STUDYING THE BEHAVIOUR OF CRUSHED STONE RAILWAY BALLAST SUBJECTED TO PERIODIC LOAD

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KEYWORDS
Railway ballast, DEM, polyhedron, periodic load

ABSTRACT

The crushed rocks of the railway ballast are subjected to repeated loads due to train traffic. Most of the forces are taken by a relatively small portion of rocks, which are located in a volume underneath the rail fastenings. In this study, a combined experimental and simulation method is introduced, which applies a load that results similar forces compared to the real ones acting in that small volume. During this test, the aggregate is disposed in a mortar, then periodic normal force is applied. The effect of different grain shapes was studied on the mechanical behaviour of the aggregate by the examination of the compression of the pack over time due to the periodic force. The crushing of the grains was also measured. We also present, how the number of time and cost demanding measurements can be reduced by the application of discrete element numerical simulation.

INTRODUCTION

The railway track structure supports and guides railway carriages, therefore carrying, distributing and conveying the load to the foundation. The upper section of the railway track structure, consisting of the rails, tie plates and sleepers is laid on the ballast, which has the required flexibility and strength to support the track structure. The ballast is situated on the sub-ballast and the subgrade soil. The primary role of the crushed stone ballast is to convey and reduce the pressure transferred from the sleepers on to the subgrade. Furthermore, the crushed stone ballast must provide sufficient resistance against the longitudinal and transversal movement of the track, ensure that the track stay level and drain off rainwater.

The mechanical behavior of the clean crushed stone ballast is determined by the geometrical and material properties of the aggregate. In response to the external forces the sliding, rearrengement and fragmentation of the particles takes place. Consequently, the loadability of the ballast changes. Besides the stress resulting from traffic load, other impacts also weaken the ballast. Fragmentation of stones also occurs during the creation and maintenance of the ballast (tamping, profiling) as well as due to weather effects like freezing.

The other significant failure form is fouling. Fine particles can move upwards from the sub-ballast and the subgrade soil into the ballast due to weather and mechanical effects. The fallen transferred goods (e.g. coal dust) and iron dust from the brakes contaminates the ballast as well.

Not every part of the ballast is loaded equally. Most of the forces are taken and spreaded by a pack of grains under the rail fastenings. D. R. Ahlbeck et al. (1979) proposed this pack to be cone-shaped. During the construction, the top layer (~100 mm) of this pack is compacted by tamping machines. By approximating the cone shape with a cuboid, a 600x280x100 mm large cuboid is alloted, which is hereafter referred as *rock beam*. On Figure 1 the rock beam is marked with the hatched area, the overall dimensions and the number of granules inside the volume are also noted.

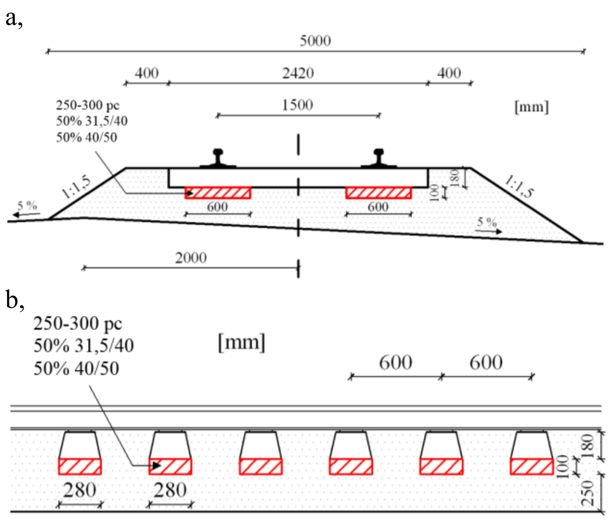

Figure 1: The Rock Beam Inside the Track Structure (a: Cross Section, b: Side Section)

