6 Initial ratios

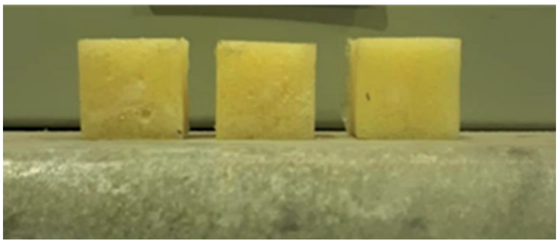


Fig. 7 Cubic polymer specimens

Fig. 8 PRB cylindrical specimens

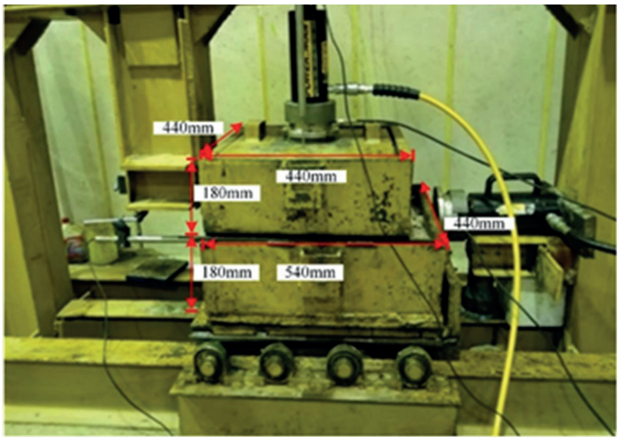


Fig. 9 Shear box apparatus

Fig. 10 Compacting ballast layers in shear box in superstructure laboratory

of isocyanate was injected into the ballast, to penetrate into the pores between the ballast aggregates and form an integrated layer.

Finally, the sample then was tested in the shear box after 24 hours. The shear strength test for soil materials is available according to ASTM D3080 [43]. For this purpose, first, the normal stresses of 0.05,0.1 and 0.15 MPa were reached to the desired values based on the applied stress to the ballast in the railway track after preparing the specimen [44]. Afterward, the horizontal load was applied so that the strain of the specimen changes at a rate of 1% strain per minute. The vertical load was also kept constant during the test. Note that the loading continues until either the applied horizontal load decreases despite the continuation of loading or the horizontal displacement of the specimen reaches 15% of the specimen length, which will be a sign of the specimen shear collapse [5, 43]. Finally, the data were recorded by a data logger.

4 Results and discussion

4.1 Polyol and isocyanate optimum mixture

Initially, the 1:1 ratio was not accepted because it was not set even after several days. In addition, the high softness of the ratios 4.5:1 and above was the reason for the rejection of these specimens. Therefore, other ratios were selected for consideration in the next step.

On the other hand, based on the results of compression tests performed on cubic specimens (Table 4 and Fig. 11), the ratios of 1.5:1 (with maximum elastic modulus) and 3:1 (with acceptable minimum elastic modulus) were selected for review in the next step. Furthermore, the ratio of 4:1 was eliminated as the result of a very low elastic modulus. The ratios of 2.5:1 and 2:1 were removed due to the proximity of its elastic modulus to the elastic modulus of the 1.5:1 ratio.

Table 4 Test Results of cubic polymer specimens

weight ratios of polyol to isocyanate	The elastic modulus (MPa)
1.5:1	0.047
2:1	0.045
2.5:1	0.043
3:1	0.016
4:1	0.0088

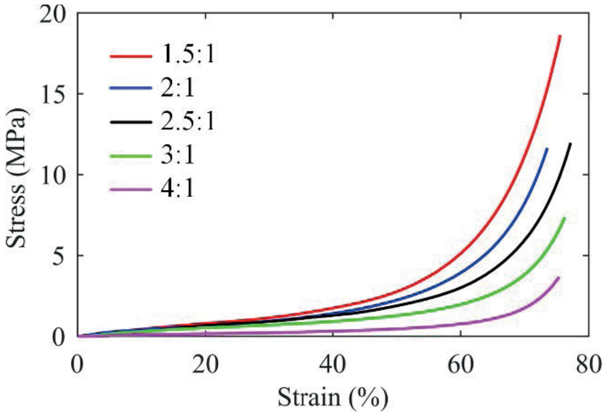


Fig. 11 Stress versus strain curve of cubic polymer

As shown in Fig. 12(a), based on the test results of cylindrical specimens (Fig. 13, Table 5), the ratio 3:1 was not accepted due to its rapid rupture in the lower pressure force Therefore, the ratio of 1.5 units polyol to 1 unit isocyanate was selected and used for the shear box tests (Fig. 12(b)).

