ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2018, № 2 (74)

UDC 625.141:620.178

S. FISCHER[1*], A. NÉMETH[2]

[1*]Dep. «Transport Infastructure», Széchenyi István University, Egyetem tér 1., Győr, Hungary, 9026, tel. + 36 (96) 613 544, e-mail fischersz@sze.hu, ORCID 0000-0001-7298-9960

[2]Dep. «Transport Infastructure», Széchenyi István University, Egyetem tér 1., Győr, Hungary, 9026, tel. + 36 (96) 613 544, e-mail nemeth.attila@sze.hu, ORCID 0000-0002-3477-6902

SPECIAL LABORATORY TESTING METHOD FOR EVALUATION PARTICLE BREAKAGE OF RAILWAY BALLAST MATERIAL

Purpose. There are special, standardized laboratory test methods to evaluate railway ballast particle breakage; they are the Los Angeles and the Micro-Deval abrasion test. The authors opine that these methods aren't the most adequate methods to assess the real ballast particle degradation because in reality never occurs these kinds of stresses and strains (i.e. particles in a rotating drum with or without steel balls and with or without water). A new laboratory test procedure is needed. The authors attempted to configure an adequate one in 2014, it is detailed in the paper, as well as the initial results and improvement possibility. This test method is related to dynamic pulsating test, the particle size distributions (PSD) had to be determined before and after fatigue. In 2017-2018 the research is supported by ÚNKP-17-4 program. **Methodology.** Multi-level steel box is utilized with a special layer structure, detailed in the paper. Five different types of railway ballast samples were tested. PSDs were defined, and regarding to the results relationship between ballast particle degradation values (according to Los Angeles and Micro-Deval abrasion tests, as well as this newly developed laboratory test method) was searched, as well as time interval between necessity railway ballast cleaning work was also calculated. **Findings.** The authors sentenced the results regarding to the self-developed laboratory test method that is able to assess the particle degradation and time interval between railway ballast cleaning work more precisely related to the real railway operation circumstances. Relationship was determined between particle breakage according to standardized and unique (non-standardized) laboratory test methods. **Originality.** The paper summarized the results a newly developed laboratory test method for evaluation of the degradation of railway ballast particles. **Practical value.** It sentenced the possibility to improve the measurements and assessments regarding to the research phase supported by the ÚNKP-17-4 project.

Keywords: railway ballast; particle degradation; particle breakage; special laboratory test method; dynamic fatigue test

Purpose

The biggest part of railways in the world (approximately 98.8% that is circa 1.1 million kilometre) has normal ballast bedded superstructure [59], in this way the usage, mechanical bearing, as well as long lifetime of railway ballast material has to be handled with specific attention in the consideration of following viewpoints [49]:

a) ballast bed solidly but flexibly supports vertically the railway track, this layer assures the relevant part of the longitudinal and transversal support with the help of friction and passive earth pressure, all of these parameters affects the geometrical and structural stability of the whole railway track,

b) ballast bed assures the rapid flowing through of water (i.e. precipitation) in the track and ballast bed, relieving the rapid drainage,

c) its texture ensures the relative simple geometrical correction: either with manual or heavy machines; the track geometry will be long-lasting; in case of obligation the ballast material is able to be recycled,

d) its energy damping perform has to be suitable high,

e) it has to decrease the stress from the ties' lower surface with prescribed volume in the accordance of the stress limit of subsoil.

Ballast bed material should have various textural parameters considering the above detailed points, they are the followings without the requirement of fullness:

i) it has to have continuous grading (PSD) according to point a) because this texture is able to guarantee the most excellent ability for compaction, thus proportionately maximal load bearing capacity,

doi: 10.15802/stp2018/130854

ii)it has to have uniform grading according to points b) and d) because the proportionately lot of void between grains guarantees the rapid flowing through of water in the structure, as well as the larger energy damping [60],

iii) it has to contain sharp edge grains according to points a) and c) because the largest inner particle friction is able to be expanded, thus durable track geometry (e.g. against vertical deformation) is able to be obtained,

iv) grains with less deterioration (breakage) characteristics have to be applied according to point b), it can be obtained by usage of railway ballast with low Los Angeles and Micro-Deval abrasion values, or by recycled ballast material (perchance by rounded grain material, i.e. river grains) [16, 46],

v) it has to have required and adequate layer width.

In search of relationship between above aspects i) to v), the problem will be evident: using of only granular materials (i.e. without chemicals and geosynthetics [19]) isn't able to be perfect because either of the base roles and requirements (points a) to e) above) will be influenced, thus ballast bed is able to be constructed regarding to these points. It has to be noticed that bitumen stabilised ballast material is also able to be applied [13].

The railway construction and maintenance profession generally prefers the technique below for railway ballast [49]:

1) it is rather from deep magmatic base rock (perchance sandy gravel or slag in secondary railway lines),

2) it should be made of high strength and frost-proof material,

3) it should have sharp edge, cubic grains without cohesion texture,

4) it should contain proportionately low fine particles and fines.

It should be contemplated that long-lasting railway track geometry depends on contamination of ballast material (it is 76% from grain degradation, 13% from underlying coarse-grained layer [52, 54]). The deteriorated fine particles and fines in the ballast bed effect seepage of the track, it also responds on geometric stability of track (i.e. on endurance of track geometry). It is obvious that degradation of ballast grains can be developed:

– the homogenous stress distribution in the interface of bottom surface of tie and ballast bed, as well as in the interaction of ballast grains is not accurate at the dimensioning and design of track layer structure and structural elements [25],

– grains aren't loaded by static impacts but dynamic, repeating-pulsating (more million loading cycles) impacts during railway operation, which stress can be developed jerk-like stress (e.g. in case of failures of rail ends, welts) and it is able to attain the plurality of static stresses [31, 34]. It is able to quicken the deterioration process [44],

– in real circumstances there are very large stresses in the interface of ties and ballast grains, including between grains that raises the degradation of grains [25],

– the contact stresses noticed above is able to be reducted by using of e.g. under sleeper pads, or PU foam or bitumen stabilised railway ballast [13].

In this article the authors present the quasi newest international research results linked to railway ballast grain deterioration, afterwards it the laboratory tests' results are detailed which tests are performed in 2014 at SIU, Győr [20, 21] that provided motivation and research basis for the continuance of the research in 2017 and 2018, as well. Research plans are indicated that is able to consider as the fulfilment and improvement of the research executed in 2014.

The authors specify why the now utilized, standardised railway ballast grain abrasion tests should be examined and modified, and they suggest introduction of other, different laboratory test methods.

In the European Union's 2014-2020 Programme Hungarian railway construction and rehabilitation projects is able to be financed by more than thousand billion Hungarian Forints [57], from which support important railway projects can be performed. The very necessary part of these projects is the ballast that is the heaviest component of superstructure. In nowadays practice it is obvious aspect that required quality ballast [9, 14, 35, 36, 39-43, 47, 52, 58] is achievable in prescribed quantity.

In the followings the authors cite those criterions because of that the future view is more shadowed, and which are prescribed that special rock physics tests (Los Angeles and Micro-Deval abrasion tests) are highly suggested with more real loading conditions than the standardised tests considering available stone-rock qualities' limits.

The particles' original – base rock-dependent – abrasion characteristics are able to be hardly al-

doi: 10.15802/stp2018/130854

tered by technology procedures, these principally depends on «aggregate wealth» and rocks' mechanical properties. In professional conferences more and more presentations are made about that environmental, nature-reservational, heritage-protective, etc. regulations hitting the stone-mining industry aggravated year by year generally mean such restrictions [35, 36] on the access of the natural «asset» that may lead to complications in base material supply and increasing quality risk on the medium term.

The authors assume that it a base issue that the ability for ballast material is worldwide required the Los Angeles and Micro-Deval abrasion tests [39, 40] in the railway ballast product standard [43]. These kind of laboratory tests can't simulate the real developed stresses of ballast (it should be noticed that in case of e.g. asphalt and concrete road pavements' «stone truss» [2, 27, 28] these laboratory tests are not the best choice). For the objective decision of conformability special laboratory degradation test should be utilized that consider the operation conditions and stresses in more real manner.

Afterwards the international literature review, own, unique solution for a special laboratory test procedure (method) are represented that can simulate the stresses in more realistic method. The results are comparable to the standardised abrasion tests [39, 40], the abrasion qualifying properties utilized worldwide [23, 25, 32], including required cycle of ballast screening work [5, 32].