The optimal grain size distribution is often studied, however, the grain shape, which has also a great effect on the mechanical loadabilty is regularly neglected. The rocks which make up the ballast are classified into two groups based on their shape: equant and flat particles. Equant particles have greater strength compared to flat ones, however the latter ones play a crucial role in the

Communications of the ECMS, Volume 33, Issue 1,
Proceedings, ©ECMS Mauro Iacono, Francesco Palmieri,
Marco Gribaudo, Massimo Ficco (Editors)
ISBN: 978-3-937436-65-4/978-3-937436-66-1(CD) ISSN 2522-2414

interlocking of ballast. This implies that there is an optimal ratio for the number of equant and flat particles at which the load bearing capacity of the rock beam is the greatest.
The presented research investigates the short-term grain sliding and crushing behaviour of the ballast due to repeated mechanical loads utilizing measurements and simulations. It also studies the effect of grain shape.

LABORATORY TESTS

Methodology of Laboratory Tests

Measurements were carried out to study the effect of repeated loads experimentally, which at the same time was also used to validate the numerical model. Equant (LZ), flat (LL) and original (mixed, LE) rocks were tested. During these tests the compressional displacement and normal force over time were registered.
As the 32/50 mm ballast rocks were too large for the test equipment, they were modelled with smaller, 20/32 mm particle size andesite, which came from the KŐKA Kő- és Kavicsbányaszati Kft's mine located in Komló, Hungary. After the periodic compressions, the grain size distributions were also measured.
The test was carried out using thick-walled steel mortar (d=170 mm, A=226,87 cm^2) and INSTRON universal (compression) testing system (Type: 5989 L 1217) (Figure 2). The pulsating loads were set between max. 50 kN and min. 3 kN, as for the number of load cycles N=10, 20 and 30 were applied.

Figure 2: The Measurement Layout for Testing Repeated Loads

Results of Laboratory Tests

The measured compressive force [kN] versus compression [mm] values together with the changes in compression [mm] over time [s] are presented on Figures 3-4. The measurement time was transformed in a way that on average one second is equivalent to one compression cycle. Natural logarithmic functions were also fitted to the compression-time graphs.

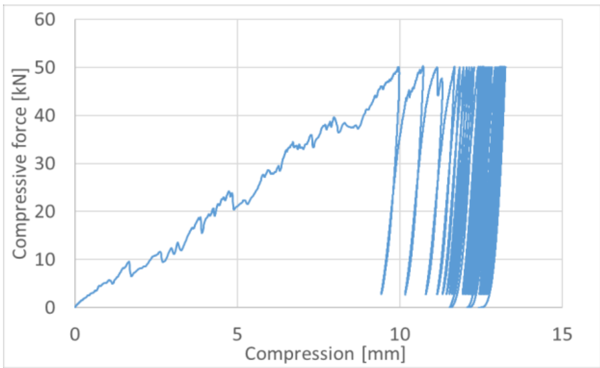

Figure 3: Compressive Force – Compression Diagram in Case of Equant (LZ 30) Pack – Measurement

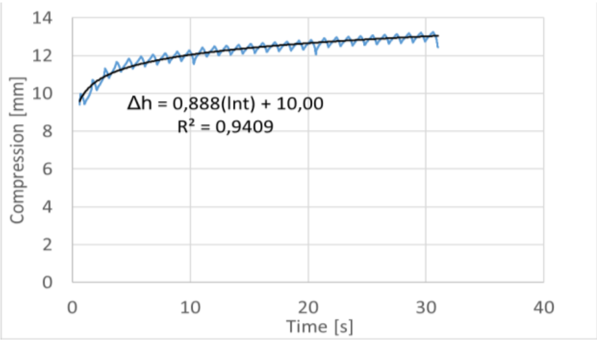

Figure 4: Compression – Time Diagram in Case of Equant (LZ 30) Pack – Measurement

For grain size distribution measurements, four sieves were used with 12, 16, 20 and 32 mm mesh size. Figure 5 represents the sieve curve before and after 30 compressions for equant rocks. The size distribution of the original aggregate is known. If the size scale is logarithmic, the distribution between measured points can be approximated by lines.

