Anna-Christina Neubauer, Bakk. rer. nat.

The effect of petrographic composition of railway ballast on the Los Angeles test

Master Thesis

For obtaining the academic degree

Master of Science

Institute of Applied Geosciences

Graz University of Technology

Supervisor: Latal Christine, Mag. rer. nat. Dr. rer. nat.

Institute of Applied Geosciences

Co-Supervisor: Bach Holger, Dipl.-Ing. Dr. techn.

Petromodel ehf

formerly: Institute of Railway Engineering and Transport Economy

Graz, November 2014

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Date | Signature

Acknowledgements

At this point, I would like to seize the opportunity to thank my supervisor and co-supervisor, colleagues, friends and family:

I want to express my gratitude to my supervisor Christine Latal and my co-supervisor Holger Bach. Thank you for your guidance, your encouragement and, most of all, your patience throughout the last years. Thank you for offering me the possibility to participate in this project. I also want to express my gratitude to Qian Liu. Thank you for your prompt and invaluable help on statistics and for all the motivating words. Furthermore, I would like to thank Mario Wiesberger, Michael Neubauer, Gregor Brunnsteiner and Tobias Ederer for providing technical assistance in order to carry out all the laboratory work.

I also would like to thank Madeleine, Elisabeth, Britta, Maike, Markus, Stefan M., Christoph, Stefan W. and Carmen for a unique period of time, exciting field trips and unforgettable memories. Special thanks go to my dear friend Bettina. Thank you for each and every day of our friendship. Last but not least, I particularly thank my family for their unconditional love and support over the years. I love you.

Abstract

Railway ballast is an important element of the track system. Due to repeated loads of traffic, particle degradation occurs and the ballast bed may not fulfil its functions satisfactorily. The loss of performance necessitates maintenance operations – the frequency of tamping or ballast cleaning processes is thus influenced by the quality of the ballast aggregates. Railway ballast has to meet high quality requirements to minimise costs for maintenance operations. Quality requirements refer to, for instance, the mechanical properties of railway ballast aggregates. In order to determine mechanical properties such as the resistance to degradation by fragmentation and / or abrasion, tests are performed at regular intervals. Test results show a high variability and the reasons for this are not sufficiently quantified.

The aim of this Master's thesis is to quantify the influence of the petrographic composition of railway ballast on the Los Angeles test. The Los Angeles test is a test method in order to determine the mechanical properties of aggregates. The homogeneity of railway ballast aggregates of four rock types (basalt, granite porphyry, dunite, granulite) was examined and a classification into subclasses was performed in case of granite porphyry, dunite and granulite. This classification was based on macroscopic criteria. Separated Los Angeles tests were performed on material of the respective subclasses and on material without prior selection. Each sample was additionally analysed by means of the measuring device Petroscope 4D®. Petroscope 4D® allows, among other things, automated measurements of geometrical properties of railway ballast aggregates in order to quantify the influence of particle geometry on the Los Angeles test as well.

Test results suggest that the visual difference within granite porphyry samples is supported by differing geometrical data and reflected by significantly varying Los Angeles values. For rock type dunite data obtained from Petroscope 4D® confirm the existence of two varieties, whereas the resulting Los Angeles values show hardly any difference. The analysis of subclass A and subclass B of rock type granulite indicates minor differences in macroscopic criteria, Los Angeles values and geometrical properties as well. Based on the homogeneous appearance of basalt aggregates no subdivision was considered, nevertheless a considerable variation of Los Angeles test results is observed.

A further aim of this Master's thesis is to answer the question whether the influence of petrographic composition or the particle geometry is more decisive for the Los Angeles test results. Different rock types show a different mechanical behaviour – the petrography of samples (mineral content, fabric) has very large influence on the Los Angeles test results. The geometry (form, angularity) is of importance, but to a lesser extent.