Methodology

The research topics connected to railway ballast material breakage have worldwide wide-ranging bibliography. Fundamentally the researchers utilized the following methods:

– laboratory testing [1, 4, 6-8, 10, 12, 15-18, 24, 26, 29, 30, 33, 38, 45, 47, 53, 55, 56],

– DEM (discrete element method) simulations and/or 3D grain shape improvements [10, 11, 12, 22, 24, 37, 53, 55],

– FEM (finite element method) simulations [10],

– field tests [3, 16, 46, 48, 50].

The noticed researchers behoved with the main subfields without the requirement of fullness:

– relationship between ballast aggregate degradation, additionally cohesion, inner friction angle and the water permeability of material and its layer was investigated [29],

– angularity breakage phenomenon [15, 37],

– relationship of PSD of ballast material and its mechanical abrasion was examined, and newly PSD was improved and induced according to more real loading conditions [26, 56],

– volumetric and axial deformations, additionally particle breakage were measured by laboratory triaxial testing regarding to different stress values (main stresses and deviator stresses) [8, 37],

– a special method was developed to be able to define PSD of ballast aggregate with using of ground penetrating radar (GPR) [4, 55],

– at DEM simulations more real particle shape generation method was researched and DEM models were validated [11, 37, 53],

– laboratory and field tests were performed with and without geosynthetic inclusions, ballast material degradation was measured [10, 15, 38, 46],

– tyre derived aggregates (TDA) were tested in case of sand fouled ballasted tracks [18],

– ballast grain degradation due to ballast tamping was investigated [1, 17],

– ballast structure with adhesive material was examined [30].

The significant declarations are below without the requirement of fullness:

– the maximum limit of Los Angeles abrasion in Brazil is 40%, in Australia is 25%, in Canada is 20% [47], the difference between the European ones and mentioned ones is very high,

– the water permeability values of the examined samples were 6.11×10^{-1}, 2.07×10^{-1}, 1.32×10^{-1} and 1.27×10^{-1} cm/s connected to special Los Angeles abrasion tests with 250, 500, 750 and 1000 revolutions, respectively [47]; the value for normal, relatively clean ballast is 3×10^{1} cm/s [47],

– the higher the deterioration of the sample, the lower the cohesion, but it doesn't affect the inner friction angle [29],

– the load bearing capacity values of both the new and the recycled ballast samples depend on the initial breakage [29],

– the cohesion of ballast samples was approximately zero after 800 revolutions in the Los Angeles drum [29],

– to assess the load bearing capacity of the mixed railway ballast sample (30% new + 70% re-

doi: 10.15802/stp2018/130854

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2018, № 2 (74)

cycled) is nearly the same as 100% new ballast sample [29],

– angularity breakage signifies the break-off of the edges and corners of grains that arises at lower stresses [37],

– confining stress plays a relevant role in the particle degradation, the larger the confining stress, the larger the breakage [37],

– the connection between confining stress and deviator stress is linear [37],

– the larger the confining stress, the larger the dilation angle (ψ) [37],

– at low confining stress levels the dilation is significant larger [37],

– the grain breakage develops first at the top and the bottom surfaces of the ballast samples during monotonic triaxial tests in the lab [37],

– the PSD of ballast is able to be defined with 70% accuracy by GPR [4],

– using of thermodynamically consistent hypoplastic model is suitable for assess of ballast degradation, the easy tractability is the benefit of this calculation method [6],

– the examination of the interface of half depth ballast and half depth sub-ballast layer was performed by cyclic triaxial test in the lab, this interface reducts the axial and volumetric deformations at the interface region [8] that will stop in case the initial compactness and the confining stress raise [8],

– the degradation after compaction the laboratory samples was much larger than during and after triaxial tests, the relevant part of the sample's breakage was observed during the first few hundred cycles [8],

– in case the compactness reaches the 98% of beginning compactness, the measured axial deformation approximates the calculated results, the effect of interface on the axial and volumetric strains reducts at 160 kPa confining stress level [8],

– five diverse grain breakage motifs were classified connected to cyclic triaxial laboratory test [8],

– correlated fresh ballast sample and samples from railway track (used ballast) after 5-year operation, the used ones were not liable to break further that is able to be clarified with the grain shape; the inner friction was lower connected to used ballast samples [16],

– the properties of ballast fouled with sand is able to be improved by TDA: e.g. damping coefficient, plastic settlement, degradation; it should be noticed that the best TDA content is 5% in the accordance with decreasing of grain breakage and stiffness; the larger the sand content, the worse the mechanical properties of the sample [18],

– special Los Angeles laboratory test series without steel balls was executed with hard sand stone railway ballast sample (22.4/63 mm grain size, Los Angeles abrasion value is between 11 and 15%), PSDs of examined samples were defined after 100, 200, 300 and 400 revolutions [55]:

- rate of grains between (40) 50 and 63 mm decreased,
- rate of grains between 22.4 and 40 mm increased,
- rate of grains between 31.5 and 40 mm raised until 200 revolutions, but reduces between 200 and 400 revolutions,
- rate of grains between 22.4 and 31.5 mm raised until 100 revolutions, after it was stabilised,
- rate of grains below 22.4 mm raised relevantly, between 100 and 400 revolutions with nearly same speed, until 100 revolutions more rapidly,
- the grain degradation was larger until 100 revolutions altogether, than afterwards,
- the rate of grains below 22.4 mm after 100 revolutions was more than 3% (mass percentage), after 400 revolutions it was more than 10%,

– the results of GPR measurements were relevantly affected by the petrographic characteristics of fouling and ballast material; the methods below are suggested for analysis of GPR measurements [55]:

- Fast Fourier Transformation (FFT),
- Wavelet Transformation,
- two and three dimensions discrete element simulations,

– according to the results of three dimensions laser scanner tests of ballast grains before and after Los Angeles tests it is able to be determined that the most relevant degradation was at the grain corners; the maximal failure depth was circa 4-9 mm, the average was circa 1 mm; the larger the particle diameter the more important the degradation [24],

– the grain breakage is relevant at low and high confining stresses during laboratory cyclic triaxial tests, in the middle interval the degradation is minimum; there are three well divisible regions [10]:

doi: 10.15802/stp2018/130854

- dilatant unstable degradation zone (DUDZ),
- optimum degradation zone (ODZ),
- compressive stable degradation zone (CSDZ),

– the optimum confining stress is circa 30-75 kPa connected to cyclic laboratory triaxial tests, it induces the minimum degradation, it is relevant for maintenance [10],

– the relevant lowest degradation was observed connected to cyclic triaxial laboratory tests according to 1.8 coefficient of uniformity (C_u), it is validated with 3D laser scanner measurements, as well, in the consideration of this point new, better PSD was determined [26],

– new, polymer-based rosin was examined, it advances the mechanical behaviour of ballast material (according to the structural and geometric stability) [30],

– the grain breakage isn't relevant in real railway track until circa the 10,000th axle; in case the value of Los Angeles abrasion value is raised from 24 to 12, the degradation decreases with 50%; in case of used ballast the Los Angeles abrasion test doesn't provide fair results [45],

– fresh ballast material is able to bear nearly 40 tamping cycles without ballast cleaning (screening) [45],

– in case of fresh railway ballast (C_u=1.5) both the strains and the breakage were larger than a recycled material (C_u=1.8); it can be clarified with the developed contact stresses [5],

– ballast samples' strains are able be chategorised into three well diverse regions according to DEM modelling and cyclic tests in lab [11, 53]:

- plastic shakedown,
- plastic creep,
- incremental collapse,

– in plastic shakedown zone the strain rate quickly reduces below than 10^{-6}, and there are some broken grains [11, 53],

– in the plastic creep zone stable and persistent strain is able to be evolved, there is some broken particles; the region of plastic creep is expanded when the confining stress raises [11, 53],

– in the incremental collapse region grain degradation and plastic strain are able to be detected that is mostly because of shearing failure [11, 53],

– at low level of confining stress, the testing frequency doesn't have affect factor, at larger confining stress the larger the testing frequency the smaller stress is needed to fail (collapse) [11, 53].

In 2014 a research report was written with the finance support of Colas Északkő Ltd.; the public parts were published in [20, 21]. Below these results are shortly detailed.

