Review paper (Artykuł przeglądowy)

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Selected solutions increasing durability of breakstone ballast in operated railway track structure

Wybrane rozwiązania zwiększające trwałość podsypki tłuczniowej eksploatowanej nawierzchni kolejowej

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Abstract. The main role of the cooperating layers in railway track structure: ballast, protective layer and subgrade is to provide load transfer and proper support of the railway track. However, the ballast is the weakest element in the ballasted railway track structure, therefore it requires the appropriate selection of material, grain size, strengthening or compaction. The used solutions in the granular material of the breakstone ballast increasing the durability of both the ballast itself and the operated railway track structure are described. The use of elastic elements according to their stiffness are recommended to increase the durability of the railway ballast at the stage of design, construction and maintenance of operated railway track structures. The recommended solutions for use in engineering practice, which can be adapted to the current cycle life of the railway track structure, are also shown.

Keywords: ballast; innovative solutions in ballast; elastic elements; durability of the ballast.

Streszczenie. Główną rolą współpracujących ze sobą warstw ziarnistych w nawierzchni kolejowej, tzn. podsypki, warstwy ochronnej i podtorza jest zapewnienie przekazywania obciążeń oraz odpowiednie podparcie rusztu torowego. Podsypka jest jednak najsłabszym elementem nawierzchni kolejowej, dlatego wymaga odpowiedniego doboru materiału, uziarnienia, wzmocnienia czy zagęszczenia. W artykule opisano stosowane rozwiązania w materiale ziarnistym podsypki tłuczniowej zwiększające trwałość zarówno samej podsypki, jak i eksploatowanej nawierzchni kolejowej. Zastosowanie elementów sprężystych wg ich sztywności rekomendowano w celu zwiększenia trwałości podsypki kolejowej na etapie projektowania, budowy i utrzymania eksploatowanych nawierzchni kolejowych. Wskazano również zalecane rozwiązania do stosowania w praktyce inżynierskiej, które można dostosować do aktualnego cyklu życia nawierzchni kolejowej.

Słowa kluczowe: podsypka; innowacyjne rozwiązania w podsypce; elementy sprężyste; trwałość podsypki.

The railway track structure deteriorates with increasing rail traffic, because vertical and lateral dynamic loads transmitted by the track increase with growth of speed and axle load. The vertical forces transferred on the rail (F_V) consist of six different components [1]. These are: static wheel force F_{V0} (100%); quasi-static force in the curve F_{Vk} (0 – 40%); dynamic force caused by rail unevenness F_{Vds} (0 – 300%); dynamic force due to wheel flattening F_{Vdh} (0 – 300%); braking force F_{Vdb} (0 – 20%); influence of F_{Vj} asymmetry, e. g. excess or deficiency of cant (0 – 10%). Increased dynamic loads are caused by imperfections in wheels or rails (e. g. wheel flattening, switches, crossings, expansion gaps between rails, imperfect welds or rail corrugation). The increased loads transferred further to the granular layers cause progressive deformations of theses layers as the trains pass, resulting in a cumulative deterioration of the track's geometry, the geometry being a basic parameter, especially on high-speed lines [2]. Settlement of the granular layers is a result of a loss of contact between grains or their cracking, under the influence of repeated dynamic loads. The settlement is equal to the sum of the deformations of the various layers used to distribute the loads transferred to the interacting layers. Article [3] presented that **ballast is the layer with the greatest contribution to the settlement of the railway track structure** (up to 50 – 70% of the total vertical deformation). The authors of publications [3 ÷ 5] proved, on the basis of railway track measurements, that the ballast settlement is „non-linear" or there is a linear relationship between the average settlement and the vertical deformation of the track. This means that an increase in ballast degradation may lead to a significant degradation of the railway track geometry. The progressive degradation of the geometry, as well as noise and vibration caused by the deformations, have been identified as important problems that need to be reduced, e.g. by modifying the vertical stiffness and aiming to achieve its homogeneous value along the track. One method to minimize these problems is to install elastic elements (e. g. under-rail pads, plastic sleepers, under sleeper pads or under ballast mats) in the railway track structure [2]. Interesting are analyzes of the possibility for predicting, using artificial neural networks, values of static and dynamic ballast modulus of recycled prototype sleeper pads (USP) in order to adjust their technical parameters (density and thickness) [6]. Moreover, vibration isolators based on recycled elastomeric materials have a potential to be widely used in ecologically sustainable railway track systems [7]. The arising vertical vibrations also

