THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

ISSN 1822-427X / eISSN 1822-4288
2017 Volume 12(3): 203–209

PREDICTION OF LIFESPAN OF RAILWAY BALLAST AGGREGATE ACCORDING TO MECHANICAL PROPERTIES OF IT

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Abstract. As the railway lifespan is the main criterion for selection of the aggregate for ballast and for planning the maintenance of the railroad, it is important to define the relationship between the particle load resistant characteristics and a lifetime of ballast in structure. Assessment of the quality of the ballast aggregate particles under dynamic and static loading reflect both, the toughness and hardness, and these are identified with the Los Angeles Abrasion and Micro-Deval Abrasion values. The model formerly developed by Canadian Pacific Railroads was adapted to predict possible loads expressed in cumulated tonnes. Different ballast aggregate mixtures were tested in the laboratory including dolomite and granite. Calculated potential gross tonnage (expressed in Million Gross Tonnes) of the railway per lifetime for each different aggregate type presented. The outcome of this research is established classification system of railway ballast aggregate and defined Los Angeles Abrasion and Micro-Deval Abrasion values of aggregate dependently on required lifetime.

Keywords: aggregate selection, ballast, lifespan, Los Angeles Abrasion, mechanical properties, Micro-Deval Abrasion.

1. Introduction

The use of poor quality ballast leads to shorter tamping intervals, a shorter ballast lifespan, and thus to increased life cycle costs (Vale, Ribeiro 2014). Railway companies employ specific quality control testing methods (McDowell *et al.* 2004) to ensure the desired mechanical behaviour (i.e., resistance to fragmentation and abrasion). In part, such tests have been used without change for several decades. The tests are meant to simulate the loads acting upon the ballast in track (Famurewa *et al.* 2015; Villarejo *et al.* 2016). Some tests results are highly variable and often show poor repeatability. The reasons for this remain undefined. Several possibilities for improvement have been suggested, for example, use of alternative test evaluation methods, adjustment of test procedures, and even the use of entirely new test methods (Bach 2013). It is usually required to determine the conformity of all its characteristics to standard requirements when evaluating the suitability of crushed stone to equip ballast aggregate. However, seeking to select the suitable crushed stone, the mechanical properties of ballast aggregate become the most important, which most determine the functioning of all prism of ballast during operation. The relation between mechanical properties and lifespan of ballast has to be identified aiming to classify the mechanical properties under the prospective cumulative traffic flows. The usage of such classification provides the opportunity to select the suitable mixture of crushed stone to equip prism of the ballast of the railway concerning supposed cumulative traffic flow during design time.

Without exception, every ballast specification attempts to assess the quality of the ballast particles under loading. Ideally, this quality measure reflects both, the hardness and toughness of the ballast particles. The typical tests that are performed on a mix of the particles by railroads worldwide include impact testing, crushing value testing, Los Angeles Abrasion (LAA) testing, and the like. These tests set only toughness of the ballast aggregation while the hardness of minerals has low influence on the results of these tests. For any couple of these tests (e.g. Los Angeles Abrasion and Impact Factor by *EN 1097–2:2010 Tests for Mechanical and Physical Properties of Aggregates – Part 2: Methods for the Determination of Resistance to Fragmentation*) pretty strong correlation is received (Gaskin,

doi:10.3846/bjrbe.2017.25

Raymond 1976), so it is enough to perform one of these tests, and LAA test is most often chosen in practice. It is noticeable that accepted practice to perform LAA tests together with impact factor tests is oversupply.

Field break down influenced by harder mineral rock is often slower because less powdering occurs at the contact points of particles, and the broken particles are more angular and coarser resulting in a slower rate of track fouling (McDowell, Bolton 1998). Comparing ballast aggregates having equal values of LAA, ballast, made of harder mineral grains, shows better results under the fieldwork (Raymond 1985). Therefore, the comparison of materials, only assessing the values of LAA and resistance to dynamic crushing, which essentially specifies toughness of rock, does not ensure selection of the most appropriate material. Rocks are made of minerals, having different hardness values. Therefore the method, allowing to evaluate overall hardness of the rock, has been needed. The method has been achieved by application of Mill Abrasion (MA) test, generally used in the mining industry (McIntyre, Plitt 1980). The indicator, showing particles resistance to wear due to grinding, is measured by this test.