In the accordance with more real stresses, strains and breakage of ballast material a creative laboratory testing method was developed. Six frames of the ten-level multi-level shear box was used, in the lowest two frames there are 20-cm-thick XPS sheets, above it is 10-cm-thick sand layer and one layer of high strength non-woven geotextile with 1200 g/m^2 mass, all three in 1.0×1.0 m surface (Figure 1-2).

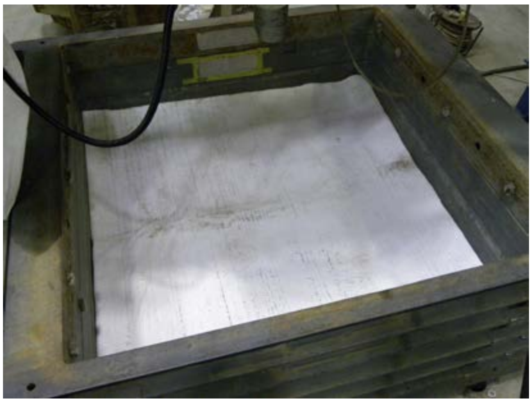

Fig. 1. Steel box (six steel frames) and 1200 g/m^2 geotextile laid onto 10 cm sand layer

Fig. 2. The «box» built from wooden sleepers

On the geotextile there is 46×46×30 cm (length×width×height) rail-way ballast sample on the center of the 1.0×1.0 m surface, between timber sleepers with 1200 g/m^2 geotextile coating (Figure 3). 3 million-cycle dynamic pulsation force is applied for each ballast sample. Five different types of 31.5/50 mm, «A» type railway ballast

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2018, № 2 (74)

samples (according to EN 13450:2002 standard, all samples were from andesite base rock) were examined (Table 1). Particle size distributions were defined before and after the innovative fatigue tests.

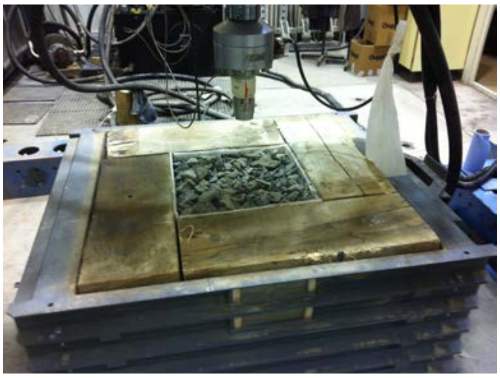

Fig. 3. Geotextile layers glued onto wooden sleepers, and either ballast sample in the «box»

Table 1

Rock mechanics parameters of ballast samples (measured by Colas Északkő Ltd.)

No. of ballast sample	LA_{RB} (%)	$M_{DE}RB$ (%)
511	14.2	3.6
514	16.7	9.7
517	23.8	16
521	18.6	16.7
522	18.55	17

Not only the Los Angeles (LA_{RB}%) and the Micro-Deval abrasion value ($M_{DE}RB$%) were determined, but particles quantity d<22.4 mm, d<0.5 mm, d<0.063 mm, the ratio d_{60}/d_{10}, as well as M and λ parameters [23], as well.

Findings

PSD diagrams before and after the 3×10^6 pulsating cycles are published in Figures 4-5.

The measured ballast degradation parameters and index numbers for the necessity of ballast sieving were calculated, which were according to the values in Table 2.

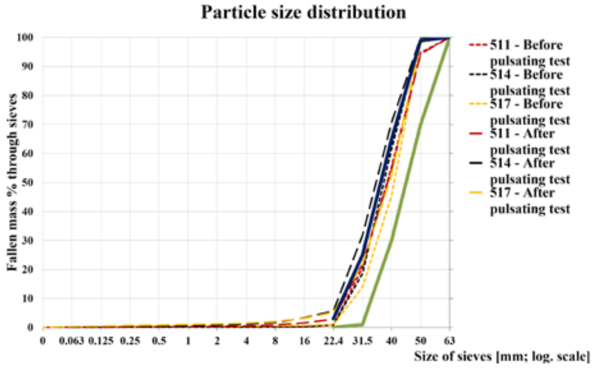

Fig. 4. Particle size distribution diagrams of 511, 514 and 517 ballast samples before and after pulsating test

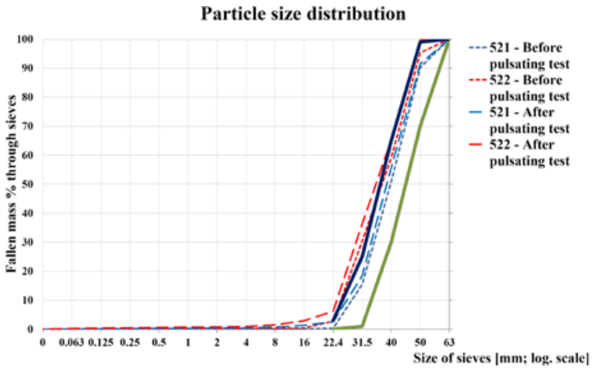

Fig. 5. Particle size distribution diagrams of 521 and 522 ballast samples before and after pulsating test

Table 2

Measured and calculated ballast breakage parameters

Measured and calculated values	No. of ballast sample				
	511	514	517	521	522
LA_{RB} (%)	14.20	16.70	23.80	18.60	18.55
$M_{DE}RB$ (%)	3.60	9.70	16.00	16.70	17.00
$LA_{RB}+M_{DE}RB$	17.80	26.40	39.80	35.30	35.55
F_V (BP) (%)	1.535	1.434	3.510	0.880	3.561
F_V (AP) (%)	5.325	10.668	12.066	4.626	10.643
ΔF_v (%)	3.790	9.234	8.556	3.746	7.082

doi: 10.15802/stp2018/130854

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2018, № 2 (74)

End of the Table 2

Measured and calculated values	No. of ballast sample				
	511	514	517	521	522
d<22.4 mm (BP) (%)	0.851	0.918	0.963	0.333	2.784
d<22.4 mm (AF) (%)	2.812	5.739	5.197	2.535	6.188
Δd<22.4 mm (%)	1.961	4,821	4.233	2.202	3.404
d<0.5 mm (BP) (%)	0.153	0.116	0.408	0.108	0.246
d<0.5 mm (AP) (%)	0.253	0.417	0.841	0.241	0.572
Δd<0.5 mm (%)	0.100	0.302	0.432	0.133	0.326
d<0.063 mm (BP) (%)	0.054	0.039	0.108	0.064	0.120
d<0.063 mm (AP) (%)	0.118	0.150	0.328	0.082	0.234
Δd<0,063 mm (%)	0.064	0.111	0.220	0.018	0.114
BBI	0.018	0.248	0.149	0.077	0.195
d_{60}/d_{10} (BP)	1.547	1.466	1.489	1.500	1.624
d_{60}/d_{10} (AP)	1.603	1.577	1.663	1.536	1.633
$\Delta d_{60}/d_{10}$	0.057	0.110	0.174	0.036	0.008
M (BP)	271.74	281.02	258.69	256.86	287.53
M (AP)	273.38	308.21	278.44	268.11	307.74
λ (BP)	1.072	1.109	1.020	1.013	1.134
λ (AP)	1.078	1.216	1.098	1.058	1.214

In Table 2 «BP» and «AP» abbreviations signify «before pulsating test» and «after pulsating test».

In Table 2 the d<22.4 mm, the d<0.5 mm, the d<0.063 mm and the d_{60}/d_{10}, as well as the calculated values of M and λ parameters described in literature [23], are indicated.

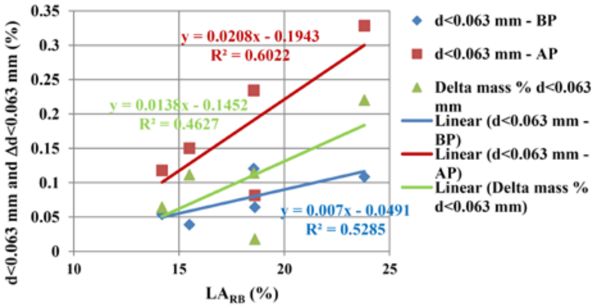

Fig. 6. Parameters d<0.063 mm and Δd<0.063 mm as a function of LA_{RB} (%)

Breakage parameters in Table 1 in function of LA_{RB} (%), $M_{DE}RB$ (%), and „LA_{RB} + $M_{DE}RB$» measured and calculated rock mechanics parameters of the ballast samples were described in several graphs. Due to content limit only one graph will be published (Figure 6).