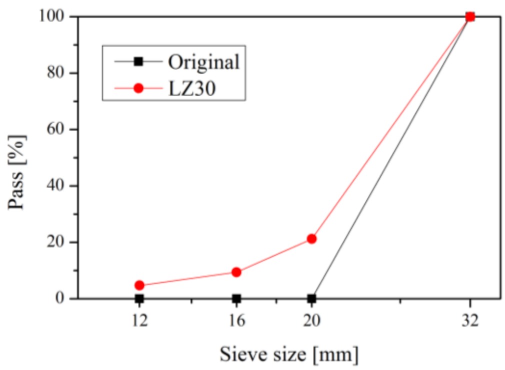

Figure 5: Sieve Sizes Before and After the Compression Process (LZ pack, 30 cycles)

Also, the *granulometric rating value* (M_i) was calculated from the particle size distributions of the pack before and after the test. Which is the sum percent passings over the sieve line at the measured points. In case of original aggregate, this value is M_0=300 (Figure 6). As this value decreases when grain crushing occur, it is a good tool to get quantitve information of fragmentation with a single number.

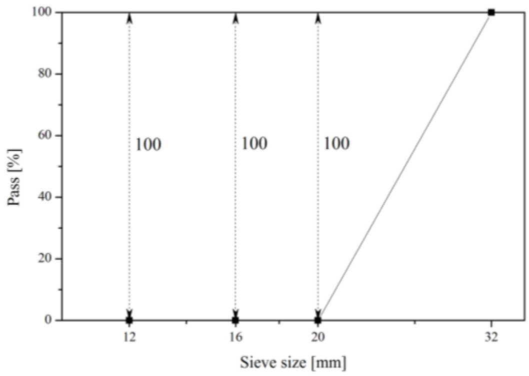

Figure 6: Calculation of Granulometric Rating Value in case of Original 20/32 Aggregete and 4 Sieves

NUMERIC SIMULATIONS

Firstly, the adequate method had to be selected during the creation of the numerical model. The discrete element method (Cundall and Strack 1979) represents the material with individual particles and interactions acting in-between them, which makes modelling of individual grains feasible. The particles (or elements) have individual degrees of motional and rotational freedom (Bagi 2007). Several different particle shapes and connection types can be defined.

The Discrete Element Model of the Crushed Stone Aggregate

The applied software is Yade (Šmilauer 2015) discrete element software. The software is Linux based and open-source, thus its operation and the embedded models can thoroughly be studied. Yade solves the basic principles of mechanics (differential equations) by numerical integration. To approximate the shape of crushed stones, polyhedral model (Eliáš 2014), which consists stiff particles was chosen. In the simulation the crushing of particles was not considered. As an approximation, the shape of crushed stone particles was formed by randomly generated polygons based on the Voronoi method. The software generates the set of particles following the prescribed particle shape and size defined by upper and lower sieve size. The size of the particles (D_i) is in line with the measured 20/32 mm aggregate. In the model the equant particles have a 2:2:1, while the flat particles have a 4:2:1 aspect ratio.
The material model of the particles in the simulation is assumed to be ideally rigid, thus the compressibility of real stones is taken into account by connections between elements. When particles make contact, normal and shear forces act between particles, these forces are also considered in the model.
The grain density (ρ) for andesite is known. The magnitude of the normal force is proportional to the overlapping (common) volume by the so-called normal volumetric stiffens (k_n) material parameter. The magnitude of the shear force is proportional to the mutual sliding and rotation of the particles by the shear stiffness (k_s) material parameter. The maximum shear force magnitude is defined by the Columb friction law based on the mutual friction angle (φ) value.
The source of the used micromechanical parameters, which are listed in Table 1 is literarure (Eliáš 2014), where they were calibrated by uniaxial compression in a mortar as well.