2. Resistance to fragmentation and wear

Resistance to fragmentation. The main reasons for ballast degradation are ballast fragmentation and wear. They destine settlement of a road and increase expenses for maintenance of track geometry (Navikas *et al.* 2016; Tennakoon *et al.* 2014). The indicator of particles resistance to fragmentation, the coefficient of Los Angeles Abrasion (*LAA*), is determined by applying Los Angeles Abrasion test under standard (*LST EN 1097–2:2010*). It is intended to assess the strength of ballast particles and potency not to crack under the sleeper. However, additional tests are needed to use to measure degradation of ballast concerning wear, which is influenced by particles mutual friction. Inner interaction of particles is an unavoidable mechanism of ballast degradation.

Resistance to wear. Ballast construction stability is reflected by *MA* test and particles resistance to wear due to grinding is determined by this test. The concept of *MA* test is based on Micro-Deval Abrasion (M_{DE}) test *EN 1097–1:2011 Tests for Mechanical and Physical Properties of Aggregates – Part 1: Determination of the Resistance to Wear (Micro-Deval)*. Mill Abrasion and Micro-Deval Abrasion assays equally allow determining the resistance to wear avoiding fragmentation (or it is imperceptible). Los Angeles Abrasion tests better measure resistance to fragmentation of particles. It has been identified that MA partially correlates with results of Deval test (Raymond, Diyaljee 1979). Mill Abrasion is the test of wet particles wear because of grinding. This test is performed by spinning 3.0 kg of ballast aggregate (fraction 19/37.5 mm) and 3.0 l of water in a porcelain jar 10.000 times. Concerning the spinning of a porcelain jar, ballast particles wrestle one over other and wear avoiding significant fragmentation of particles, taking place at the time of *LAA* test (Selig, Boucher 1990).

Alternatively, ballast aggregate is assessed to analogical resistance to wear due to grinding, applying Micro-Deval Abrasion test, which is described in *EN 1097–1:2011* and *ASTM D6928-10 Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* M_{DE} test is performed by spinning of 10 kg ballast aggregate (fraction 31.5/50 mm) and 2.0 l of water in a metal jar 10.000 times. When the metal jar is spinning ballast particles, wrestle one over other and wear as in the time of *MA* test, avoiding significant fragmentation of particles.

3. Prediction model for ballast aggregate lifespan

Rocks having a predominance of hard minerals were noted to have low *MA* values. Rocks consisting of similar minerals were also noted to have a variation in values based on their degree of induration or compactness, which added to the significance of the test for assessing rock hardness (Raymond 1985). These observations mean that operating the probable performance of ballast aggregate on the road needs to be evaluated combining the results of *LAA* and *MA* tests. The study of ballast degradation has been performed by Canadian Pacific Railroads (CPR) order (Klassen *et al.* 1987). There has been determined that different relative performance of rocks, intended to ballast aggregate, is represented by Abrasion Number (N_A), which is determined as the sum of *LAA* value and five *MA* values:

$$N_A = LAA + 5MA , \tag{1}$$

where N_A – Abrasion Number, %; *LAA* – Los Angeles Abrasion value, %; *MA* – Mill Abrasion value, %.

Procedures of MA test (Raymond, Diyaljee 1979) and determination of N_A indicator have been included into CPR normative specifications. Canadian Pacific Railroad has connected N_A values of used material for ballast aggregation with the observed life of ballast, which is expressed in accumulated traffic flow Million Gross Tons (MGT) to result in breakdown to the point where the ballast needed renewal. Lifespan has been determined to ballast that is under wooden sleepers. Railway sections, which were severely affected by environmental factors and heavily fouled by outside fouling sources, have not been included in the latter study. Furthermore, the model does not evaluate ballast fouling by fine particles due to ballast tamping under the sleeper, done during the routine repairs, seeking to rebuild the track geometry. However, the received results allow prognostication of ballast lifespan under ideal operating conditions, whereas comparing lifespan indicators of different aggregates it is possible to select the suitable option from both the economic and engineering points of view.

$$Life = 10^6 \exp\left(8.08 - 0.0382 N_A\right) , \tag{2}$$

where *Life* – lifespan of the ballast, expressed in accumulated traffic flow MGT.