According to the results, the following assertions can be formulated:

– there is no considerable correlation between any material characteristics related to grain breakage and their variation, moreover the measured and calculated rock mechanic properties. This result wasn't unforeseen because of the base assemblage of laboratory tests (rotating steel drum full with ballast grains with or without steel balls vs. a «box» full with ballast, pulsated by dynamic cyclic loads),

doi: 10.15802/stp2018/130854

– in the paper [17] the grain breakage due to ballast tamping was investigated in the laboratory, its authors couldn't confirm correlation between the Los Angeles abrasion value of the samples and the grains' shape characteristics,

– the needed cycle values of ballast screening work were calculated in the accordance with the earlier practice data of MÁV (Hungarian Railways) and international bibliography [5, 33].

Originality and practical value

The authors have supplementary plans compared to the research executed in 2014: more accurate measurement of the variation of ballast grains' degradation as a function of pulsating cycles (or elapsed time during the fatigue test) with the manner detailed below:

– testing of minimum two types of ballast samples with diverse rock mechanic properties,

– minimum three separate measures connected to certain railway ballast material samples, definition of PSD before and after fatigue tests with the following load cycles: 0.1 million; 0.2 million; 0.5 million; 1 million and 1.5 million (the ÚNKP project doesn't finance the laboratory measurements until 3 million loading cycles),

– separate ballast sample has to have for each fatigue test, i.e. the test series will be like the following:

- ballast sample should be cleaned and washed (the particles more than 22.4 mm are needed for the tests),
- PSD should be determined (BP – before pulsating test),
- 0.1 million loading cycles should be utilized,
- PSD should be determined (AP – after pulsating test),
- the ballast sample has to be thrown away,
- another (new) ballast sample should be cleaned and washed (the grains more than 22.4 mm are needed for tests),
- PSD should be measured (BP – before pulsating test),
- 0.2 million loading cycles should be used,
- PSD should be determined (AP – after pulsating test),
- the ballast sample has to be thrown away,
- etc. until 1.5 million loading cycles.

– grain quantity d<22.4 mm, d<0.5 mm, d<0.063 mm, the ratio d_{60}/d_{10}, moreover M and λ parameters should be defined,

– the goal is to effort determine mathematical-physical trends and correlation between characteristics (see above point) and loading cycles.

The noticed measurements will also be performed using of fresh railway ballast samples from andesite base rocks, as these measurements were executed in the research in 2014. The dynamic fatigue test series will be able to be begun in March, 2018, the full results is able to be published in May-June, 2018.

Conclusions

This article details a research's introductory results (literature review) supported by ÚNKP-17-4 New National Excellence Program of Ministry of Human Capacities. The exact topic in the ÚNKP project is the «Innovative breakage test method of railway ballast material». The up-to-date international research achievements were resulted related to standardized and non-standardized, additionally seperate laboratory breakage test methods and discrete element simulations of ballast materials. Afterwards these points the results of the research test series performed at the Széchenyi István University (SIU) in the year 2014 were shortly presented. It provided a concept and research base for the extension of the research between 2017 and 2018, as well. The new research plan was introduced and detailed for the new R&D, it can be scored as the enhancement of the earlier research. The authors would like to prepare the continuation of this article with the details of the fulfilled R&D.

Acknowledgements

This paper is supported by the ÚNKP-17-4 New National Excellence Program of Ministry of Human Capacities.

doi: 10.15802/stp2018/130854

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2018, № 2 (74)

LIST OF REFERENCE LINKS

1. Al-Saoudi, N. K. S. Behaviour of Track Ballast Under Repeated Loading / Namir K. S. Al-Saoudi, Khawla H. Hassan // Geotechnical and Geological Engineering. – 2013. – Vol. 32. – Iss. 1. – P. 167–178. doi: 10.1007/s10706-013-9701-z.
2. Ambrus, K. Útépítési zúzottkövek és zúzottkavicsok aszfaltkeverékek gyártásához, felületi bevonatok készítéséhez [Electronic resource] / K. Ambrus, I. Pallós. – 2012. – Available at: http://docplayer.hu/9502775-Utepitesi-zuzottkovek-es-zuzottkavicsok-aszfaltkeverekek-gyartasahoz-feluleti-bevonatok-keszitesehez.html. – Title from the screen. – Accessed : 23.04.2018.
3. Anbazhagan, P. Study of ballast fouling in railway track formations / P. Anbazhagan, T. P. Bharatha, G. Amarajeevi // Indian Geotechnical Journal. – 2012. – Vol. 42. – Iss. 2. – P. 87–99. doi: 10.1007/s40098-012-0006-6.
4. An Investigation into the railway ballast grading using GPR and image analysis / M. G. Brancadoro, L. Bianchini Ciampoli, C. Ferrante, A. Benedetto, F. Tosti, A. M. Alani // 9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR) : Conference Paper (Edinburgh, 2017, June 28–30). – Edinburgh, Scotland, 2017. doi: 10.1109/IWAGPR.2017.7996043.
5. Arangie, P. B. D. The influence of ballast fouling on the resilient behaviour of the ballast pavement layer // Proc. of 6th Intern. Heavy Haul Railway Conf. (Cape Town, 1997, April 6–10). – Cape Town, 1997. – P. 241–256.
6. Bajpai, P. Theoretical assessment of railway ballast degradation under cyclic loading / P. Bajpai, A. Das // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. doi: 10.1201/9781315100333-267.
7. Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – 394 p.
8. Bian, X. Experimental study on cyclic deformation and particle breakage of railway ballast / X. Bian, D. Sun, W. Li // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 1801–1809.
9. Claisse, P. Rail ballast: conclusions from a historical perspective / P. Claisse, C. Calla // Proceedings of the Institution of Civil Engineers – Transport. – 2006. – Vol. 159. – Iss. 2. – P. 69–74. doi: 10.1680/tran.2006.159.2.69.
10. Christie, D. The performance of rail track incorporating the effects of ballast breakage, confining pressure and geosynthetic reinforcement / D. Christie, S. Nimbalkar, B. Indraratna // Bearing Capacity of Roads, Railways and Airfields : Proc of the 8th Intern. Conf. (June 29–July 2, 2009, Unversity of Illinois at Urbana, Champaign, Illinois, USA). – London, 2009. – P. 5–24.
11. Cumulative deformation characteristic and shakedown limit of railway ballast under cyclic loading / J. Xiao, D. Zhang, Y. Wang, Z. Luo // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 1899–1904.
12. Current research into ballasted rail tracks: model tests and their practical implications / B. Indraratna, Q. Sun, N. T. Ngo, C. Rujikiatkamjorn // Australian Journal of Structural Engineering. – 2017. – Vol. 18. – Iss. 3. – P. 204–220. doi: 10.1080/13287982.2017.1359398.
13. D’Angelo, G. Optimisation of bitumen emulsion properties for ballast stabilisation / G. D’Angelo, D. Lo Presti, N. Thom // Materiales de Construcción. – 2017. – Vol. 67. – Iss. 327. – P. 124. doi: 10.3989/mc.2017.04416.
14. DB. «TL DBS 918 061: Technische Lieferbedingungen Gleisschotter» (TL DBS 918 061: Technical delivery conditions Railway ballast). – Berlin, 2006/08.
15. DEM analysis of angular ballast breakage under cyclic loading / Z. Hossain, B. Indraratna, F. Darve, P. K. Thakur // Geomechanics and Geoengineering. – 2007. – Vol. 2. – Iss. 3. – P. 175–181. doi: 10.1080/17486020701474962.
16. Diógenes, D. F. Evaluation of the ballast aggregates shape properties using digital image processing techniques / D. Diógenes, R. Maia, V. Castelo // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 2003–2008.
17. Douglas, S. C. Ballast Quality and Breakdown during Tamping / S. Caleb Douglas // 2013 Joint Rail Conference : Conf. Paper (Knoxville, Tennessee, USA, April 15–18, 2013). – 2013. doi: 10.1115/JRC2013-2553.