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cause fatigue of the cooperating elements (e.g. the fastening system) and may initiate loosening of the ballast, which, after reaching a critical level of grain acceleration, leads to ballast plasticization [8, 9].

Changes in the geometric position of rail tracks also occur as a result of changes in their support and works performed in the track (track tamping or ballast cleaning). The cause of the track deformations is a differentiation of support characteristics in the track's various cross-sections, resulting from uneven settlement of the ballast during operation, increased deformations especially due to the so-called ballast displacement from under sleepers, or weak subgrade. As a result of unevenness, increasing due to these factors, a reduction of contact between the sleeper and the ballast layer (e. g. the effect of hanging sleepers [10, 11]) can occur. The stiffness of the track in an unloaded state (without loads from vehicles) causes the sleepers to rest on the ballast with varying degree of support. In the most unfavorable case, there may be a complete lack of contact between the sleeper and the ballast. Having only an unloaded railway track it is difficult to estimate effects of such local unevenness when the track works in a vertical plane. The changes in the track support by the ballast can only be described when it is loaded, after applying load from, for example, a locomotive axle [12, 13].

Ballast in the railway track structure

The ballast in the railway track is a layer of loose, coarse-grained stone aggregate with a grain diameter of 31.5 – 50.0 mm and sharp edges. Requirements for the ballast are included in Polish regulations [14, 15], which provide basic recommendations regarding aggregate for railway ballast and basic regulations for production and acceptance of natural and recycled ballast used in railway tracks. The main problems that arise in an operated ballast are crushing, abrasion and contamination. Successive optimization of its grain size is mainly related to minimizing the cleaning and make-up processes during routine railway track maintenance activities [16, 17].

Figure 1 shows the criteria for the ballast cleaning . The ballast regains it's full working function after being profiled and cleaned. The general rules for cleaning and replenishing the ballast are as follows [16]:

■ ballast cleaning becomes necessary when more than 30% of grains have a diameter of less than 22 mm;

■ cleaning of the ballast is absolutely necessary when the contamination exceeds 40%.

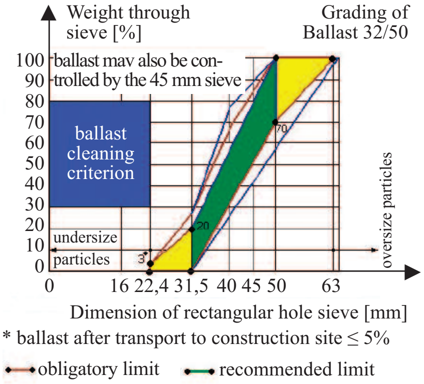


Fig. 1. Criterion of ballast cleaning [16]
Rys. 1. Kryterium oczyszczania podsypki [16]

Fulfillment of the tasks set for ballast in the railway structure is achieved by [17]:

● proper profile and size of the ballast pile;

● use of bedding materials with high compressive strength, resistant to weather conditions and with sufficiently low crushability;

● good compaction and maintenance of the ballast;

● placing ballast on a stable, properly shaped and drained track subgrade.

