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RESEARCH ARTICLE

Breakage Test of Railway Ballast Materials with New Laboratory Method

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Abstract

This paper summarizes the results of a R&D work in 2014. Five different types of andesite railway ballast material with different LA_{RB} (%) (Los Angeles abrasion) as well as $M_{DE}RB$ (%) (Micro-Deval abrasion) values were investigated in laboratory with pulsating test which models the real condition much better (the used parameters were determined accordance with international dynamic design method). Grain size distributions related to the five several aggregates were defined before and after pulsating tests. Particle breakages were then calculated by different method publicized in international literature. Relationships were searched between particle breakages due to laboratory test and LA_{RB} (%) as well as $M_{DE}RB$ (%) values of railway ballast samples. Time interval (cycle) of ballast cleaning work were attempted to compute with help of special parameters used by Hungarian and other railway companies underlined the limits of calculation method. Finally recommendations were formulated related to use of this new laboratory test method for estimation of ballast particle breakage.

Keywords

railway engineering, ballast, laboratory, breakage test, Los Angeles value, Micro-Deval value

1 Introduction

There is an increasing social demand for rail improvement and maintenance works started in the past years and currently being made. An absolutely necessary accessory of these works is the railway ballast aggregate, which takes up a significant part of the structure mass. In current practices it is considered evident that the ballast store material of the required quality is available for us in the necessary quantity.

In the following part of the article there will be a summary of the factors which make the picture a lot more complicated and made it necessary to examine the stress on the ballast structure, the behaviour of the ballast structure in the limits of the stone material quality available for us with a laboratory procedure modelling reality better than rock physics tests and examine the reasonableness of current limit values.

It is known that on the basis of modification 4 in MÁV 102345/1995 PHMSZ 'Railway substructure and ballast quality acceptance regulations instruction' [1] that came into operation in January 2010, the regulations of December 2008 [2] for parameters of railway ballasted material usage resistance and breakage resistance were aggravated. According to modification 3 in 2008 there was a (positive) tolerance range determined for Los Angeles breakage and Micro-Deval abrasion as well, which was deleted in modification 4 of January 2010, and the values for speed categories were partly modified, mostly made stricter.

This modification (must have) resulted in certain aggravation in the requirements for ballast material producers, as a consequence, the number of stone quarries that are able to fulfil the base material demand of railways designed for 120 km/h, which means high speed in Hungarian circumstances at adequate capacity have reduced to few. In addition to this, the number of potential suppliers has been significantly reduced by the aggravation in case of 80-120 km/h speed.

Unfortunately, the natural breakage and abrasion characteristics of stones can be modified with technological solutions only to a limited extent; they basically depend on the material wealth and the mechanical characteristics of stones. On the basis of modification 4 of 102345 PHMSZ MÁV instruction,

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Table 1 Differences between required values of [1] and [2] (own edited)

Mechanical properties	LA_{RB} (%)				$M_{DE}RB$ (%)			
	between 2008 and 2009		since 2010		between 2008 and 2009		since 2010	
V_{lim} (km/h)	Required value	Max. tolerance	Required value	Max. tolerance	Required value	Max. tolerance	Required value	Max. tolerance
V>160	16	+2 (neg. is not limited)	16	–	11	+2 (neg. is not limited)	11	–
160≥V>120	16	+4 (neg. is not limited)	16	–	11	+4 (neg. is not limited)	11	–
120≥V≥80	16	+4 (neg. is not limited)	16	–	11	+4 (neg. is not limited)	15	–
80>V≥40	24	+4 (neg. is not limited)	20	–	15	+4 (neg. is not limited)	15	–
V<40	24	+4 (neg. is not limited)	24	–	15	+4 (neg. is not limited)	15	–

the railway ballasted products that had been suitable for as well as 160 km/h speed railways according to the former version did not meet the stricter requirements or only at a significant quality risk. Not only the market conditions of certain stone quarries have been damaged but the quantity of the mineral wealth suitable for this purpose has been reduced significantly. Due to the limited material wealth available that is concentrated in fewer quarries providing ballast stone material suitable for the regulation, not only the transport routes have changed but delivery costs have significantly increased, as well. Furthermore, the exploitation time of the mineral wealth has decreased because of the higher exploitage of the fewer quarries.