Kurzfassung

Gleisschotter ist ein entscheidendes Element in Bezug auf den Konstruktionsaufbau von Eisenbahnstrecken. Aufgrund wiederholter Verkehrslasten kommt es zu einer zunehmenden Schädigung des Gleisschotters und das Schotterbett kann seine Funktionen nicht mehr zufriedenstellend erfüllen. Dieser Leistungsverlust erfordert wiederum Wartungsarbeiten – die Häufigkeit von Gleisstopfungsmaßnahmen oder einer Reinigung des Schotterbettes werden somit von der Qualität der Gesteinskörnung beeinflusst. Gleisschotter muss strenge Qualitätsanforderungen erfüllen um in weiterer Folge die Kosten für Wartungsarbeiten zu minimieren. Diese Qualitätsanforderungen beziehen sich unter anderem auf die mechanischen Eigenschaften von Gleisschotter. Um mechanische Eigenschaften wie zum Beispiel den Widerstand gegen Zertrümmerung und Abrieb zu bestimmen, werden in regelmäßigen Abständen Untersuchungen durchgeführt. Die Testergebnisse weisen beträchtliche Schwankungen auf, jedoch sind die Gründe hierfür nicht ausreichend erfasst.

Das Ziel dieser Masterarbeit besteht darin, den Einfluss der petrographischen Zusammensetzung von Gleisschotter auf den Los Angeles Test zu bestimmen. Der Los Angeles Test dient der Bestimmung mechanischer Eigenschaften von Gesteinskörnungen. Die Homogenität von vier verschiedenen Gesteinen (Basalt, Granitporphyr, Dunit, Granulit) wurde überprüft und im Fall von Granitporphyr, Dunit und Granulit wurde eine Unterteilung in Subklassen vorgenommen. Diese Unterteilung wurde anhand von makroskopischen Kriterien getroffen. Für alle Gleisschottermaterialien wurden getrennte Tests an den jeweiligen Subklassen sowie an unsortiertem Material durchgeführt. Jede Probe wurde zusätzlich mit dem Messgerät Petroscope 4D® analysiert. Petroscope 4D® ermöglicht unter anderem automatisierte Messungen verschiedener geometrischer Daten um den Einfluss der Geometrie auf den Los Angeles Test ebenfalls zu bestimmen.

Die Testergebnisse zeigen, dass optische Unterschiede innerhalb des Gesteins Granitporphyr sowohl durch unterschiedliche geometrische Eigenschaften als auch durch abweichende Los Angeles-Ergebnisse widergespiegelt werden. Im Fall von Dunit bestätigen Daten des Messgerätes Petroscope 4D® die Existenz von zwei Varietäten, während die Los Angeles-Ergebnisse kaum Unterschiede aufweisen. Die Untersuchung von Subklasse A und Subklasse B des Gesteins Granulit weist geringe Unterschiede in Bezug auf die makroskopischen Kriterien, die Los Angeles-Ergebnisse sowie die geometrischen Eigenschaften auf. Aufgrund des homogenen Erscheinungsbildes von Basalt wurde keine Einteilung in Subklassen vorgenommen, dennoch zeigen die Los Angeles-Ergebnisse große Schwankungen.

Ein weiteres Ziel dieser Masterarbeit ist die Beantwortung der Frage, ob die petrographische Zusammensetzung oder die Geometrie des Gleisschotters einen größeren Einfluss auf die Ergebnisse des Los Angeles Tests hat. Unterschiedliche Gesteinsarten weisen unterschiedliche mechanische Eigenschaften auf. Die petrographische Zusammensetzung (Mineralgehalt, Gefüge) hat einen sehr großen Einfluss auf die Ergebnisse des Los Angeles Tests. Die Geometrie (Form, Kantigkeit) ist ebenfalls wichtig, aber in einem geringeren Ausmaß.

Contents

List of Abbreviations

EN	Europäische Norm
ER	elongation ratio
FI	Flakiness Index
FR	flatness ratio
LA_{RB}	Los Angeles value for railway ballast
ÖBB	Österreichische Bundesbahnen
PNR	particle number ratio
SI	Shape Index
VA	volume of angles

1 Introduction

1.1 General background and problem definition

Ballasted track systems provide the majority of tracks in use today. In its initial state, railway ballast is composed of angular, crushed and uniformly graded rock aggregates. Changes in angularity and gradation of railway ballast aggregates occur due to repeated loads of traffic and may affect the condition of the ballast bed adversely. The loss of performance necessitates maintenance operations – the frequency of tamping and ballast cleaning processes is influenced by the quality of ballast aggregates.

Increasing maintenance costs have made the selection of appropriate aggregates for each ballast application a matter of financial importance (Raymond, 1985). To minimise the expenses, railway companies ask for high-quality railway ballast aggregates.