Seeking to adapt CPR model for use in Lithuania, correction coefficients are used. Description and assumptions, applied to calculations, are presented further.

Measurement units. Calculating by analysed model, the results are received by widely used mass measurement unit "short ton" (marking ton): 1 ton = 0.9074847 t = 907.1847 kg. It is accepted in Europe that 1 t = 1000 kg, so correction coefficient: A_k = 1000/907.1847 has to be applied to calculation model of ballast lifespan. It is accepted that A_k = 1.102.

Axle load. Canadian Pacific Railroad used model has been adapted to maximum axle load of 30 tones. Maximum axle load of 25 t is applied in Lithuania, so it is needed to determine correction coefficient B_k that allows assessing the difference between different permissible axle loads. The impact to the ballast is approximately equal to half impact for the track (Esveld 2011), and ballast degradation directly affects the geometry of a road. Besides, 10% increase in ballast stress conditions faster decreases of the road geometry quality from 1.2 to 1.5 time. The examined model is applied to greater axle load of 20% than permissible axle load of 25 t in Lithuania. Therefore, ballast degradation, when maximum 25 t axle load is allowed, is at least slower of B_k times: $B_k = 1 + 0.2 \times 2 = 1.400$. It is accepted B_k =1.400.

Sleepers. Used model of CPR has been applied to prognosticate ballast lifespan when wooden sleepers are used in the superstructure. Therefore, correction coefficient C_k has to be determined, allowing to assess the influence of sleeper type. Using concrete sleepers, dynamic loads and stresses in ballast are up to 25% greater than using wooden sleepers (Selig, Waters 1994), so ballast degradation under concrete sleepers is at least C_k times faster (than at wooden tracks): $C_k = 1 + 0.2 \times 2.5 = 1.500$. Correction coefficient, reverse to value C_k: $C_k^{-1} = 1/1.500 = 2/3$ is taken for adjustment of lifespan calculation model. It is accepted that $C_k^{-1} = 0.667$.

Determination of the resistance to wear. There were no previous studies found where *MA* and Micro-Deval Abrasion tests determine the relation in received results. However, it is known that *MA* test concept is based on Micro-Deval Abrasion (M_{DE}) test (Klassen *et al.* 1987; Raymond 1985). Indicators of the same rock *MA* and M_{DE} are usually very similar. So it is assumed that $MA = M_{DE}$ and then Abrasion Number is:

$$N_A = LAA + 5M_{DE}, \tag{3}$$

where N_A – Abrasion Number, %; *LAA* – Los Angeles Abrasion value, %; M_{DE} – Micro-Deval Abrasion value, %.

Durability to the ballast is identified in cases when wooden and concrete sleepers are used. Therefore, "Life" symbolising durability is changed respectively to symbols L_M and $L_{\frac{G}{B}}$.

When wooden sleepers are used in the construction, Equation (2) is adjusted for identification of ballast durability L_M, using previously accepted coefficients of adjustment, A_k and B_k:

$$L_M = A_K B_K \left(10^6 \exp\left(8.08 - 0.0382 N_A\right)\right) = \\ = 1.102 \cdot 1.400 \left(10^6 \exp\left(8.08 - 0.0382 N_A\right)\right). \tag{4}$$

When N_A opened out in Equation (4) according to Equation (3), the final equation for ballast durability is received, when sleepers are wooden, to calculate:

$$L_M = 1.5428\left(10^6 \exp\left(8.08 - 0.0382 N_A\right)\right). \tag{5}$$

When concrete sleepers are used to identify ballast durability ($L_{\frac{G}{B}}$) in construction, Equation (5) is adjusted using previously accepted correction coefficient C_k^{-1} :

$$L_{\frac{G}{B}} = C_k^{-1} L_M = 0.667 L_M. \tag{6}$$

The final equation used to calculate ballast durability when sleepers are concrete:

$$L_{\frac{G}{B}} = C_k^{-1} L_M = 1.029\left(10^6 \exp\left(8.08 - \\ 0.0382\left(LAA + 5M_{DE}\right)\right)\right). \tag{7}$$

Using Equations (3)–(5) it is possible to calculate the prognostic ballast durability due to fixed values of mechanical properties. The prognostic ballast durability is expressed as MGT.