In professional events more and more presentations are made about the fact that environmental, nature-reservational, heritage-protective, etc. regulations hitting the stone-mining industry aggravated year by year generally mean such restrictions on the access of the natural wealth that might lead to problems in base material supply and increasing quality hazard on the medium term [3].

Unfortunately, the modification of the limit value in 102345/1995 PHMSZ was not completed with other explanations or justification. The number of quarries that can appear as suppliers for railways designed for high speed in Hungarian circumstances (160 km/h) has been significantly reduced due to the aggravation of the regulation. The examination of these effects was included as one of the goals of the research.

The main goal of our research was to evaluate available railway ballast material described with given rock mechanics parameters with a laboratory breakage test modelling real operation circumstances. Our attempt is to find and make a relationship between the breakage resulted in the unique laboratory test (parameters characterizing breakage) and Los Angeles breakage resistance and Micro-Deval abrasion resistance parameters to understand the expected behaviour of ballasted material products not permitted under the current regulation in case of building them into railways in comparison with permitted products.

Considering the breakage measured in the laboratory and the number of load cycles, the cycle of ballast cleaning work can be defined – naturally taking suitable approximations and simplifications into consideration.

2 MÁV 102345/1995 PHMSZ Instruction

In Table 1 mechanical requirements for railway ballast materials according to modifications 3 and 4 in MÁV 102345/1995 PHMSZ Instruction are summarized. When figures are examined in the table it can be seen that the requirement system for the Los Angeles breakage (abrasion) resistance parameter was aggravated without exception in 2010, for the adhesion resistance parameter in the V = 80 – 120 km/h speed category the maximum limit value of modification No. 3 was set as requirement.

Analysing the values of Table 1 it is worth recognizing that in case of V ≥ 120 km/h speed (which does not have an upper limit) standardized limit values are set in the instruction. More attention should have been paid to this by the instruction writers, because probably more stress is put on a ballast material built into a V > 160 km/h railway.

3 Parameters characterizing ballast material breakage

Based on Hungarian and international literature, the breakage of ballast material can be described with the following parameters:

- Aggregate Impact Value, AIV [4],
- Resistance to impact [4],
- Ballast Breakage Index, BBI [5, 6, 7, 8],
- Marsal Breakage (B_g) [5],
- Hardin Breakage [5].
- Lee and Farhoomand Breakage [5].

The examination of the AIV and resistance to impact is made with ballast samples filled into cylinders, a body with given mass is dropped on the ballast sample from a formerly determined height, then the ballast stone is sieved though a 2-mm-sieve. The breakage value can be calculated from the values of the mass fallen through the sieve correlated to the original mass values.

Ballast Breakage Index (BBI) was introduced by Indraratna and Lackenby to numerize how the ballast material quality changes during deterioration [5]. This parameter is used in other relevant papers [6, 7, 8] The knowledge of the particle size distribution diagram before and after the examination is needed to calculate the index. The calculation relation is the following:

$$BBI = A/\left(A+B\right). \tag{1}$$

Understanding A and B values are helped by Figure 1.

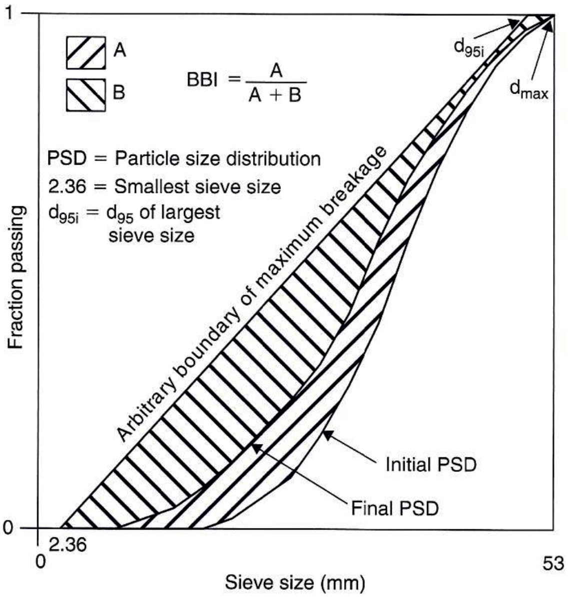

Fig. 1 Calculation of BBI [8]

Marsal breakage, Hardin breakage and Lee and Farhoomand breakage parameters can only be applied after breakage tests on ballast materials smaller than 2.0 mm.