During the operation of a jointless railway track, various forms of wheel-rail contact, sleeper-ballast contact, and unfavorable, unintentional imperfections at the contact between the track and ground surface occur. Under the influence of passing trains, imperfections occur in the wheel and rail surface, reducing the durability of the railway surface [11,18]. As shown by the experience of European railways [2], the recommended value of vertical stiffness of the track is 50 – 80 kN/mm (due to dynamic loads, energy dissipation, energy costs, deterioration of its condition, costs incurred during maintenance).

Stresses transferred to the ballast and railway subgrade

I performed a field research and an analysis of unevenness in the railway track. In the case of the generated unevenness, by track lifting along a length of two sleeper spacings, the following values were obtained in section no. 2 (Figure 2a):

It should be emphasized that the simulated inequality changes the value of the force transferred from the rail to the railway sleeper (Figure 2b) from 44.284 kN to 59.763 kN (by 34.95%). This force causes an average stress acting on the ballast (under the sleeper), that is calculated from the following formula [19]:

$$\sigma_z^{pod} = \frac{2 \cdot Q_{max}}{\alpha \cdot A} \; [\text{MPa}] \qquad (1)$$

where:

Q_{max} – maximum force transferred from the rail to the railway sleeper [kN];

A – sleeper support area [m^2];

α – sleeper deflection coefficient [-] (1.0 in the case of a concrete sleeper, 0.8 – a wooden sleeper).

The obtained from the tests (Figure 2b) value of the force, with the adopted dynamic coefficient, causes a change in the stress transferred to the ballast from 0.28 MPa up to 0.44 MPa (at the permissible value of 0.5 MPa for hard rock ballast [19]). These values allow to visualize the scale of a change that takes place, and above all, the increased stresses transferred to the ballast. The stress transferred to the railway subgrade is calculated depending on the ballast thickness, sleeper dimensions and the current condition of the ballast – using a parameter η [19, 20]:

$$\sigma_z^{tor} = \frac{1{,}5 \cdot Q_i}{[3 \cdot (p_p - s_g) + w] \cdot h_p \cdot tg(\eta)} \; [\text{MPa}] \qquad (2)$$

where:

Q_i – force transferred from the rail to the sleeper [kN];

p_p – sleeper length [m]; s_g – track width [m];

w – sleeper width [m];

h_p – ballast thickness [m];

η – angle of stress propagation in the ballast [°], depending on the ballast condition; η = 36° (good condition), η = 35° (average condition); η = 32° (bad condition).

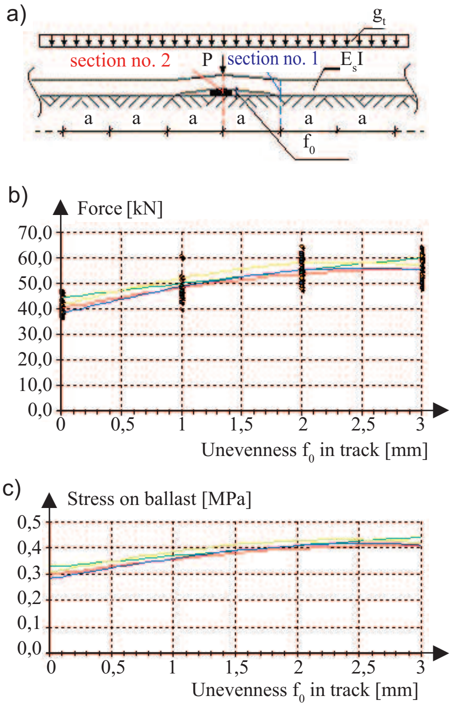


Fig. 2. Analysis of the irregularity in the railway track (own calculations): a) the scheme of the generated irregularity; b) the force transferred from the rail to the sleeper; c) stress transferred to the ballast due to the generated irregularity (for the assumed dynamic coefficient of 2.0) where: f_0 – the generated irregularity in the railway track, mm; P – applied force: 90 kN/wheel; E_S•I – track stiffness in the vertical plane (I=1819 cm^4), MNm^2; g_t – track weight 0.0022 MN/m; a – sleeper spacing 0.6 m