doi: 10.15802/stp2018/130854

18. Esmaeili, M. Experimental assessment of cyclic behavior of sand-fouled ballast mixed with tire derived aggregates // M. Esmaeili, P. Aela, A. Hosseini // Soil Dynamics and Earthquake Engineering. – 2017. – Vol. 98. – P. 1–11. doi: 10.1016/j.soildyn.2017.03.033.
19. Fischer, Sz. A vasúti zúzottkő ágyazat alá beépített georácsok vágánygeometriát stabilizáló hatásának vizsgálata : PhD thesis / Sz. Fischer ; Széchenyi István Egyetem. – Győr, 2012. – 148 p.
20. Fischer, Sz. A vasúti zúzottkövek aprózódásvizsgálata egyedi laboratóriumi módszerrel / Sz. Fischer // Sínek Világa. – 2015. – Vol. 57, No 3. – P. 12–19.
21. Fischer, Sz. Breakage Test of Railway Ballast Materials with New Laboratory Method / Szabolcs Fischer // Periodica Polytechnica Civil Engineering. – 2017. – Vol. 61, No 4. – P. 794–802. doi: 10.3311/PPci.8549.
22. Gaitskell, P. Use of digital imaging for gradation and breakage of railway ballast / Peter Gaitskell1, Mohamed A. Shahin // Australian Geomechanics. – 2013. – Vol. 48. – P. 81–88.
23. Gálos, M. Ágyazati kőanyagok: A kutatás eredményei. 2 rész. / M. Gálos, L. Kárpáti, D. Szekeres // Sínek Világa. – 2011. – Vol. 55, No 1. – P. 6–13.
24. Guo, Y. L. Ballast degradation analysis by Los Angeles Abrasion test and image analysis method / Y. L. Guo, G. Q. Jing // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 1811–1815.
25. Indraratna, B. Advanced rail geotechnology – Ballasted track / Buddhima Indraratna, Wadud Salim, Cholachat Rujikiatkamjorn. – London : CRC Press, 2011. – 432 p.
26. Indraratna, B. Laboratory assessment of the role of particle size distribution on the deformation and degradation of ballast under cyclic loading / Buddhima Indraratna, Yifei Sun, Sanjay Nimbalkar // Journal of Geotechnical and Geoenvironmental Engineering. – 2016. – Vol. 142. – Iss. 7. – P. 0401601601–0401601612. doi: 10.1061/(ASCE)GT.1943-5606.0001463.
27. Kausay, T. Adalékanyagok kőzetfizikai tulajdonságai. Út- és hídépítési műszaki előírások és alkalmazási tapasztalataik [Electronic resource] / T. Kausay. – Budapest, 2011. – Available at: http://www.betonopus.hu/szakmernoki/kozut-2-adalekanyag-kozetfizika.pdf. – Title from the screen. – Accessed : 03.05.2018.
28. Kausay, T. Zúzott betonadalékanyagok kőzetfizikai tulajdonságai a szabályozásban / T. Kausay // Mérnökgeológia Kőzetmechanika 2008. – Budapest, 2008. – P. 259–270.
29. Kolos, A. Change of ballast strength properties during particle abrasive wear / Alexey Kolos, Anastasia Konon, Pavel Chistyakov // Procedia Engineering. – 2017. – Vol. 189. – P. 908–915.
30. Kondratov, V. The development of a high performance material for a ballast layer of a railway track / Valery Kondratov, Valentina Solovyova, Irina Stepanova // Procedia Engineering. – 2017. – Vol. 189. – P. 823–828.
31. Kurhan, M. B. Railway Track Representation in Mathematical Model of Vehicles Movement / M. B. Kurhan, D. M. Kurhan // Наука та прогрес транспорту. – 2017. – № 6 (67). – С. 40–48. doi: 10.15802/stp2017/118380.
32. Lichtberger, B. Track compendium: Formation, Permanent Way, Maintenance, Economics / B. Lichtberger. – Hamburg : Eurailpress Tetzlaff-Hestra GmbH & Co, 2005. – 634 p.
33. McDowell, G. Performance of geogrid-reinforced ballast / Glenn McDowell, Peter Stickley // Ground Engineering. – 2006. – January. – P. 4–6.
34. Major, Z. Special problems of interaction between railway track and bridge / Z. Major // Pollack Periodica. – 2013. – Vol. 8. – Iss. 2. – P. 97–106. doi: 10.1556/Pollack.8.2013.2.11.
35. MÁV. «A 102345/1995 PHMSZ előírás 3. számúmódosítása» (Modification 3 in MÁV 102345/1995 PHMSZ. 'Railway substructure and ballast quality acceptance regulations instruction'). – Budapest, 2008. – 5 p.
36. MÁV. «A 102345/1995 PHMSZ előírás 4. számú módosítása». (Modification 4 in MÁV 102345/1995 PHMSZ. 'Railway substructure and ballast quality acceptance regulations instruction'). – Budapest, 2010. – 14 p.
37. Micro-analysis of Ballast Angularity Breakage and Evolution by Monotonic Triaxial Tests / Guixian Liu, Guoqing Jing, Dong Ding, Xiaoyi Shi // Environmental Vibrations and Transportation Geodynamics. – Singapore, 2017. – P. 133–144. doi: 10.1007/978-981-10-4508-0_12.
38. Migration of fine particles from subgrade soil to the overlying ballast / G. S. Ghataora, M. P. N. Burrow, R. S. Kamalov, M. Wehbi, P. Musgrave // Railway Engineering – 2017 : Conf. Paper (Edinburgh, 2017, June 21–22). – Edinburgh, 2017.
39. MSZ EN 1097-1:2012. «Kőanyaghalmazok mechanikai és fizikai tulajdonságainak vizsgálata. 1. rész: A kopásállóság vizsgálata (mikro-Deval)». (Tests for mechanical and physical properties of aggregates. Determination of the resistance to wear (micro-Deval). – Budapest, 2012. – 35 p.