4. Assessment of results of ballast aggregate lifespan prognostic calculations

Prognostic lifespan calculations are performed assessing indicators of Los Angeles Abrasion and Micro-Deval Abrasion. Therefore, the received results of these calculations is a complex evaluation of crushed stone mixture (mineral materials) most important mechanical properties. Experimental research has been performed in a laboratory seeking to determine and evaluate mechanical properties of various origin crushed stone from different suppliers. Two dolomite and three granite crushed stone mixtures from three different suppliers were selected and researched. Crushed stone mixtures of dolomite were encoded D1 and D2. Granite crushed stone mixtures have been encoded G1, G2, and G3.

After each test of *LAA* and M_{DE} dried samples were primarily analysed visually. Most individual photos of each mixture (after *LAA* and M_{DE} tests) are presented respectively in Figs 1–2. Los Angeles Abrasion and Micro-Deval Abrasion indicators identified by laboratory research are given in Table 1. Abrasion Number N_A and prognostic lifespan of ballast aggregate L_M and $L_{\frac{G}{B}}$ for researched materials in a laboratory are calculated according to Equations (3)–(5) (Table 1).

The determined results of particles resistance to wear and fragmentation and maximum permissible parameter

Table 1. Prognostic calculations results of ballast aggregate lifespan

Material	Indicators, determined in laboratory		Calculated indicators		
	Los Angeles Abrasion	Micro-Deval Abrasion	Abrasion Number	Ballast durability when sleepers are	
	%			wooden, MGT	concrete, MGT
D1	21.1	10.6	74.1	294	196
D2	22.7	12.4	84.7	196	131
G1	14.7	5.1	40.2	1073	715
G2	9.2	4.9	33.7	1375	917
G3	14.6	7.3	51.1	707	472

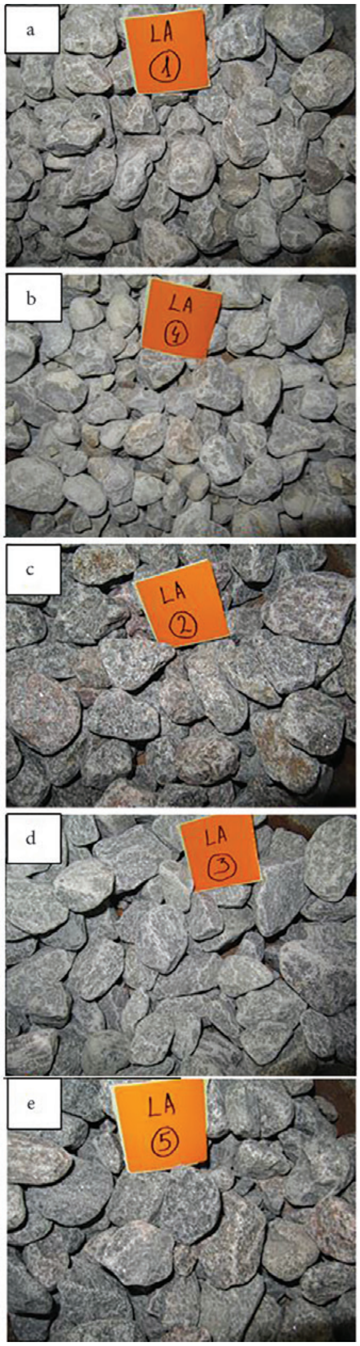

Fig. 1. The dried samples after the Los Angeles Abrasion test (Figure parts a, b, c, d, e provide the D1, D2, G1, G2, G3 mixtures)