Rys. 2. Analiza wywołanej nierówności w torze kolejowym (obliczenia własne): a) schemat wywoływanej nierówności; b) siła przekazywana z szyny na podkład; c) naprężenie przekazywane na podsypkę wskutek generowanych nierówności (w przypadku przyjętego współczynnika dynamicznego 2,0), gdzie: f_0 – nierówność wywołana w torze kolejowym [mm]; P – przyłożona siła 90 kN/koło; ES·I – sztywność toru w płaszczyźnie pionowej (I = 1819 cm^4) [MNm^2]; g_t – ciężar toru 0,0022 MN/m; a – rozstaw podkładów 0,6 m

A permissible stress acting on the track surface, taking into account the number of load cycles n (during operation), is calculated from the following formula [16]:

$$\sigma_{dop}^{tor} = \frac{0{,}006 \cdot E_{v2}}{1+0{,}7\cdot log(n,10)} \text{ [MPa]} \qquad (3)$$

where:
E_{v2} – deformation modulus [MPa] [21];
n – number of load cycles [-].

Assuming the following data for calculations:

a) value of the force transferred from the rail to the sleeper Q = 50 kN and Q = 100 kN;

b) length of pp sleeper = 2.5 m; track width sg = 1.5 m; sleeper width w = 0.27 m;

c) angle of stress propagation in the support [°]; η = 36° (good condition) and η = 32° (bad condition);

d) deformation modulus E_{v2} at the values: 60, 100 and 120 MPa and the number of load cycles (n) in the range of $2{\cdot}10^2 \div 2{\cdot}10^7$, the relationships shown in Figure 3 and Figure 4 were obtained:

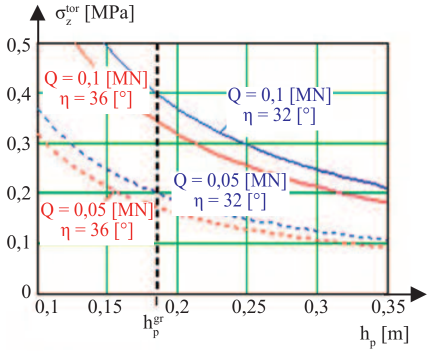


Fig. 3. The stress transferred on railway subgrade (concrete sleeper)

Rys. 3. Naprężenie przekazywane na torowisko (podkład betonowy)

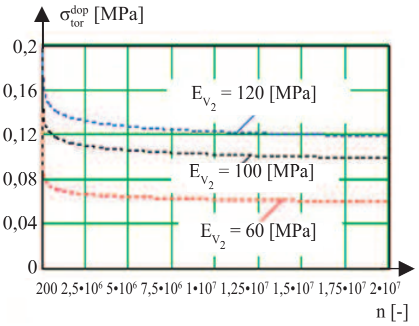


Fig. 4. The allowable stress acting on the surface of railway subgrade

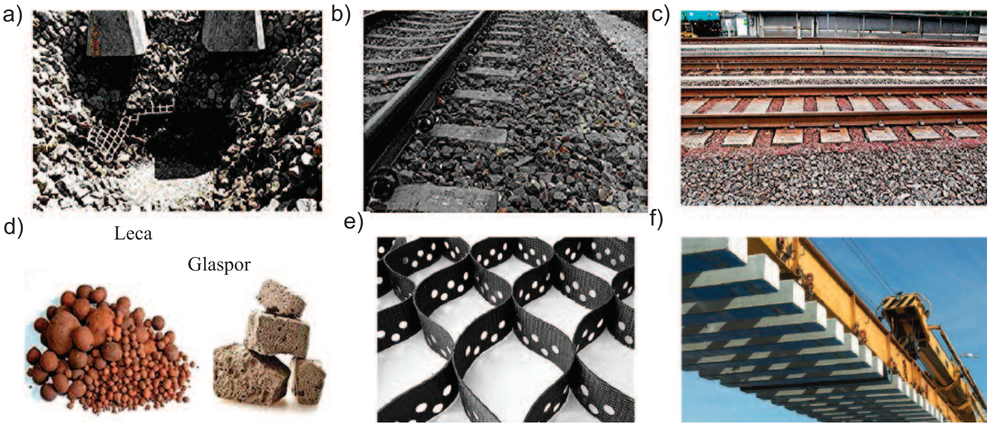
Rys. 4. Dopuszczalne naprężenie działające na powierzchnię torowiska