Table 1: Micromechanical Parameters of the DEM Model

	Stones	Mortar and plate	Unit
ρ	2600	7800	kg/m^3
k_n	$2{\cdot}10^{13}$	$2{\cdot}10^{14}$	N/m^3
k_s	$2{\cdot}10^{8}$	$2{\cdot}10^{9}$	N/m
φ	0,6	0,4	rad

The model of the measurement device's geometry is detailed in a previous publication (Orosz et al. 2017). The aggregate with predetermined particle distribution and flakiness index is settled in the mortar by gravitational deposition. The initial compaction is reached by preloading the particles with forces equivalent to the weight of the top part (15 kg) used in the experiments. The resultant geometry can be seen on Figure 7.

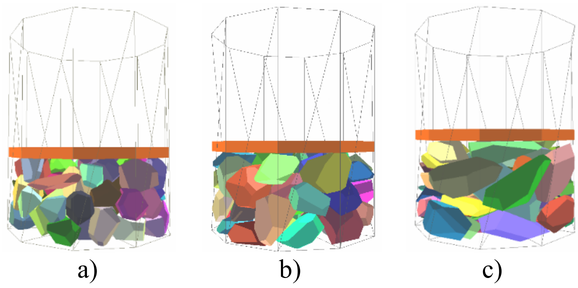

Figure 7:
a) The Original (Containing 30 pc% Flat Particles);
b) 100 pc% Equant;
c) 100 pc% Flat Particle Pack after Preloading

The preloaded, hence compacted packs were subjected to periodic load for 30 cycles. The magnitude of the normal force in accordance with the laboratory measurements was between 3 and 50 kN. The loading procedure was driven by displacement, resulting in a more stable simulation.

Simulation Results

Since the particles were unbreakable in the simulation, the particle size distribution did not change. In the model, compaction occurs only due to the displacement and sliding of particles. During the measurements, particle fregmentation occurred mostly during the first load cycle, thus when evaluating the simulation, we did not consider fragmentation in the model and the compaction was adjusted to match the measurement results.
Simulation results are presented in forms of compressive force [kN] – compression [mm] and compression [mm] – time [s] graphs on Figures 8-9.

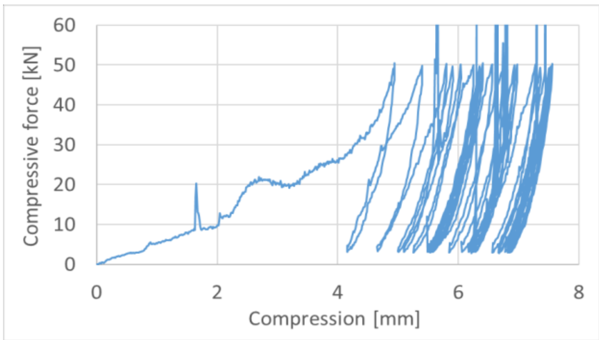

Figure 8: Compressive Force – Compression Diagram in Case of Equant (LZ) Pack – Simulation

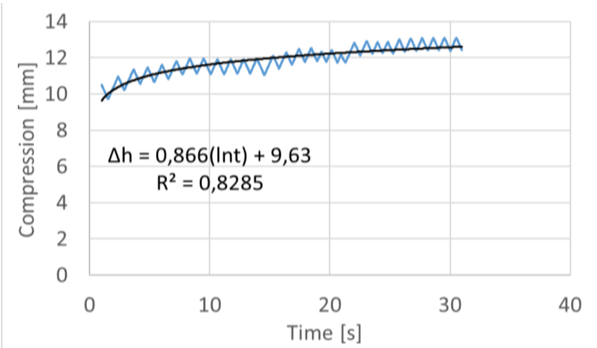

Figure 9: Compression – Time Diagram in Case of Equant (LZ) Pack – Simulation

COMPARING AND EVALUATING THE RESULTS

Compaction

During the evaluation procedure, the measured compressive force versus compression and compression versus time diagrams were compared with the simulation results. As the simulations were speeded up in comparison to the measurements to save computational time, the times were transformed to get a same basis.
The steepness of the natural logarithm regression function ("a" value) fitted onto to the compression versus time graph was selected as the characteristic value. These values for the 30-cycle laboratory measurements and the computer simulation as well are presented in Table 2 as a function of flat particle ratio.