40. MSZ EN 1097-2:2010. «Kőanyaghalmazok mechanikai és fizikai tulajdonságainak vizsgálata. 2. rész: Az aprózódással szembeni ellenállás meghatározása». (Tests for mechanical and physical properties of aggregates. Methods for the determination of resistance to fragmentation). – Budapest, 2010. – 35 p.
41. MSZ EN 933-3: Kőanyaghalmazok geometriai tulajdonságainak vizsgálata. 3. rész: A szemalak meghatározása. Lemezességi szám. – Budapest, 2012. – 12 p.
42. MSZ EN 1367-2: Kőanyaghalmazok termikus tulajdonságainak és időjárás-állóságának vizsgálati módszerei. 2. rész: Magnézium-szulfátos eljárás. – Budapest, 2010. – 16 p.
43. MSZ EN 13450:2003. «Kőanyaghalmazok vasúti ágyazathoz». (Aggregates for railway ballast). – Budapest, 2003. – 33 p.
44. Nagy, R. Description of rail track geometry deterioration process in Hungarian rail lines No. 1 and No. 140 / R. Nagy // Pollack Periodica. – 2017. – Vol. 12. – Iss. 3. – P. 141–156. doi: 10.1556/606.2017.12.3.13.
45. Nålsund, R. Prediction of railway ballast service life / R. Nålsund // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 2055–2061. doi: 10.1201/9781315100333-291.
46. Nimbalkar, S. Field assessment of ballasted railroads using geosynthetics and shock mats / S. Nimbalkar, B. Indraratna // Procedia Engineering. – 2016. – Vol. 143. – P. 1485–1494. doi: 10.1016/j.proeng.2016.06.175.
47. Pavia, C. E. L. Study Of Railway Ballast Fouling By Abrasion-Originated Particles / Cassio E. L. de Paiva, Mauro L. Pereira, Lia L. Pimentel // Railway Engineering – 2017 : Proc. of the 14th Intern. Conf. (Edinburgh, Scotland, UK, 21st–22nd June 2017). – Edinburgh, 2017.
48. Performance Assessment of Synthetic Shock Mats and Grids in the Improvement of Ballasted Tracks / B. Indraratna, S. Nimbalkar, C. Rujikiatkamjorn, T. Neville, D. Christie // Proc. of the 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering. – Paris, 2013. – P. 1283–1286.
49. Railway Construction / Sz. Fisher, B. Eller, Z. Kada, A. Németh. – Győr : Universitas-Győr Nonprofit Kft., 2015. – 334 p.
50. Roadbed improvement of an existing railway line located in cold region by reusing crushed deteriorated ballast / L. Fu, J. Xiao, S. Zhou, D. Zhang, Y. Wang, W. Liu, L. Jiang // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 1845–1850.
51. Sadeghi, J. M. Developing Track Ballast Characteristic Guideline In Order To Evaluate Its Performanc / J. M. Sadeghi, J. Ali Zakeri, M. Emad Motieyan Najar // International Journal of Railway. – 2016. – Vol. 9. – Iss. 2. – P. 27–35. doi: 10.7782/IJR.2016.9.2.027.
52. Selig, E. T. Track Geotechnology and Substructure Management Ernest / T. Selig, John M. Waters. – London : Thomas Telford, 1994. – 446 p.
53. Shakedown behaviors of railway ballast under cyclic loading / Junhua Xiao, De Zhang, Kai Wei, Zhe Luo // Construction and Building Materials. – 2017. – Vol. 155. – P. 1206–1214. doi: 10.1016/j.conbuildmat.2017.07.225.
54. Shi, X. Prediction of permanent Deformation in Railway Track : PhD thesis / X. Shi ; University of Nottingham. – Nottingham, 2009. – 262 p.
55. Some results on the properties and behavior of railway ballast / E. Fortunato, A. Paixão, S. Fontul, J. Pires // Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece). – London, 2017. – P. 1877–1884.
56. Sun, Y. Identification of ballast grading for rail track / Yifei Sun, Chen Chen, Sanjay Nimbalkar // Journal of Rock Mechanics and Geotechnical Engineering. – 2017. – Vol. 9. – Iss. 5.– P. 945–954. doi: 10.1016/j.jrmge.2017.04.006.
57. Szalóki, F. Múlt, jelen, jövő az EU-s támogatások tükrében [Electronic resource] // XVIII Közlekedésfejlesztési és Beruházási Konferencia (Bükfürdő, 2017, April 26–28). – Bükfürdő, 2017. – Available at: http://ktenet.hu/download.php?edid=1484. – Title from the screen. – Accessed : 28.02.2018.
58. Track ballast in Austria: Parts 1, 2, 3 [Electronic resource]. – P. 1–11. – Available at: https://www.plassertheurer.com/fileadmin/user_upload/Mediathek/Publikationen/ri_12888990.pdf. – Title from the screen. – Accessed : 14.05.2018.
59. Weinreich, Z. Nagysebességű vasutak pályafenntartási kitűzése / Z. Weinreich // Sínek Világa. – 2011. – Vol. 53, No 6. – P. 27–31.
60. Wichtmann, T. Effect of uniformity coefficient on G/Gmax and damping ratio of uniform to well graded quartz sands / T. Wichtmann, T. Triantafyllidis // Journal of Geotechnical and Geoenvironmental Engineering. – 2013. – Vol. 139. – Iss. 1. – P. 59–72.

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2018, № 2 (74)

С. ФІШЕР[1*], А. НЕМЕС[2]

[1*]Каф. «Інфраструктура транспорту», Університет Іштвана Сечені, пл. Університетська, 1, Д'єр, Угорщина, 9026, тел. + 36 (96) 613 544, ел. пошта fischersz@sze.hu, ORCID 0000-0001-7298-9960
[2]Каф. «Інфраструктура транспорту», Університет Іштвана Сечені, пл. Університетська, 1, Д'єр, Угорщина, 9026, тел. + 36 (96) 613 544, ел. пошта nemeth.attila@sze.hu, ORCID 0000-0002-3477-6902

СПЕЦІАЛЬНИЙ МЕТОД ЛАБОРАТОРНИХ ВИПРОБУВАНЬ ДЛЯ ОЦІНКИ РУЙНУВАННЯ ЧАСТОК МАТЕРІАЛУ ЗАЛІЗНИЧНОГО БАЛАСТУ

Мета. Існують спеціальні стандартизовані методи лабораторних випробувань для оцінки руйнування часток залізничного баласту: це установки для тестів на стирання Лос-Анджелес і Мікро-Деваль. Автори вважають, що ці методи не є достатньо адекватними для оцінки реального руйнування часток баласту, оскільки в дійсності такі напруження й деформації не відбуваються (як у барабані, що обертається, з або без стальних кульок та з водою й без води). Потрібна нова процедура лабораторних випробувань, тому метою статті є обґрунтування нової процедури цих випробувань. У 2014 році автори зробили спробу конфігурації адекватного методу і оприлюднили перші результати. Цей метод випробувань пов'язаний з динамічним пульсуючим тестом, причому розподілення розмірів часток (РРЧ) визначається як до, так і після деформацій втоми. В 2017–2018 рр. дослідження отримали новий розвиток за підтримки програми UNKP-17-4. **Методика.** Автори застосовують багаторівневу стальну коробку зі спеціальною структурою шарів, докладно опис надано в роботі. Було випробувано п'ять різних типів зразків залізничного баласту. Були визначені характеристики РРЧ, в тому числі й у вигляді співвідношення між показниками руйнування частинок баласту за іншими методами (у відповідності до випробувань на стирання в установках Лос-Анджелес, Мікро-Деваль та новим розробленим лабораторним методом випробувань). Також було визначено часовий інтервал між необхідними роботами з очищення баласту залізничної ділянки. **Результати.** Автори отримали результати, що показують напрямок подальшого розвитку лабораторного методу випробувань, який дає можливість оцінити руйнування часток та визначити часовий інтервал між роботами з очищення баласту на залізничній ділянці, більш точно пов'язаний з реальними умовами експлуатації залізничної колії. Показники руйнування часток наводяться як у відповідності до стандартизованих методів лабораторних випробувань, так і в унікальному (не стандартизованому) виді. **Наукова новизна.** В роботі об'єднані результати розробленого методу лабораторних випробувань для оцінки руйнування часток залізничного баласту. **Практична значимість.** Обґрунтовано рекомендації щодо подальшого вдосконалення вимірювань і отримання реальних оцінок в рамках програми досліджень за підтримки проекту UNKP-17-4.

Ключові слова: залізничний баласт; знос часток; руйнування часток; спеціальний метод лабораторних досліджень; динамічний тест на стирання

С. ФИШЕР[1*], А. НЕМЕС[2]

[1*]Каф. «Инфраструктура транспорта», Университет Иштвана Сечени, пл. Университетская, 1, Дьер, Венгрия, 9026, тел. + 36 (96) 613 544, эл. почта fischersz@sze.hu, ORCID 0000-0001-7298-9960
[2]Каф. «Инфраструктура транспорта», Университет Иштвана Сечени, пл. Университетская, 1, Дьер, Венгрия, 9026, тел. + 36 (96) 613 544,эл. почта nemeth.attila@sze.hu, ORCID 0000-0002-3477-6902

СПЕЦИАЛЬНЫЙ МЕТОД ЛАБОРАТОРНЫХ ИСПЫТАНИЙ ДЛЯ ОЦЕНКИ РАЗРУШЕНИЯ ЧАСТИЦ МАТЕРИАЛА ЖЕЛЕЗНОДОРОЖНОГО БАЛЛАСТА

Цель. Существуют специальные стандартизированные методы лабораторных испытаний для оценки разрушения частиц железнодорожного балласта: это установки для тестов на истирание Лос-Анджелес и Микро-Деваль. Авторы полагают, что эти методы не являются достаточно адекватными для оценки реаль-

doi: 10.15802/stp2018/130854

ного разрушения частиц балласта, поскольку в действительности данные виды напряжений и деформаций не происходят (как во вращающемся барабане со стальными шариками или без них, и с водой или без воды. Необходима новая процедура лабораторных испытаний, поэтому целью статьи является обоснование новой процедуры этих испытаний. В 2014 году авторы сделали попытку сконфигурировать адекватный метод и опубликовали первоначальные результаты. Этот метод испытаний связан с динамическим пульсирующим тестом, причем распределение размеров частиц (РРЧ) должно определяться как до, так и после усталостных деформаций. В 2017–2018 гг. исследования получили новое развитие при поддержке программы UNKP-17-4. **Методика.** Авторы используют многоуровневую стальную коробку со специальной структурой слоев, представляют подробное ее описание в статье. Проведено испытание пяти различных типов образцов железнодорожного балласта, определены характеристики РРЧ, в том числе и в виде соотношения между показателями разрушения частиц балласта по другим методам (в соответствии с испытаниями на истирание в установках Лос-Анджелес, Микро-Деваль, и новым разработанным лабораторным методом испытаний). Также определен временной интервал между необходимыми работами по очистке балласта железнодорожного участка. **Результаты.** Авторы получили результаты, показывающие направление дальнейшего развития лабораторного метода испытаний, который дает возможность оценить разрушение частиц и определить временной интервал между работами по очистке балласта на железнодорожном участке более точно в зависимости от реальных условий эксплуатации железной дороги. Показатели разрушения частиц приводятся как в соответствии со стандартизированными методами лабораторных испытаний, так и в уникальном (не стандартизированном) виде. **Научная новизна.** В работе обобщены результаты разработанного метода лабораторных испытаний для оценки разрушения частиц железнодорожного балласта. **Практическая значимость**. Обоснованы рекомендации по дальнейшему усовершенствованию измерений и получению реальных оценок в рамках программы исследований, поддерживаемой проектом UNKP-17-4.