As indicated by observations and measurements on the track in use (e.g. measurements by a measuring trolley), the author's test (Figure 2c) and analyzes [10 – 12], during operation the permissible stresses transferred from the railway sleeper to the ballast and the track may be exceeded.

Granular material of breakstone ballast

The basic material for the ballast is crushed stone with sharp edges, obtained from hard magmatic intrusive rocks (diorite, gabbro, granite, syenite) and extrusive rocks (basalt, porphyry). In the ballast track structure, the ballast is the weakest element in the rail-sleeper-ballast system. Therefore, there is a need to increase its durability. One of the solutions used is a selection of the crushed stone by quality, type and grain composition. **Crushed stone ballast solutions used to slow down its degradation and increase the durability of a used railway track are as follows:**

- elimination of the ballast layer from the railway track structure (ballastless track solutions);
- use of components that increase the resistance of the ballast layer to fragmentation (deconsolidation), e.g. a ballast composite in the form of a layer of crushed stone reinforced with geogrids [22] - photo a;
- local chemical stabilization (surface spraying with a special binder based on polyurethane resins) [22, 23] – photo b;
- stabilization of the crushed stone ballast using polyurethane foam injected into the windows between the sleepers;
- laying special mats stabilizing the position of ballast grains or using ballast bags [24] on the high-speed line (photo c);
- reducing overloads occurring on a railway embankment put a flexible (weak) base by using light [25], natural and artificial granular materials (e.g. Leca – light expanded clay aggregate or Glasopor – foamed glass aggregate [26]) – photo d; additional advantages of light materials include: low bulk density, low water absorption and high durability;
- using elastic elements in the superstructure [2, 27 ÷ 30] – photos e and f, such as:
  - soft rail pads with stiffness up to 80 kN/mm [2] (effective in reducing the pressure transferred to the track and reducing vibrations of sleepers and ballast); reducing the stiffness of these pads can reduce vibration and noise from sleepers and ballast particles;
  - soft underlay pads (Under Sleeper Pads – USP) – effective in reducing settlement and vibration of the ballast;



Solutions used in the granular material of the breakstone ballast increasing the durability of the operated railway track structure: a) breakstone composite [22]; b) chemical stabilization of the ballast [22]; c) ballast bag [24]; d) lightweight granular materials [26]; e) geosynthetics [37]; f) under sleeper pads (USP) [38]

Stosowane rozwiązania w materiale ziarnistym podsypki tłuczniowej zwiększające trwałość eksploatowanej nawierzchni kolejowej: a) kompozyt tłuczniowy [22]; b) stabilizacja chemiczna podsypki [22]; c) worki podsypkowe [24]; d) lekkie materiały ziarniste [26]; e) geosyntetyki [37]; f) podkładki podpodkładowe (USP) [38]

– under sleeper pads increase the contact surface between the sleeper and the ballast stones (from 5 – 8% up to 30 – 35% with a deformability of 0.2 N/mm^3) and reducing the pressure on the ballast by approx. 10 – 25%;

– reduction of the force transferred to the ballast caused by the "hanging sleepers" effect;

– stiff under sleeper pads – effective in reducing the thickness of the ballast;

– soft under sleeper pads (0.08 – 0.15 N/mm^3) [6, 29] should be installed into the superstructure to reduce the stresses transmitted to the ballast;