4 Determination of the necessity of ballast cleaning work

Cycle of ballast cleaning work was 14 years in the TMK (planned preventive maintenance) system at MÁV, there are no exact data for it in the railway diagnostics-based, condition-depending maintenance system applied since the end of the 1990s.

Many different applied and recommended methods are published by Lichtberger [4].

- method recommended in ORE study [4, 9],
- method used by South African Railway Company [4, 10].

According to the ORE study ballast cleaning must be performed when the quantity of the ballast particles fallen through the 22.4-mm sieve is bigger than 30 mass %.

The method used by the South African Railway Company is the following, the F_V value must be calculated based on the following formulas:

$$F_v = 0.4 \times F_{19} + 0.3 \times F_{6.7} + 0.2 \times F_{1.18} + 0.4 \times F_{0.15} \tag{2}$$

where

$$F_{19} = \left(D_{19} \times 100\right)/27. \tag{3}$$

$$F_{6.7} = \left(D_{6.7} \times 100\right)/18. \tag{4}$$

$$F_{1.18} = \left(D_{1.18} \times 100\right)/11.5. \tag{5}$$

$$F_{0.15} = \left(D_{0.15} \times 100\right)/5.5. \tag{6}$$

“D” is the fallen mass % through the given diameter sieve.

If $F_v \geq 80$ %, ballast cleaning work is needed.

BBI published by Indraratna et al. [5] can be suitable to determine the necessity for sieving, the condition is BBI = 1.0.

5 Laboratory pulsating test

5.1 The arrangement/set-up of the pulsating test

The 6 lower frames of a 10-floor shear box published in literature [11] were used for the laboratory pulsating test. The frames were tightly screwed to each other to avoid horizontal relative displacement. The cylindrical rolls belonging to the shear box were not fitted under the box.

The layer structure built in the shear box from top to bottom was the following:

- 30-cm-thick ballast material (cross section: 46 × 46 cm),
- one layer Viacon GEO PP TC 1200 type, thermal-treated, high strength non-woven geotextile laid on the whole of the 1.0 m × 1.0 m surface,
- 10-cm-thick sand layer on the whole the 1.0 m × 1.0 m surface,
- one layer Naue Secutex 151 GRK geotextile laid on the whole of the 1.0 m × 1.0 m surface,
- Austrotherm Thermopan XPS thermal insulation sheets laid on the whole of 1.0 m × 1.0 m surface in 20-cm thickness.

The ballast samples were placed into a 46 cm × 46 cm-basic-area, 30 cm-deep box formed in the middle of the shear box with exclusion made with railway wooden sleeper. In order to reduce wall effect and its possible exclusion the four inner walls (where the ballast particles contact the wood bottom) of the box were covered in one layer Viacon GEO PP TC 1200 type geotextile. A 460 × 420 mm-surfaced, thick steel loading plate was put on the ballast particles for a more even load spread. The structure is described in Figures 2–4 without the load plate.

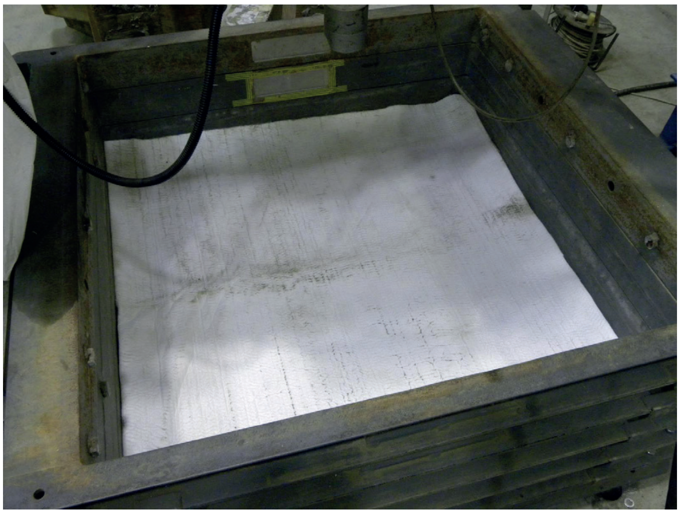

Fig. 2 Steel box and Viacon GEO PP TC 1200 geotextile laid onto 10-cm-sand layer

Fig. 3 Steel box and Viacon GEO PP TC 1200 geotextile laid onto 10-cm-sand layer, and the "box" built from wooden sleepers