Ключевые слова: железнодорожный балласт; износ частиц; разрушение частиц; специальный метод лабораторных испытаний; динамический тест на истирание

REFERENCES

1. Al-Saoudi, Namir K. S., & Hassan, Khawla H. (2013). Behaviour of Track Ballast Under Repeated Loading. *Geotechnical and Geological Engineering, 32(1),* 167-178. doi: 10.1007/s10706-013-9701-z. (in English)
2. Ambrus, K., & Pallós, I. (2012). *Útépítési zúzottkövek és zúzottkavicsok aszfaltkeverékek gyártásához, felületi bevonatok készítéséhez.* Retrieved from http://docplayer.hu/9502775-Utepitesi-zuzottkovek-es-zuzottkavicsok-aszfaltkeverekek-gyartasahoz-feluleti-bevonatok-keszitesehez.html. (in Hungarian)
3. Anbazhagan, P., Bharatha, T. P., & Amarajeevi, G. (2012). Study of ballast fouling in railway track formations. *Indian Geotechnical Journal, 42(2),* 87-99. doi: 10.1007/s40098-012-0006-6. (in English)
4. Brancadoro, M. G., Bianchini Ciampoli, L., Ferrante, C., Benedetto, A., Tosti, F., & Alani, A. M. (2017). An Investigation into the railway ballast grading using GPR and image analysis. *9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR): Conference Paper (Edinburgh, June 28-30).* doi: 10.1109/IWAGPR.2017.7996043. (in English)
5. Arangie, P. B. D. (1997). The influence of ballast fouling on the resilient behaviour of the ballast pavement layer. *Proc. of 6th Intern. Heavy Haul Railway Conference (Cape Town, April 6-10),* 241-256. (in English)
6. Bajpai, P., & Das, A. (2017). Theoretical assessment of railway ballast degradation under cyclic loading. *Bearing Capacity of Roads, Railways and Airfields: Proc. of the 10th Intern. Conference (June 28-30, Athens, Greece).* doi: 10.1201/9781315100333-267. (in English)
7. Bearing Capacity of Roads, Railways and Airfields: Proc. of the 10th Intern. Conference (June 28-30, Athens, Greece). (2017). London. (in English)
8. Bian, X., D., Sun, D., & Li, W. (2017). Experimental study on cyclic deformation and particle breakage of railway ballast. *Bearing Capacity of Roads, Railways and Airfields: Proc. of the 10th Intern. Conference (June 28-30, Athens, Greece),* 1801-1809. (in English)
9. Claisse, P., & Calla, C. (2006). Rail ballast: conclusions from a historical perspective. *Proceedings of the Institution of Civil Engineers-Transport, 159(2),* 69-74. doi: 10.1680/tran.2006.159.2.69. (in English)
10. Christie, D., Nimbalkar, S., & Indraratna, B. (2009). The performance of rail track incorporating the effects of ballast breakage, confining pressure and geosynthetic reinforcement. *Bearing Capacity of Roads, Railways and Airfields: Proc of the 8th Intern. Conference (June 29-July 2, Unversity of Illinois at Urbana, Champaign, Illinois, USA),* 5-24. (in English)

11. Xiao, J., Zhang, D., Wang, Y., & Luo, Z. (2017). Cumulative deformation characteristic and shakedown limit of railway ballast under cyclic loading. *Bearing Capacity of Roads, Railways and Airfields: Proc. of the 10th Intern. Conference (June 28-30, Athens, Greece),* 1899-1904. (in English)
12. Indraratna, B., Sun, Q., Ngo, N. T., & Rujikiatkamjorn, C. (2017). Current research into ballasted rail tracks: model tests and their practical implications. *Australian Journal of Structural Engineering, 18(3),* 204-220. doi: 10.1080/13287982.2017.1359398. (in English)
13. D'Angelo, G., Presti, D. Lo, & Thom, N. (2017). Optimisation of bitumen emulsion properties for ballast stabilization. *Materiales de Construcción, 67(327),* 124. doi: 10.3989/mc.2017.04416. (in English)
14. TL DBS 918 061: Technische Lieferbedingungen Gleisschotter (2006). Berlin, 2006/08. (in German)
15. Hossain, Z., Indraratna, B., Darve, F., & Thakur, P. K. (2007). DEM analysis of angular ballast breakage under cyclic loading. *Geomechanics and Geoengineering, 2(3),* 175-181. doi: 10.1080/17486020701474962. (in English)
16. Diógenes, D. F., Maia, R., & Castelo, V. (2017). Evaluation of the ballast aggregates shape properties using digital image processing techniques. *Bearing Capacity of Roads, Railways and Airfields: Proc. of the 10th Intern. Conference (June 28-30, Athens, Greece)*, 2003-2008. (in English)
17. Douglas, S. C. (2013). Ballast Quality and Breakdown during Transport. *2013 Joint Rail Conference: Conference Paper (Knoxville, Tennessee, USA, April 15-18).* doi: 10.1115/JRC2013-2553. (in English)
18. Esmaeili, M., Aela, P., & Hosseini, A. (2017). Experimental assessment of cyclic behavior of sand-fouled ballast mixed with tire derived aggregates. *Soil Dynamics and Earthquake Engineering, 98,* 1-11. doi: 10.1016/j.soildyn.2017.03.033. (in English)
19. Fischer, S. (2012). A vasúti zúzottkő ágyazat alá beépített georácsok vágánygeometriát stabilizáló hatásának vizsgálata: PhD thesis. Győr. (in Hungarian)
20. Fischer, S. (2015). A vasúti zúzottkövek aprózódásvizsgálata egyedi laboratóriumi módszerrel. *Sínek Világa, 57(3),* 12-19. (in Hungarian)
21. Fischer, S. (2017). Breakage Test of Railway Ballast Materials with New Laboratory Method. *Periodica Polytechnica Civil Engineering, 61(4),* 794-802. doi: 10.3311/PPci.8549. (in English)
22. Gaitskell, P., & Shahin, M. A. (2013). Use of digital imaging for gradation and breakage of railway ballast. *Australian Geomechanics, 48,* 81-88. (in English)
23. Gálos, M., Kárpáti, L., & Szekeres, D. (2011). Ágyazati kőanyagok: A kutatás eredményei. 2 rész. *Sínek Világa, 55(1),* 6-13. (in Hungarian)
24. Guo, Y. L., & Jing, G. Q. (2017). Ballast degradation analysis by Los Angeles Abrasion test and image analysis method. *Bearing Capacity of Roads, Railways and Airfields: Proceedings of the 10th International Conference (June 28–30, 2017, Athens, Greece),* 1811-1815. (in English)
25. Indraratna, B., Salim, W., & Rujikiatkamjorn, C. (2011). *Advanced rail geotechnology – Ballasted track.* London: CRC Press. (in English)
26. Indraratna, B., Sun, Y., & Nimbalkar, S. (2016). Laboratory assessment of the role of particle size distribution on the deformation and degradation of ballast under cyclic loading. *Journal of Geotechnical and Geoenvironmental Engineering, 142(7),* 0401601601-0401601612. doi: 10.1061/(ASCE)GT.1943-5606.0001463. (in English)
27. Kausay, T. (2011). Adalékanyagok kőzetfizikai tulajdonságai. *Út- és hídépítési műszaki előírások és alkalmazási tapasztalataik.* Budapest. Retrived from http://www.betonopus.hu/szakmernoki/kozut-2-adalekanyag-kozetfizika.pdf. (in Hungarian)
28. Kausay, T. (2008). Zúzott betonadalékanyagok kőzetfizikai tulajdonságai a szabályozásban. *Mérnökgeológia Kőzetmechanika,* 259-270. (in Hungarian)
29. Kolos, A., Konon, A., & Chistyakov, P. (2017). Change of ballast strength properties during particle abrasive wear. *Procedia Engineering, 189,* 908-915. (in English)
30. Kondratov, V., Solovyova, V., & Stepanova, I. (2017). The development of a high performance material for a ballast layer of a railway track. *Procedia Engineering, 189,* 823-828. (in English)
31. Kurhan, M. B., & Kurhan, D. M. (2017). Railway track representation in mathematical model of vehicles movement. *Science and Transport Progress, 6(72),* 40-48. doi: 10.15802/stp2017/118380. (in English)
32. Lichtberger, B. (2005). *Track compendium: Formation, Permanent Way, Maintenance, Economics.* Hamburg: Eurailpress Tetzlaff-Hestra GmbH & Co. (in English)
33. McDowell, G., & Stickley, P. (2006). Performance of geogrid-reinforced ballast. *Ground Engineering, January,* 4-6. (in English)
34. Major, Z. (2013). Special problems of interaction between railway track and bridge. *Pollack Periodica, 8(2),* 97-106. doi: 10.1556/Pollack.8.2013.2.11. (in English)