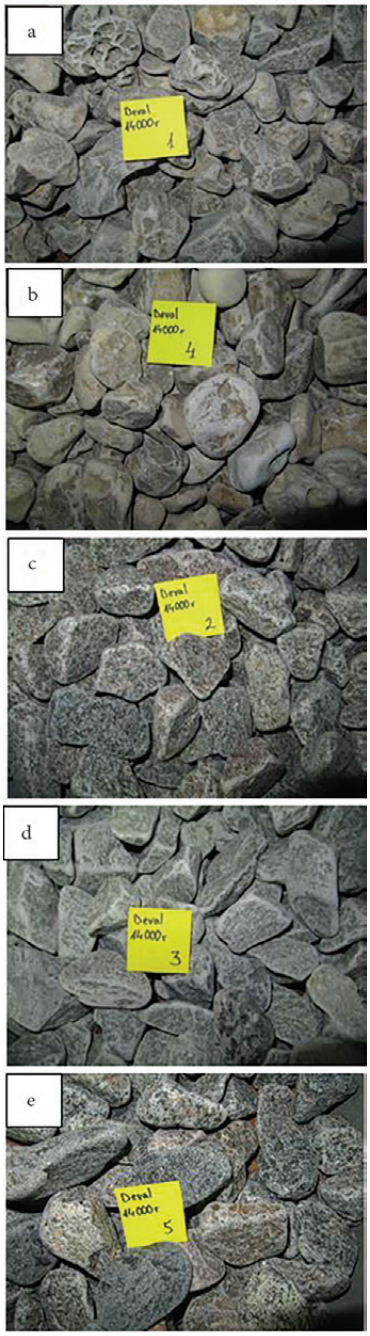

Fig. 2. The dried samples after the Micro-Deval Abrasion test (Figure parts a, b, c, d, e provide the D1, D2, G1, G2, G3 mixtures)

values in Lithuania and foreign countries are given in Fig. 3. It is seen that according to existing regulatory documents in Lithuania the mentioned indicators of all researched materials in the laboratory are admissible because maximum allowed value of Micro-Deval Abrasion indicator is not exceeded, and Los Angeles Abrasion indicator is not rationed.

The significant difference is seen in prognosticated sizes of lifespan, presented in results of calculations (Table 1), when sleepers are wooden and when sleepers are of concrete. The difference is averagely 33% concerning correction coefficient C_k, used to evaluate the influence of concrete sleepers to the rapidity of ballast degradation.

After comparison of performed calculation results of crushed stone mixtures G2 and D2, it was found that lifespan of different materials differs seven times dependently on mechanical indicators. Despite this, it is prognosticated that dolomite crushed stone mixture D1 can hold out almost 200 MGT of traffic loads. These results show lifespan of ballast aggregate under ideal operating conditions. It is accepted that there is no fouling out of blanketing sand, subgrade and any other external source.

Seeing that 76% of ballast fouling appear due to degradation of it (Selig, Waters 1994), it is possible to reduce the prognostic lifespan of 200 MGT for 24% and approximately receive prognostic lifespan of 150 MGT. Calculated by analogy lifespan $L_{\frac{G}{B}}$ of crushed granite mixture G2, 688 MGT is received. The latter parameter has already become closer to reality because there is 397 km of railway sections in 2015 where 595 MGT were transported through them at an average. Sections have been determined where more than 890 MGT (0.9 km), 740 MGT (18.3 km), and 690 MGT (42.4 km) were transported. Major repair has been delayed in all these sections. High traffic volume is in most of these sections, but road condition is good enough.

However, ballast degradation due to ballast tamping, performed during the time maintenance or routine repair, is not evaluated. Ballast degrades much faster during tamping, and real lifespan mostly depends on the periodicity of ballast tamping. Besides, ballast fouling from outside or fouling due to sub-soil penetration changes. For example, fouling from outside sources on roads of stations are significantly higher, and penetration of sub-soils is stopped if geotextile is used for equipment of subgrade. Concerning the latter reasons, it has been decided to do lifespan prognostic calculations assuming that operating conditions are ideal.

After calculations by analogy presented in Table 1 under Equations (3)–(7), the separate graphic models of ballast durability prognostication were made: Fig. 4, when sleepers are wooden and Fig. 5 when sleepers are of concrete. These graphic models (Fig 4–5) are further used as the basis for classification of Los Angeles Abrasion and Micro-Deval Abrasion indicators. Values of parameters of classified mechanical properties are divided into five categories, as it is submitted in Table 2.