Fig. 4 Viacon GEO PP TC 1200 geotextile layers glued onto wooden sleepers, and either ballast sample in the "box"

5.2 Parameters used in the test

5.2.1 Ballast materials

We were given a quantity of 500–500 kg railway ballast material in bag 'packaging' by Colas Északkő Ltd. for laboratory tests on 15 October 2014. Our aim was not the qualification of the different types of ballast material one by one, but making general deductions from their test results. Therefore, the origin of the samples will not be named, they will be referred to as five types of ballast samples identified with code numbers in this article.

All the five ballast samples are andesite, permitted quality for different railway speeds under the current regulation, and there were some samples consciously out of the allotted limit values. (These latter ones are not released as ballast material currently, they were produced only for the experiment.)

Before laboratory tests the amount of 80–100 kg samples were sieved, the particle size distribution was determined for the given material based on the values. In each case the material used for pulsating test was sieved (Naturally, the same sample was sieved after pulsating).

Due to content limit the particle size distribution diagram before pulsating test will not be included. The bottom and top particle size distribution border lines described further on belong to the 'A'-type 31.5/50 mm ballast stone determined in MSZ EN 13450:2003 standard [12].

The rock mechanics examination of ballast samples according to standards [13, 14] were provided to us by Colas Északkő Ltd., the results are published in Table 2.

Table 2 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

5.2.2 Static E_2 modulus of layer structure made of Thermopan XPS sheet and a 10-cm-thick sand layer

Static E_2 modulus measurement was performed on a layer structure made of 20-cm-thick Austrotherm Thermopan XPS sheets and a 10-cm-thick sand layer placed above them. From the two tests the mean of s_2 settlement evolved in the second load cycle was 3.306 mm.

$$E_2 = 67.5 / s_2 = 67.5 / 3.306 = 20.42\ MPa. \tag{7}$$

The same elasticity basic layer was used in all laboratory tests.

5.2.3 Load values of the pulsating test

During the pulsating test the following load parameters were applied:

$$D = 300mm\left(steel\ circle\ shaped\ load\ \ plate\right). \tag{8}$$

$$A = 460 \times 420 = 93{,}200mm^2\left(surf.\ of\ steel\ load.\ plate\right). \tag{9}$$

$$F_{min} = 20\ kN. \tag{10}$$

$$F_{max} = 120.74\ kN,\ rounded\ up:\ 121.0kN. \tag{11}$$

$$m = 3 \times 10^6\left(repetition\ cycles\right). \tag{12}$$

$$f = 7Hz\ \left(sinus\ load\right). \tag{13}$$

Calculation of F_{max} value

$$A_{load\ plate} = 460 \times 420 = 193{,}200mm^2. \tag{14}$$

$$A_{half\ sleeper\ base\ contact\ area} = 800 \times 200 = 160{,}000mm^2. \tag{15}$$

$$p_1 = A_{load\ plate} / A_{half\ sleeper\ base\ contact\ area} = 1.2075. \tag{16}$$

$$F_{stat,wheel} = 112.5kN. \tag{17}$$

$p_2 = 0.4$ from the wheel load above the sleeper the evolving reaction force on the sleeper is about 40% of the wheel load.

$p_3 = 1.111$ (5/9 division instead of 1/2 because of force eccentricity).

$p_4 = 2.0$ (dynamic multiplier taken with high safety).

$$F_{max} = F_{stat,wheel} \times p_1 \times p_2 \times p_3 \times p_4 = \qquad (18)$$
$$= 112.5 \times 1.2075 \times 0.40 \times 1.111 \times \times 2.0 = 120.74\ kN \sim 121.0.$$

Calculation of p4 factor and its meaning:

$$p_4 = 1 + (t \times s). \qquad (19)$$

t = 3 counted (99.7% statistic safety based on the Zimmermann-Eisenmann method),

$$s = n \times j. \qquad (20)$$

$$j = 1 + (V - 60)/140. \qquad (21)$$

If n = 0.3 (medium substructure and/or railway track condition), V = 75.4 km/h.

If n = 0.2 (good substructure and/or railway track condition), V = 153 km/h,

If n = 0.1 very good substructure and/or railway track condition), V > 200 km/h.