doi: 10.15802/stp2018/130854

35. A 102345/1995 PHMSZ előírás 3. számú módosítása (Modification 3 in MÁV 102345/1995 PHMSZ. ’Railway substructure and ballast quality acceptance regulations instruction’), 5 MÁV (2008). (in Hungarian)
36. A 102345/1995 PHMSZ előírás 4. számú módosítása. (Modification 4 in MÁV 102345/1995 PHMSZ. ’Railway substructure and ballast quality acceptance regulations instruction’), 14 MÁV (2010). (in Hungarian)
37. Guixian Liu, Guoqing Jing, Dong Ding, & Xiaoyi Shi. (2017). Micro-analysis of Ballast Angularity Breakage and Evolution by Monotonic Triaxial Tests. *Environmental Vibrations and Transportation Geodyna-mics*, 133-144. doi: 10.1007/978-981-10-4508-0_12. (in English)
38. Ghataora, G. S., Burrow, M. P. N., Kamalov, R. S., Wehbi, M., & Musgrave, P. (2017). Migration of fine particles from subgrade soil to the overlying ballast. *Railway Engineering – 2017: Conference Paper (Edinburgh, 2017, June 21–22).* (in English)
39. Kőanyaghalmazok mechanikai és fizikai tulajdonságainak vizsgálata. 1. rész: A kopásállóság vizsgálata (mikro-Deval). (Tests for mechanical and physical properties of aggregates. Determination of the resistance to wear (micro-Deval), 35 MSZ EN 1097-1:2012 (2012). (in Hungarian)
40. Kőanyaghalmazok mechanikai és fizikai tulajdonságainak vizsgálata. 2. rész: Az aprózódással szembeni ellenállás meghatározása. (Tests for mechanical and physical properties of aggregates. Methods for the determination of resistance to fragmentation), 35 MSZ EN 1097-2:2010 (2010). (in Hungarian)
41. Kőanyaghalmazok geometriai tulajdonságainak vizsgálata. 3. rész: A szemalak meghatározása. Lemezességi szám. 12 MSZ EN 933-3 (2012). (in Hungarian)
42. Kőanyaghalmazok termikus tulajdonságainak és időjárás-állóságának vizsgálati módszerei. 2. rész: Magnézium-szulfátos eljárás.16 MSZ EN 1367-2 (2010). (in Hungarian)
43. Kőanyaghalmazok vasúti ágyazathoz. (Aggregates for railway ballast). 33 MSZ EN 13450:2003 (2003). (in Hungarian)
44. Nagy, R. (2017). Description of rail track geometry deterioration process in Hungarian rail lines No. 1 and No. 140. *Pollack Periodica, 12(3),* 141-156. doi: 10.1556/606.2017.12.3.13. (in English)
45. Nålsund, R. (2017). Prediction of railway ballast service life. Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece), 2055-2061. doi: 10.1201/9781315100333-291. (in English)
46. Nimbalkar, S., & Indraratna, B. (2016). Field assessment of ballasted railroads using geosynthetics and shock mats. *Procedia Engineering, 143,* 1485-1494. doi: 10.1016/j.proeng.2016.06.175. (in English)
47. Pavia, C. E. L., Pereira, M. L., & Pimentel, L. L. (2017). Study Of Railway Ballast Fouling By Abrasion-Originated Particles. *Railway Engineering: Proc. of the 14th Intern. Conf. (Edinburgh, Scotland, UK, 21st–22nd June 2017).* (in English)
48. Indraratna, B., Nimbalkar, S., Rujikiatkamjorn, C., Neville, T., & Christie, D. (2013). Performance Assessment of Synthetic Shock Mats and Grids in the Improvement of Ballasted Tracks. *Proc. of the 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering,* 1283-1286. (in English)
49. Fisher, S., Eller, B., Kada, Z., & Németh, A. (2015). *Railway Construction.* Győr: Universitas-Győr Nonprofit Kft. (in Hungarian)
50. Xiao, L. Fu, J., Zhou, S., Zhang, D., Wang, Y., Liu, W., & Jiang, L. (2017). Roadbed improvement of an existing railway line located in cold region by reusing crushed deteriorated ballast. *Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece),* 1845-1850. (in English)
51. Sadeghi, J. M., Zakeri, J. Ali, & Najar, M. E. M. (2016). Developing Track Ballast Characteristic Guideline In Order To Evaluate Its Performanc. *International Journal of Railway, 9 (2),* 27-35. doi: 10.7782/IJR.2016.9.2.027. (in English)
52. Selig, E. T., & Waters, J. M. (1994). *Track Geotechnology and Substructure Management Ernest*. London: Thomas Telford. (in English)
53. Junhua Xiao, De Zhang, Kai Wei, & Zhe Luo (2017). Shakedown behaviors of railway ballast under cyclic loading. *Construction and Building Materials, 155,* 1206-1214. doi: 10.1016/j.conbuildmat.2017.07.225. (in English)
54. Shi, X. (2009). *Prediction of permanent Deformation in Railway Track* (PhD thesis). University of Nottingham, Nottingham. (in English)
55. Fortunato, E., Paixão, A., Fontul, S., Pires, J. (2017). Some results on the properties and behavior of railway ballast. *Bearing Capacity of Roads, Railways and Airfields : Proc. of the 10th Intern. Conf. (June 28–30, 2017, Athens, Greece),* 1877-1884. (in English)

doi: 10.15802/stp2018/130854

56. Sun, Y., Chen, C., & Nimbalkar, S. (2017). Identification of ballast grading for rail track. *Journal of Rock Mechanics and Geotechnical Engineering, 9(5),* 945-954. doi: 10.1016/j.jrmge.2017.04.006. (in English)
57. Szalóki, F. (2017). Múlt, jelen, jövő az EU-s támogatások tükrében. *XVIII Közlekedésfejlesztési és Beruházási Konferencia (Bükfürdő, 2017, April 26–28).* Retrived from http://ktenet.hu/download.php?edid=1484. (in Hungarian)
58. Track ballast in Austria: Parts 1, 2, 3, *1-11*. Retrived from https://www.plassertheurer.com/fileadmin/user_upload/Mediathek/Publikationen/ri_12888990.pdf. (in English)
59. Weinreich, Z. (2011). Nagysebességű vasutak pályafenntartási kitűzése. *Sínek Világa, 53(6),* 27-31. (in Hungarian)
60. Wichtmann, T., & Triantafyllidis, T. (2013). Effect of uniformity coefficient on G/Gmax and damping ratio of uniform to well graded quartz sands. *Journal of Geotechnical and Geoenvironmental Engineering, 139(1),* 59-72. (in English)

Ass. Prof. D. M. Kurhan, Dr. Sc. (Tech.) (Ukraine) recommended this article to be published

Received: Jan. 10, 2018
Accessed: April 04, 2018