Rail access roads, local and connecting railway lines belong to the railway category "Other roads", presented in

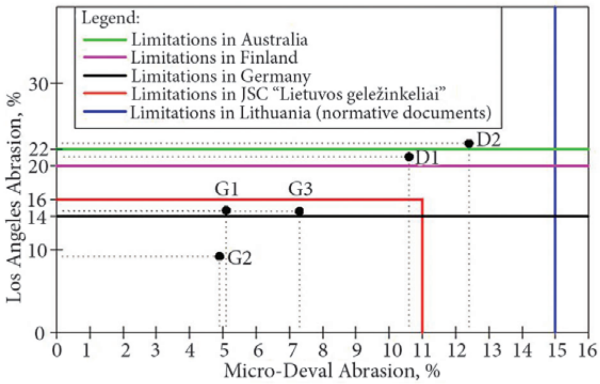

Fig. 3. Determination results of particles resistance to wear and fragmentation and maximum permissible values of these parameters in Lithuania and abroad

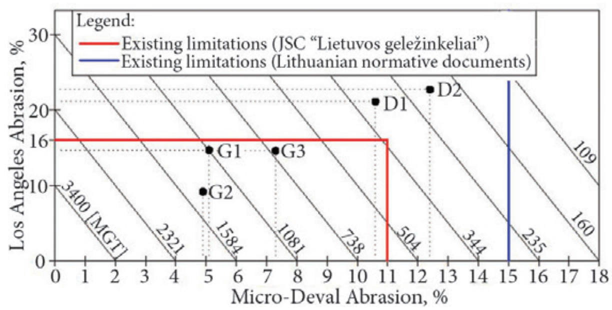

Fig. 4. Lifespan prognostic graphic model of ballast aggregate as sleepers are made of wood

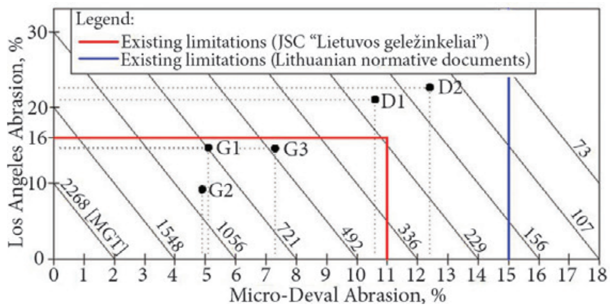

Fig. 5. Lifespan prognostic graphic model of ballast aggregate as sleepers are made of concrete

Table 2. Division of ballast aggregate mechanical properties categories

Category of ballast mechanical properties	Category of the railway line	Annual traffic volume, MGT
K-1	GLK–Highway	–
	GLK–High traffic volume	≥50
K-2	GLK-I	30–50
K-3	GLK-II	8–30
	GLK-III	
K-4	GLK-IV	≤8
	Other roads	2–8
K-5	Other roads	≤2

Table 2. Highway rail lines for passenger trains to run at 160 km/h until 200 km/h are assigned to category K-1 of ballast mechanical properties.

As it has been mentioned, graphs in Figs 4–5 are taken as the basis for classification of Los Angeles Abrasion and Micro-Deval Abrasion indicators. Suggested restriction limits to each category are being inscribed given in Fig. 3, where identification results of particles resistance to wear and resistance to fragmentation and maximum allowed sizes of these parameters in Lithuania and abroad are given.

The suggested Los Angeles Abrasion and Micro-Deval Abrasion value classification when sleepers are wooden and when they are of concrete are respectively presented in Fig 6–7. They show that the recommended restriction limits do not exceed the maximum permissible size ($M_{DE} \leq 15\%$) specified in current Lithuanian normative documents. The defined boundaries ($LA_{RB} \leq 16\%$; $M_{DE} \leq 11\%$) by JSC "Lietuvos geležinkeliai: includes categories K-1, K-2 and partly K-3 of ballast mechanical properties. Highways, High traffic volume, I, II and III categories of railways are given in Table 2. The suggested classification of Los Angeles Abrasion and Micro-Deval Abrasion values divides materials only considering mechanical properties. Thus the conditions are fixed not only for usage of granite but also for the usage of another crushed stone in rail lines, where is (or it is expected to be) low annual traffic volume.