5.2.4 Parameters of high strenght non-woven geotextile used in the tests, and particle size distribution functions

Viacon GEO PP TC 1200 geotextile was applied in the pulsating test. The geotextile was ensured by László Kárpáti, senior engineer of Viacon Hungary Ltd, which we appreciate posteriorly, too. The parameters of the geotextile can be found at the webpage of Geotex 2000 [15].

Particle size distribution diagrams before and after the 3×10^6 pulsating cycles are published in Figures 5–6.

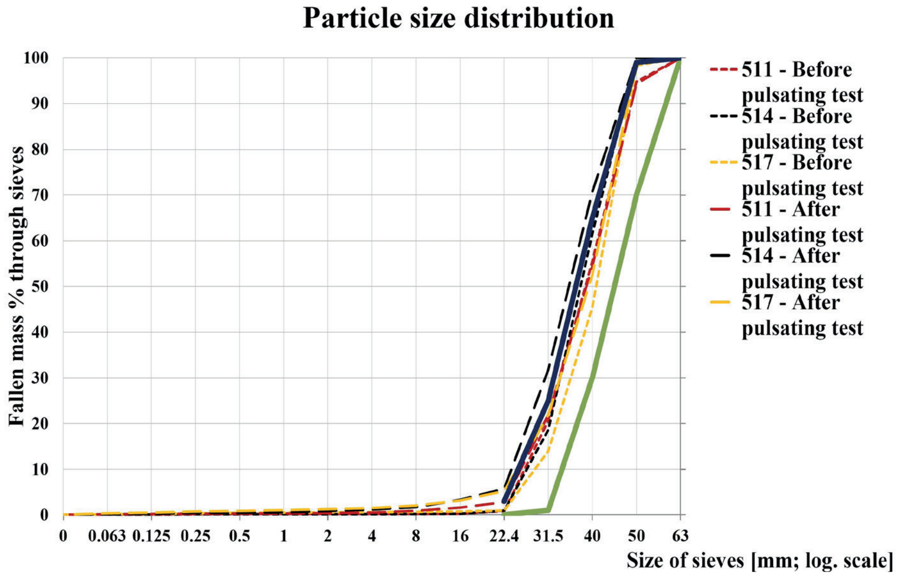

Fig. 5 Particle size distribution diagrams of 511, 514 and 517 ballast samples before and after pulsating test

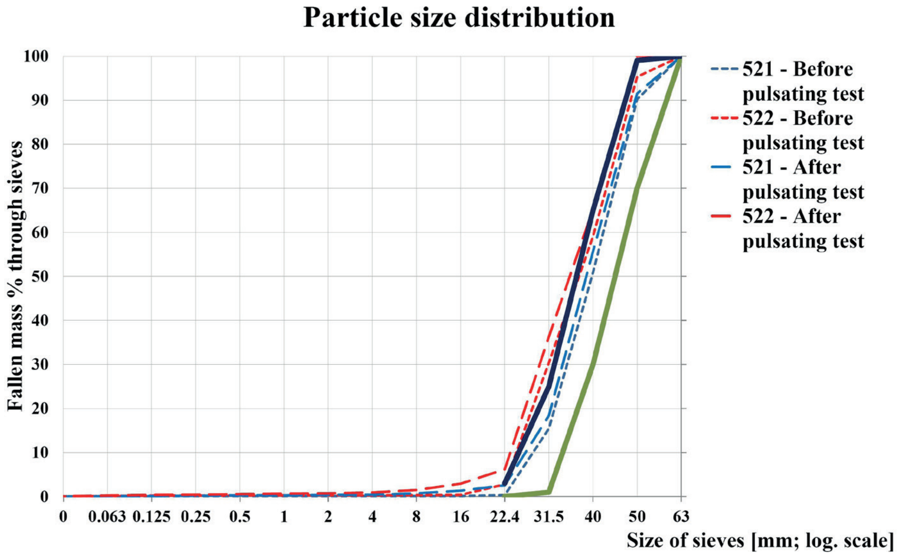

Fig. 6 Particle size distribution diagrams of 521 and 522 ballast samples before and after pulsating test

Due to content limit only ballast sample 517 will be described after pulsating with the breakage particles as an example (Figure 7).