– pads with medium stiffness (0.15 – 0.25N/mm^3) [6, 29] are most suitable to achieve a progressive change in the stiffness of the whole track;

– under ballast mat (Under Ballast Mats – UBM) – allows for an increase of contact area between the ballast layer and the protective layers, significantly reducing the stresses transferred by the ballast to the railway subgrade, thus causing less settlement;

– the under ballast mat protects the ballast, significantly reducing the contact of the ballast with the railway subgrade and providing a greater flexibility of the track system, thanks to which the load of trains is distributed over a larger area, thus reducing the transferred stresses;

– under ballast mats (UBM) are used mainly to reduce low-frequency vibrations transferred to the ground and to increase track flexibility, but it is advisable to use soft mats (with a modulus of less than 0.06 N/mm^3) [30, 31]); at the same time, these mats reduce the stress transferred to the track or protective layers of the subgrade;

■ successive cleaning and refilling of the ballast (Figure 1);

■ new methods for analyzing the particle size distribution of the railway ballast using image processing techniques [32] or well-thought-out recycling of ballast [13];

■ methods of mechanical compaction of the ballast [33 – 35] or selection of grain size and grain shape [36];

■ innovative railway sleepers (e.g. the Spanish project called Aurigidas [24]).

Conclusions

The use of the weakest element, i.e. ballast, in a ballasted railway track structure requires the use of appropriate solutions to extend the operational durability of both the railway track superstructure and the ballast itself. The following groups of solutions are used:

a) group I – elimination of ballast in the railway surface (ballastless tracks);

b) group II – strengthening the crushed stone ballast (e.g. ballast composite, chemical stabilization or ballast mats and ballast bags);

c) group III – attempts of using various types of light, durable, natural and artificial granular materials;

d) group IV – use of elastic elements on the surface (rail padss, USP or UBM);

e) group V – successive cleaning and refilling of the ballast and methods of analyzing the distribution of railway ballast particles using e.g. image processing techniques;

f) group VI – further search for optimal grain size, ballast material and effective methods of mechanical compaction of the railway ballast.

Theoretical analyses, laboratory tests, observations and measurements in the track, as well as experience successively gained in many countries allow us to optimize the methods and solutions used, which significantly influence the behavior of the track during its operation. The use of elastic elements in the railway surface (appropriately selected rail pads, under sleeper pads (USP) or under ballast mats (UBM)) should be treated as recommendations aiming to increase the durability of the railway ballast at the design and construction stages, and especially during the long-term maintenance of used railway track structures (table).

Selected currently used solutions presented in the paper allow to increase the durability of railway ballast (as separate solutions or by a synergic well-thought-out coincidence). Recommended solutions for use in engineering practice can be adapted to the current life cycle of the railway track:

1) at the design stage, e.g. selection of appropriate parameters of rail pads, USP or UBM;

2) at the operation and maintenance stage, e.g. tamping, refilling and cleaning of the ballast, chemical stabilization or replacement of rail pads (which are subject to rapid degradation and are most often the first to be qualified for replacement) at the replacement (major repair) stage, e.g. using USP, UBM or plastic sleepers.

The use of elastic elements in the railway track structure according to their stiffness [2]
Zastosowanie elementów sprężystych w nawierzchni wg ich sztywności [2]

Field of aplication	Rail pads		USP		UBM	
	stiff	soft	sztywne	miękkie	sztywne	miękkie
Decrease in rail deflection	+		+			
Reduction of damage in sleepers		+				
Reduction in sleeper movements and vibrations			+			
Decrease in ballast stettlement due to stress reduction				+	+	+
Decrease in the stress trnsmitted to sublayers		+				
Reduction in stiffness changes		+		+		
Longer life of fastener system	+					
Reduction in ballast degradation				+	+	+
Reduction in sleeper and ballast vibration		+				
Decrease in ballast layer thickness			+		+	+

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