Table 2: Steepness of Logarithmic Regression for the Tested Packs ("a" Values)

Ratio of flat particles	0%	30%	100%
Measurement "a" value	0,888	0,664	0,585
Simulation "a" value	0,866	0,917	1,01

Conclusions can be drawn from the measurements themselves, but the experimental results also can be used to validate the simulation model, which can be applied to extend the results without performing new measurements. Table 3 shows the extended "a" values of the logarithmic functions by DEM simulations.

Table 3: Steepness of Logarithmic Approximation ("a" Values) Based on Simulations

Ratio of flat particles	0%	10%	20%	30%	100%
Simulation "a" value	0,866	1,37	1,26	0,917	1,01

Crushing

Because the particles were unbreakable in the simulations, information were gathered about the particle crush in measeurements with the use of sieve measurments and granulometric rating values.
The *characteristic value of change* (λ_i) is the quotient of the granulometric rating values after (M_i) and before (M_0) the application of periodic load, expressed as a percentage. The original granulometric rating value for the studied 20/32 mm particle size is M_0=300 and the values after the compression cycles are listed in Table 4. The calculated characteristic values of change are shown in Table 5.

Table 4: Granulometric Rating Values after Being Subjected to Periodic Loads

	M_{10}	M_{20}	M_{30}
Equant (LZ)	284,8	283,7	264,7
Flat (LL)	240,9	240,2	246,4
Original (LE)	282,9	268,7	280,5
Average	269,5	264,2	263,9

Table 5: The Characteristic Values of Change

	λ_{10} [%]	λ_{20} [%]	λ_{30} [%]
Equant (LZ)	94,9	94,6	88,2
Flat (LL)	80,3	80,1	82,1
Original (LE)	94,3	89,6	93,5
Average	89,8	88,1	88,0

CONCLUSIONS

Using a 20/32 mm particle size pack as sample, we were able to model the effect of shape in case of the 32/50 mm railway track ballast. The acquired results are adequate to evaluate the behavior of the stone pack for various number of load cycles.

The discrete element simulations are capable of reproducing the effects of repeated loads. The qualitative simulation results are in accordance with the laboratory tests, but the model needs further refinements to quantitively reproduce the laboratory tests. By using computer simulation one can decrease the number of time consuming and costly laboratory tests. This requires a target-oriented laboratory test to determine the fundamental parameters for the computer simulation. Such model can be used to evaluate the behavior of the crushed stone ballast for different composition and number of load cycles.

In further stages of the research it is advised to conduct more measuremnts in order to get statstically reliable data. The discrete element model can be improved by refining the paramers and taking particle breakage into account. The results also showed the importance of proper initial compaction, which also have to be studied in detail.

We recommend that simulations are completed for various crushed stone ballast types generally used to create the track bed. The conducted and evaluated simulation should provide the basis for answering the arising matters concerning the construction and maintenance of the railway track structure.

ACKNOWLEDGEMENT

The authors are thankful for the fellow workers of the Department of Engineering Geology and Geotechnics, BME: Gyula Emszt retired department engineer, Bálint Pálinkás laboratory technician and Péter Molnár architect from Struktúra Kft.

The research reported in this paper was supported by the Higher Education Excellence Program of the Ministry of Human Capacities in the frame of Artificial intelligence research area of Budapest University of Technology and Economics (BME FIKP-MI).

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