Fig. 7 Ballast sample 517 after pulsating test

5.3 Evaluation of laboratory measurement tests

The formerly introduced ballast material breakage parameters and index numbers for the necessity of ballast sieving were calculated, which were according to the values in Table 3.

Table 3 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
d<22.4 mm (BP) (%)	0.851	0.918	0.963	0.333	2.784
d<22.4 mm (AP) (%)	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 3 "BP" and "AP" abbreviations mean "before pulsating test" and "after pulsating test".

In Table 3 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 [16], are indicated.

Breakage parameters in Table 3 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 8).

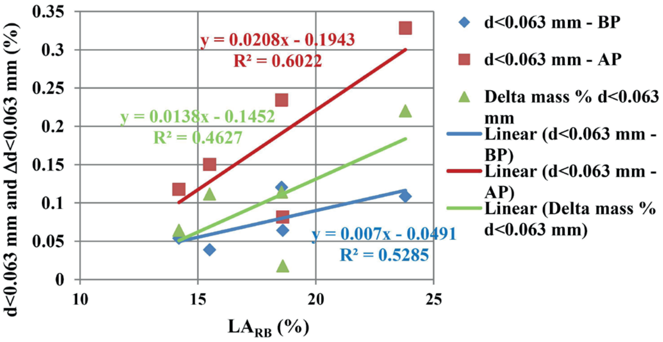

Fig. 8 Parameters d < 0.063 mm and Δd < 0.063 mm as a function of LA_{RB} (%)

Based on Figure 8 and the graphs not published here the following statement can be made:

- There is no (strong) correlation between one breakage parameter and its change and the measured and calculated rock mechanics parameters found.
- During Los Angeles and Micro-Deval abrasion test the ballast particles are examined under circumstances significantly different from their real (in railway track) load, stress, consequently, the lack of correlation between these parameters and the measured particle breakage received during the unique laboratory test described in the current research and development work, which models the real behaviour of ballast beam particles at real repeated load is not fully surprising and unexpected.
- In literature [17] where particle breakage caused by machine tamping was examined in laboratory circumstances, a correlation between LA_{RB} (%) and particle shape factors was impossible to be found.

5.4 Calculation of the cycle of ballast cleaning work based on the results of laboratory measurements

In this chapter the cycle of ballast cleaning work will be estimated based on the results received from laboratory pulsating particle degradation (breakage) test test of andesite railway ballast material samples originating from five different quarries. The following approximations and simplifications were taken into consideration in the calculation:

Table 4 Calculated mininum time interval of ballast cleaning work 1.

No. of ballast sample	LA_{RB} (%)	$M_{DE}RB$ (%)	Calc. no. of cycle from F_V=80 % (number of through-rolled axles ×10^6)	Calc. no. of cycle from d<22.4 mm =30% (number of through-rolled axles ×10^6)	Calc. no. of cycle from BBI=1.0 (number of through-rolled axles ×10^6)	Min. number of cycles (number of through-rolled axles ×10^6)	Min. number of cycles (number of through-rolled axles ×225 kN ×10^6)	Min. time interval of ballast cleaning work (year)*
511	14.20	3.60	63.33	45.90	166.87	45.90	1,032.76	68.85
514	16.70	9.70	25.99	18.67	12.09	12.09	272.06	18.14
517	23.80	16.00	28.05	21.26	20.18	20.18	454.12	30.27
521	18.60	16.70	64.07	40.88	39.00	39.00	877.53	58.50
522	18.55	17.00	33.89	26.44	15.37	15.37	345.84	23.06

*: calculated from 15 Million through-rolled axles a year

Table 5 Calculated mininum time interval of ballast cleaning work 2.

No. of ballast sample	LA_{RB} (%)	$M_{DE}RB$ (%)	LA_{RB} + $M_{DE}RB$	Calc. no. of cycle from d<22.4 mm =30% (number of through-rolled axles ×10^6)	Min. number of cycles (number of through-rolled axles ×10^6)	Min. number of cycles (number of through-rolled axles ×225 kN ×10^6)	Min. time interval of ballast cleaning work (year)*
511	14.20	3.60	17.80	45.90	45.90	1,032.76	68.85
514	16.70	9.70	26.40	18.67	18.67	420.05	28.00
517	23.80	16.00	39.80	21.26	21.26	478.34	31.89
521	18.60	16.70	35.30	40.88	40.88	919.70	61.31
522	18.55	17.00	35.55	26.44	26.44	594.82	39.65