4.2 Ballast Shear Strength

In this study, a large-scale direct shear test was performed to investigate the shear behavior of ballast when reinforced with TAFP. The shear stress versus shear strain curves for NSB and PRB under three normal stresses of 0.05, 0.1 and 0.15 MPa are shown in Figs. 14(a), (b) and (c), respectively. In these curves, the shear stress versus shear strain, regardless of the type of specimens, first increases to achieve a maximum value and then gradually diminishes due to failures in the specimen [5]. The maximum shear stress is considered as the shear strength [44].

According to the maximum shear stress values of the specimens shown in Fig. 15, it can be seen that the shear strength of ballast under three normal stresses of 0.05,0.1 and 0.15 MPa increased by 109%, 64.7%, and 52.4%,

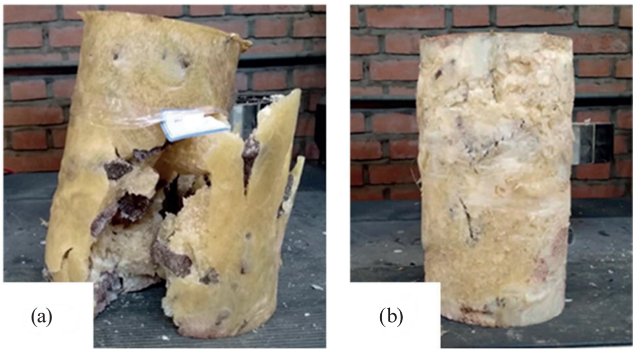


Fig. 12 Cylindrical specimens of ratio a) 1.5:1 and b) 3:1 (polyol to isocyanate) under pressure test