Railway ballast in Austria is subject to regulations provided by the Austrian Federal Railways. The suitability of aggregates for use as railway ballast is determined by evaluating the material in terms of its mechanical, geometrical, physical and chemical properties. Mechanical properties play a decisive role – to perform well in track, ballast aggregates have to be tough enough to resist fragmentation and hard enough to resist abrasion (Raymond, 1985). Determination of mechanical properties includes three test methods (ÖBB, 2007): (1) Micro-Deval test; (2) Impact test; (3) Los Angeles test. The Micro-Deval test is used to determine resistance to abrasion (Österreichisches Normungsinstitut, 2011). Methods for the determination of resistance to fragmentation are Impact test and Los Angeles test (Österreichisches Normungsinstitut, 2006).

Eleven suppliers cover the ballast demand of Austrian Federal Railways (ÖBB, 2009). Periodical material inspections are conducted to identify changes in quality of ballast aggregates. Austrian Federal Railways evaluate mechanical properties every six months (ÖBB, 2007). Consequently, the time interval between consecutive material inspections is fairly wide. Hofer and Bach (2012) point to disadvantages of the quality assurance system: Ballast of inferior quality may not be detected over a long period. In the meantime, production and delivery remain unaffected and substandard aggregates are used as railway ballast. In fact, a time series analysis of test results indicates considerable variations in the quality of respective materials. According to Bach et al. (2012) variability of mechanical properties is explained by: (a) fluctuation of petrographic composition; (b) alternating geometry of aggregates; (c) blasting and crushing technique; (d) technical processing. Individual criteria are well-established but data regarding the extent of their influence are limited.

1.2 Objective and scope of work

The aim of this thesis is to establish a correlation between petrographic composition, geometrical parameters and mechanical properties of railway ballast aggregates. More precisely, the influence of petrographic composition and its variations as well as the influence of geometrical parameters and its variations on the Los Angeles test results is evaluated. Resistance to degradation by wear and fracture is governed by rock type, particle shape and gradation (Selig and Boucher, 1990). As the gradation is standardised for the Los Angeles test, results are exclusively influenced by rock type and particle shape.

Sample material represents four rock types and originates from an equal number of quarries. Each quarry serves as a supplier of railway ballast in Austria. Rock types basalt, granite porphyry, dunite and granulite are examined according the following test sequence (Fig. 1):

1. The influence of petrography is evaluated by a manual sorting of railway ballast aggregates and an associated classification into subclasses (subclass A and subclass B). The classification is based on macroscopic criteria (e.g. colour, texture, structure, degree of alteration, particle shape) and performed in order to determine the effect of variations on the quality of railway ballast materials.
2. 85 Los Angeles tests are carried out in order to determine the mechanical properties of railway ballast aggregates. Separate tests are performed on material of respective subclasses and on material without prior selection (random sample).
3. The assessment of the influence of particle geometry and its variations is assisted by machine vision. The measuring device Petroscope 4D® determines various geometrical parameters prior and subsequent to the Los Angeles testing. Furthermore, Petroscope 4D® allows the estimation of the petrographic composition by means of reflectance spectra.
4. Test results are compared and analysed with statistical methods.

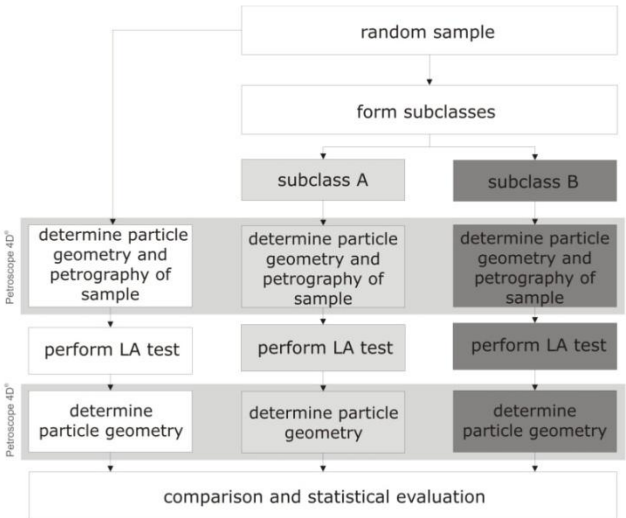


Fig. 1: Test sequence and work procedure.

2 Literature review - railway ballast functions and quality requirements

2.1 Railway ballast functions

According to Selig and Waters (1994) ballasted track structures are composed of two categories of components: (1) superstructure; (2) substructure. The superstructure consists of rails, fastening system and sleepers. Ballast, subballast and subgrade represent the substructure. Fig. 2 depicts the individual components of the track structure.