*: calculated from 15 Million through-rolled axles a year

- Neither machine-made nor manual tamping indicated breakage is taken into consideration.
- Deterioration effect accelerated by substructural defect or superstructural defect is not taken into consideration.
- Other ballast polluting effects (dust, concrete sleeper abrasion, breakage, in case of water pockets the increase of fine particle content in the ballast bed because of evolving pumping effect due to repeated dynamic load, etc.) are neglected.
- In the whole ballast cross section such amount of breakage does not evolve as the one that was measured in our laboratory tests, for example ballast particles in real tracks hardly break in the ballast shoulder and the slope of the ballast bed, our approach at this point was that these outer parts without breakage in the ballast bed were neglected and our calculation reflected the whole cross section.
- The calculation was made on the basis of initial breakage values and the ones after 3×10^6 pulsating cycles, for the determination of more exact regression functions at least 2–3 further measurement results would be needed in case of each ballast sample.
- In the calculation the Kelenföld-Hegyeshalom railway line and the average annual approximate through-rolled tons load (about 15 million tons/direction) of this railway track was set as basis.
- Only 225 kN axle load was taken into consideration (it is true for freight trains, for passenger trains about 180 kN value would be more realistic).

The determination of the necessity of ballast cleaning work was made with the methods described earlier (Table 4).

As it was mentioned before, the cycle of ballast cleaning work was about 10–15 years at MÁV when TMK system was applied. Although there are significant simplifications in our calculation, the 18-year cycle time resulted in the case of No. 514 ballast stone sample on the Kelenföld-Hegyeshalom railway line would be smaller than the long-ago 10–15-year value of MÁV.

As cycle times are analysed it is obvious that ballast stone sample No. 511 – supported by the significantly low LA_{RB} (%) $M_{DE}RB$ (%) values and the laboratory breakage test results – owns one of the best rock mechanics parameters out of the five, with a resulted cycle of ballast cleaning work of nearly 69 years. When all the ballast contamination effects are considered, the 10–15-year-long ballast cleaning work time interval of the TMK system can presumably be kept with this type of railway ballast material.

In Table 5 the base of the calculation was prepared only with the mass percentage proportion of d < 22.4 mm particles. This is nearer the determination of the Hungarian theoretical ballast cleaning necessity. A ballast cleaning is usually performed to estimate the amount of ballast material under the railway track (generally before the ballast cleaning). The d < 20…23 mm particles are removed from the ballast bed by the ballast-cleaner machine, this is called waste material from ballast cleaning.

According to the data in Table 5, minimum time intervals of ballast cleaning work have partly changed (increased), e.g. with the ballast stone sample coded 514 from 18 years to 28 years.

6 Conclusions

The importance of aligned research work in connection with the topic is highlighted by the research results, in which it is practical to include:

- A new laboratory method for ballast breakage test was developed by the author detailed in this paper. It is recommended to use for evaluation the ballast breakage more precisely than Los Angeles and Micro-Deval abrasion values, because of the more realistic boundary conditions.
- The measurement of the quality-quantity-capacity-location of the mineral wealth available as the first step.
- A widespread test-series to be started, in which a high number of laboratory experiments and the introduced half-operation experiment should be included, furthermore, the condition and load of recently built railway tracks should be analysed.
- The expected base material demand of railway investments should be determined at least on medium-term.
- Following the above, requirements should be supervised relying on the objective results in terms of sustainability.

Further research possibilities are expressed based on the performed literature research and the results of laboratory measurements:

- laboratory measurements with different border conditions (e.g. changing the E_2 modulus of the layer structure modelling the substructure, possibly usage of under ballast mat),
- examination of special structured (higher rigidity) ballast materials (e.g. bonded ballast) [18],
- the more precise measurement of the temporal change of breakage (in pulsating cycle number), e.g. with the following method:
    - at least 3–5 unique examinations from each ballast sample, recording particle size distribution before and after pulsating:
      - for 5×10^5 pulsating cycles,
      - for 1×10^6 pulsating cycles,
      - for 2×10^6 pulsating cycles,
      - for 3×10^6 pulsating cycles,
      - for 5×10^6 pulsating cycles.
- The refinement of calculation method of cycle of ballast cleaning work.

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