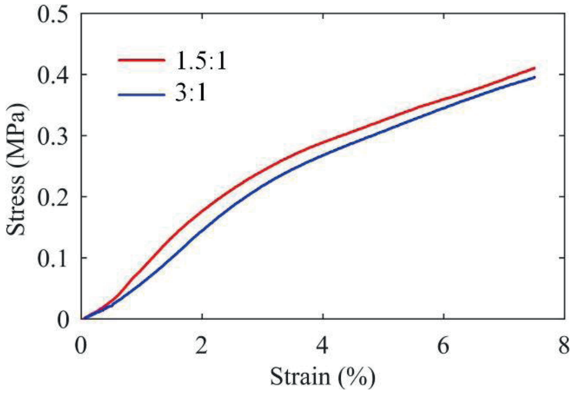
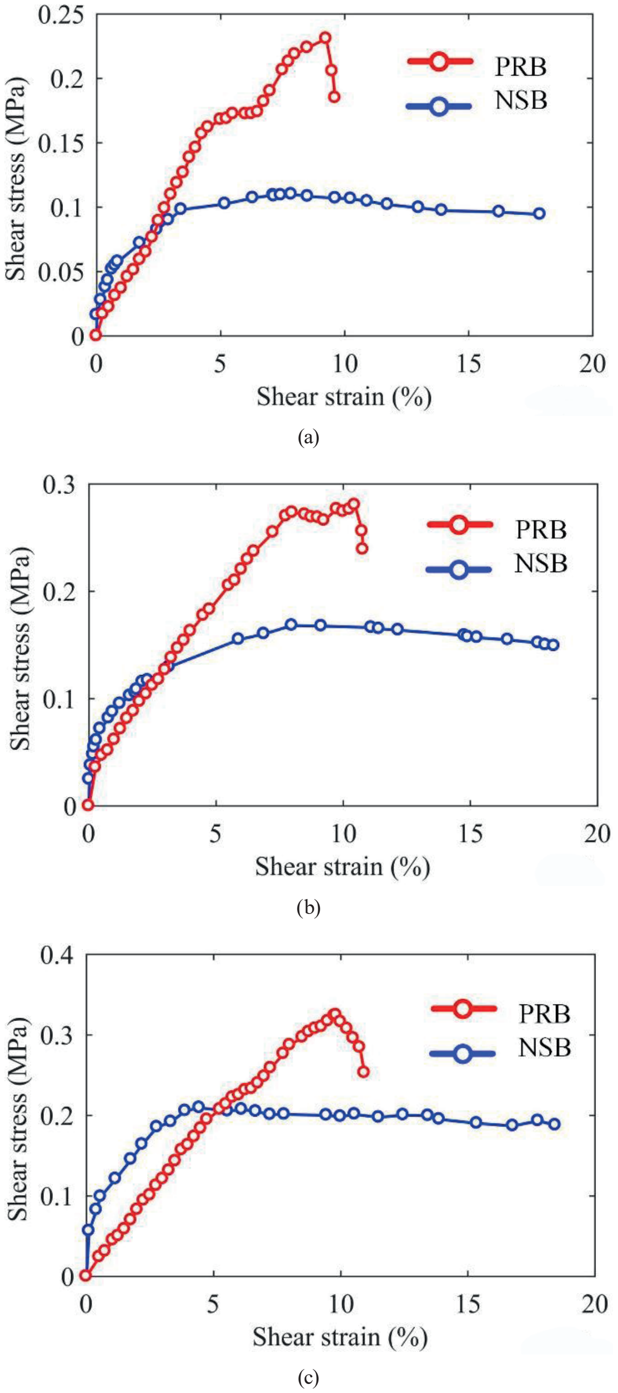


Fig. 13 Stress versus strain curve of cylindrical specimens of PRB

Table 5 Test Results of PRB cylindrical specimens

weight ratios of polyol to isocyanate	The elastic modulus (MPa)
1.5:1	0.052
3:1	0.061



(a)

(b)

(c)

Fig. 14 Shear stress versus shear strain curves for NSB and PRB under three normal stresses of a) 0.05, b) 0.1 and c) 0.15 MPa

respectively, after injection of TAFP. However, in sand-contaminated ballast, the shear strength under the mentioned normal stresses decreases by 27.3%, 35.7%, and 50%, respectively [5].

The reason for the increase in the shear strength and lateral resistance of the ballast in the presence of polyurethane is the bonding ballast particles or in other words, the formation of an integrated body. This can be clearly seen in Fig. 16. In Fig. 16(b) polyurethane fills the pores between the ballast grains and eventually bonds them together, while in Fig. 16(a) there is no bond between the ballast grains without the polyurethane. Therefore, using this polyurethane in tracks prone to buckling and needing a high lateral strength will ensure safety.

The shear strength of granular materials varies nonlinearly in terms of the normal stress [45, 46]. While this relationship was established linearly for PRB, as can be seen in Table 6. Due to the amount of R2, the shear behavior of the polyurethane reinforced ballast (PRB) can be predicted with more accuracy at higher overheads. In this table, N is the normal stress and S is the maximum shear stress.

Mohr-Coulomb diagram for PRB and NSB is shown in Fig. 17. The cohesion coefficient and internal friction angle using the following Eq. (1)

$$\tau = \sigma_n tan\phi + c \tag{1}$$

are calculated where τ (MPa) is shear stress, σ_n (MPa) is normal stress, ϕ (°C) is internal friction angle, and C (MPa) is cohesion coefficient.

As expected, according to Table 7, the internal friction angle has not changed very much by polyurethane injection into the ballast (9.53%), while the cohesion coefficient increased significantly (160.4%). This is due to the integration of ballast particles and elevated ballast shear strength.