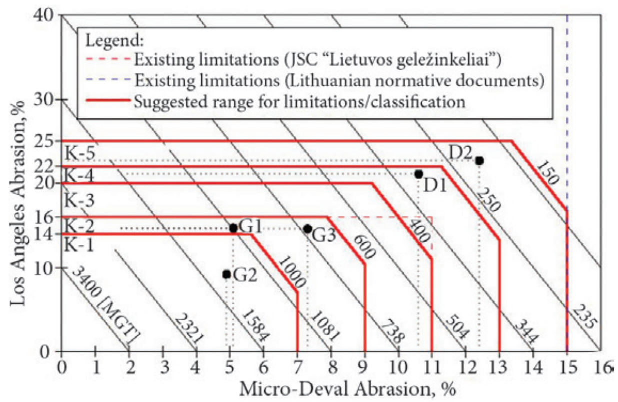

Fig. 6. Classification of Micro-Deval Abrasion and Los Angeles Abrasion indicators as sleepers are made of wood

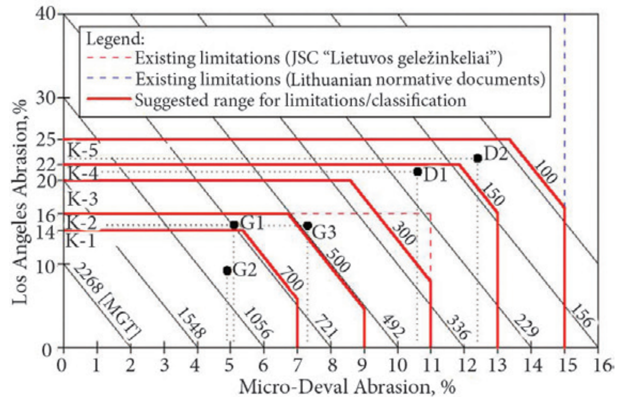

Fig. 7. Classification of Micro-Deval Abrasion and Los Angeles Abrasion indicators as sleepers are made of concrete

5. Conclusions

1. Toughness and hardness of ballast aggregate particles directly influence the residual life of ballast prism of the railroad. Those two parameters as summarized indicators can be successfully used for railway ballast aggregates classification.

2. Determining railway lifespan using Canadian Pacific Railroads model for railway with concrete sleepers it is recommended to use correction coefficients for the maximum permissible axle load of 25 t as it is defined in Europe:

- correction coefficient for units of measurement: A = 1.102;
- correction coefficient for load on the axle: B = 1.400;
- correction coefficient for sleeper type: C-1 = 0.667.

3. Micro-Deval Abrasion test showed a wide distribution of values dependently on aggregate material type and mine. Two dolomite and three granite crushed stone ballast aggregate values differed from 4.9% up to 12.4% and the satisfied technical regulation requirement to a maximum value of 15%.

4. Los Angeles Abrasion test values differed in quite same distribution range from 9.2% up to 22.7%. However, there are no legal requirements for this characteristic.

5. Values of toughness and hardness differed very reasonably dependently on aggregate type. The results showed that values Los Angeles Abrasion of dolomite crushed stone aggregates differed about 7.6%, Micro-Deval Abrasion – 17.0%. As for granite Los Angeles Abrasion – 59.8% and Micro-Deval Abrasion – 49.0%.

6. The calculated Abrasion Number differed 151.3% and changed from 33.7% (crushed granite) to 84.7% (crushed dolomite). It shows that toughness and hardness of granite ballast aggregates are very much dependent on mine location and in construction projects the requirements for railway ballast must be defined as required lifetime (expressed in Million Gross Tonnes), Abrasion number, Los Angeles Abrasion and Micro-Deval Abrasion.

7. Ballast durability prognosis mathematical and graphical models were initiated after best practice analysis and ballast aggregates laboratory research. Performance indicators and limit values for each category were developed taking into account ballast aggregate resistance to wear and resistance to fragmentation.

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Received 03 April 2017; accepted 06 June 2017