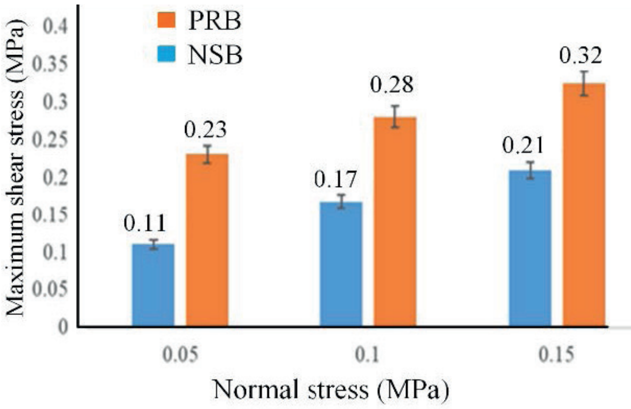


Fig. 15 Diagram of Maximum shear stress versus normal stress for NSB and PRB under three normal stresses of 0.05, 0.1 and 0.15 MPa

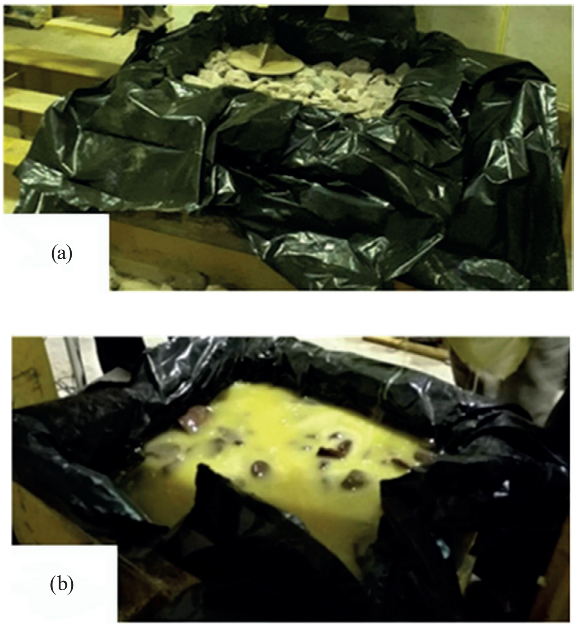


Fig. 16 a) Shear box filled with only ballast; b) Shear box filled with ballast and polyurethane

4.3 Ballast dilatation

Dilation shows the alterations in the volume of granular material when shear deformations are created.

The dilatancy angle following the Eq. (2)

$$\psi = tan^{-1}\left(\left(d\left(d\_v\right)\right)/d\left(d\_h\right)\right)_{max} \qquad (2)$$

can be calculated where ψ(°C) is dilatancy angle and $(d(d\_v)/d(d\_h))_{max}$ are the maximum changes of vertical displacement to horizontal displacement.

Fig. 18 shows the volumetric deformation behavior of ballast samples with and without polyurethane reinforcement. As can be seen in this figure, all specimens have a contractile behavior that increases in volume as the experiment progresses, or in the other words, the contractile behavior becomes a dilation behavior in the presence of any normal stress. According to the values of the dilation angle mentioned in Fig. 19, the injection of polyurethane affects the amount of dilation angle and in normal stresses of 0.05, 0.1, and 0.15 MPa, the dilation angle of the reinforced ballast with TAFP is reduced by 36.4%, 57.2%, and 197.8%, respectively. Also, with increasing normal stress, a decrease in the dilation angle of each sample is observed. Therefore, the use of polyurethane reduces the displacement of ballast particles significantly. In fact, NSB

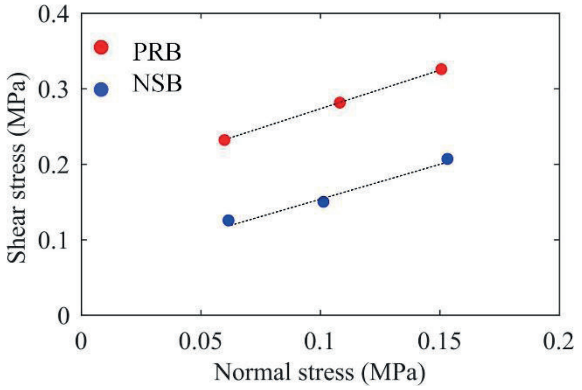


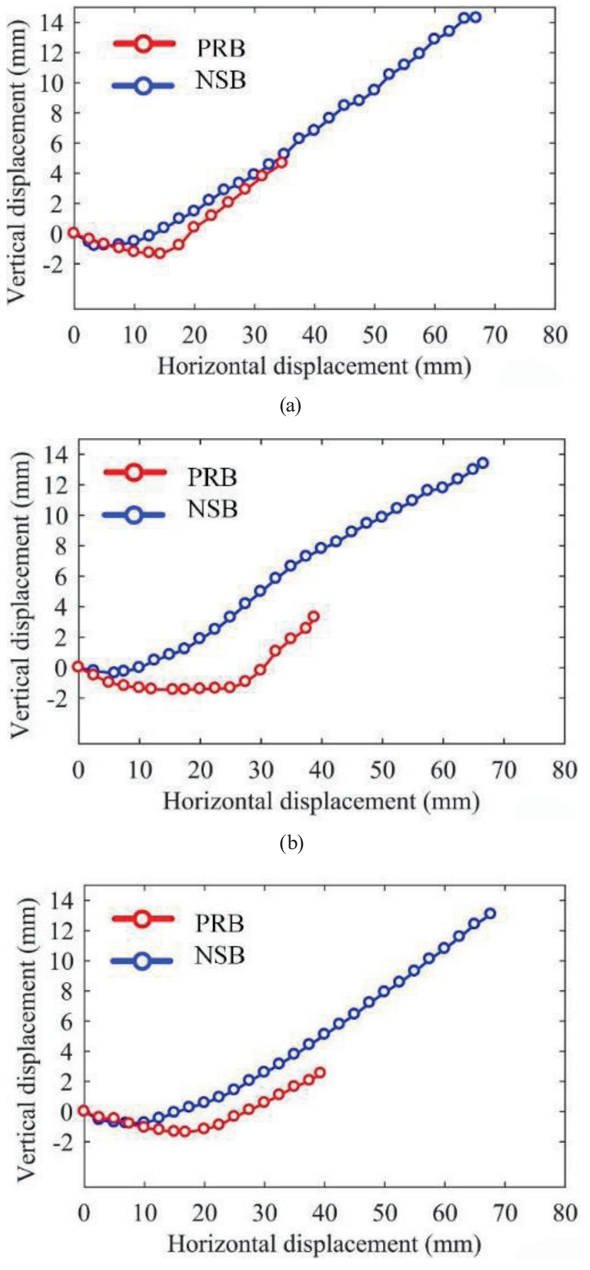
Fig. 17 Mohr-Coulomb failure envelope diagram for NSB and PRB

Table 7 cohesion coefficient and internal friction angle of NSB and PRB

specimen	cohesion coefficient (MPa)	internal friction angle (Degree)
NSB	0.064	41.97
PRB	0.168	45.97

Table 6 Normal stress-shear stress regression equations of PRB and NSB

Materials	Logarithmic regression equations		Power regression equations		Linear regression equations	
NSB	$S = 0.0898\ln(N) + 0.3779$	$R^2 = 0.9972$	$S = 0.6447N0.5887$	$R^2 = 0.9988$	$S = 0.9942N + 0.0631$	$R^2 = 0.9906$
PRB	$S = 0.084\ln(N) + 0.48$	$R^2 = 0.9862$	$S = 0.5769N0.3074$	$R^2 = 0.9948$	$S = 0.9389N + 0.1848$	$R^2 = 0.9999$



(a)

(b)

(c)

Fig. 18 Vertical displacement versus horizontal displacement curves for NSB and PRB under normal stresses of a) 0.05, b) 0.1 and c) 0.15 MPa

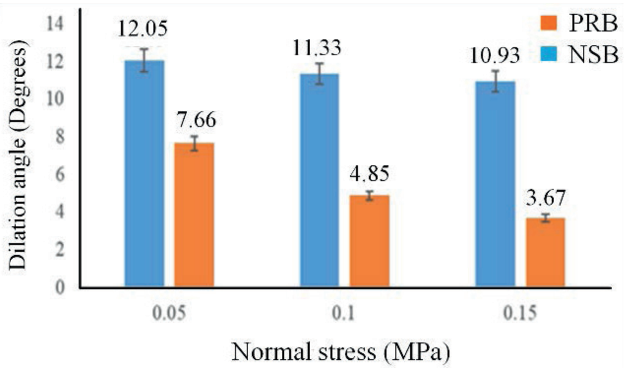


Fig. 19 Diagram of dilation angle versus normal stress for NSB and PRB

can be easily dilated due to the low locking force between its particles at low normal stresses [46], while using TAFP in the ballast changes the state of the ballast layer from the porous medium to the continuous environment and integrates the ballast layer. Therefore, even at low overheads, it shows less dilation than ballast without polyurethane. On the other hand, the distribution of normal and horizontal stresses occurs uniformly with decreasing stresses at different levels due to the integration of the ballast layer. In fact, this layer acts like a slab track with high elasticity. In other words, the locking mechanism of ballast grains increases sharply.

In addition, at a certain overhead, the contraction behavior of the PRB changed to dilatation after a while, in comparison with NSB. In other words, in the presence of polyurethane, the ballast dilates at a higher shear strain. For example, at a normal stress of 0.15 MPa, for the PRB and the NSB, the maximum dilations are 2.52 and 13.06 mm, respectively occurred at 27.5 and 17.5 mm. As can be seen in Table 8 [27, 47], the maximum shear stress, internal friction angle and cohesion coefficient of PRB are increased more than the other two methods, indicating that this polyurethane performs better.

5 Conclusions

Injecting polyurethane in the ballasted tracks can be used to fill the space between ballast particles to both prevent the penetration of sand and any kind of contamination completely and improve ballast properties. Also, it can make the ballast layer an integrated, sustainable, and maintenance-free structure such as tamping. PRB for stabilizing ballast in desert areas that are softened due to sand penetration has not been considered in the literature review. Therefore, in the present research, while

Table 8 Comparison of PRB with Elastotrack and Geogrid

Reinforcement method	Cohesion coefficient (MP)	Comparison with NSB	Internal friction angle (Degree)	Comparison with NSB	Maximum shear stress under vertical stress of 0.15 (MPa)	Comparison with NSB
Geogrid [47]	-	-	58	7.4% increase	0.25	16.2% increase
Elastotrack [27]	0.201	106.5% increase	29.3	28% reduction	0.38	Unchanged
PRB	0.168	162.5% increase	45.97	9.5% increase	0.32	52.4% increase

using a domestic cost-effective polyurethane, an attempt has been made to observe its effects in stabilizing the ballast of railway tracks in desert areas in comparison with filling the ballast with sand. For this purpose, large-scale direct shear tests have been performed under three normal stresses, and the effect of polyurethane on the modification of ballast shear parameters has been demonstrated through these tests. The results demonstrated the improvement of ballast shear behavior in the presence of polyurethane. Based on the obtained results, it can be stated that after the injection, the ballast becomes an integrated structure, all its pores are filled, and the stress distribution in it becomes more uniform.

As a result, it can be said that the problem of sand infiltration into ballast pores in sandy areas is solved. Also, the problems related to the ballast tracks prone to buckling are tackled.

The set of results is summarized as follows:

- The maximum shear stress of PRB increased under three normal stresses of 0.05,0.1 and 0.15 MPa by 109%, 64.7%, and 52.4%, compared to NSB.
- The maximum shear stress of PRB specimens increased linearly with increasing normal stress. Thus, the shear behavior of ballast in the presence of polyurethane at different normal stresses can be predicted.
- Injection of polyurethane in ballast reduced the ballast dilation angle under normal stresses of 0.05, 0.1, and 0.15 MPa by 36.4%, 57.2%, and 66.4%, respectively.
- The internal friction angle of PRB increased by 9.5%, compared to the NSB.
- The cohesion coefficient of PRB rose 160.4%, compared to the NSB.

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