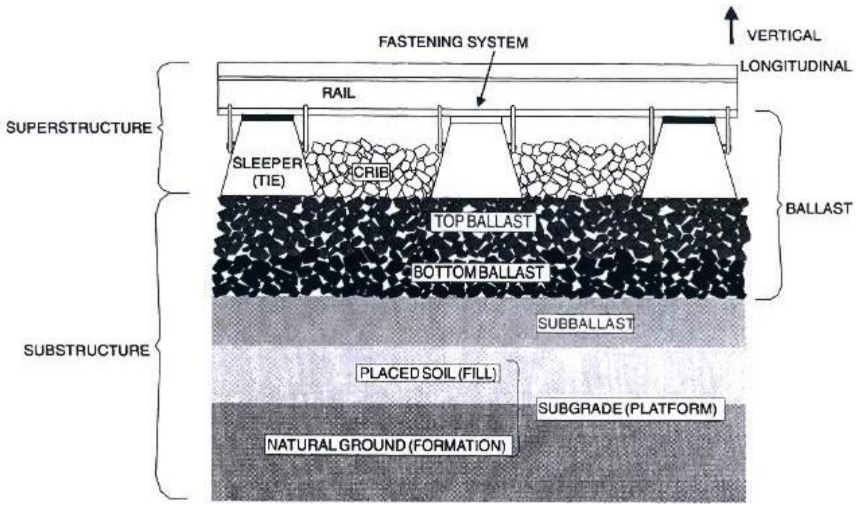


Fig. 2: Longitudinal profile of ballasted track structure (Selig and Waters, 1994).

Railway ballast performs various functions, the most important are: (a) to resist vertical, lateral and longitudinal forces in order to retain the track in its required position; (b) to provide energy absorption and resiliency for the track; (c) to offer voids for deposition of fouling material and movement of particles through the ballast; (d) to facilitate maintenance and lining operations (to adjust track geometry) by the ability to rearrange ballast particles with tamping; (e) to secure drainage of water; (f) to distribute pressures from the sleeper bearing area to acceptable stress levels for the underlying material. Furthermore, ballast particles provide an insulating layer in order to mitigate frost problems of underlying materials and prevent vegetation growth. The absorption of airborne noise and the facilitation of electrical resistance between rails are additional functions of the ballast bed (Selig and Waters, 1994).

2.2 Railway ballast requirements

Angular, crushed, hard aggregates, which are uniformly graded, free of dust and dirt, and not prone to cementing action are considered to be suitable railway ballast materials. Though, there is no global consensus on precise specifications that will result in the best possible track performance (Selig and Waters, 1994).

Austrian Federal Railways are in charge of the conformity assessment of railway ballast aggregates in Austria. The quality assurance procedure of Austrian Federal Railways includes: (a) quality controls performed by the respective supplier of ballast material (internal quality controls); (b) quality controls performed by personnel of Austrian Federal Railways (external quality controls) (ÖBB, 2007). External quality controls are performed to validate or invalidate results of internal quality controls. If substandard aggregates are detected, a temporary ban on the delivery of railway ballast is imposed against the respective supplier. The ban will be set aside as soon as a positive reassessment of conformity is pronounced.

Within the scope of the initial aggregate selection (aggregates are approved for use as railway ballast for the very first time) as well as during the above-mentioned monitoring of the processed material, the following properties are determined (ÖBB, 2007): (a) mechanical properties; (b) geometrical properties; (c) physical properties and (d) chemical properties.

The emphasis of this Master's thesis is placed on both mechanical and geometrical properties of railway ballast aggregates. Due to this reason, test methods related to mechanical and geometrical properties are described in detail. No further explanations are given on physical properties (e.g. resistance to weathering and particle density) or chemical properties (e.g. content of semimetals and metals).

2.2.1 Mechanical properties

Performance of a railway system is governed by the interaction of track components (Selig and Waters, 1994). Railway ballast is considered as critical element regarding the performance. Due to repeated loads of traffic and resultant forces acting within the ballast bed, deterioration phenomena such as particle fragmentation, chipping and particle abrasion occur. All three mechanisms are illustrated in Fig. 3.

The distribution of pressures from the sleeper bearing area to acceptable stress levels for the underlying material is considered to be one of the most important functions of railway ballast aggregates. The distribution of pressures or loads is inhomogeneous and concentrated locally at specific contact points (Aikawa, 2009). Adjacent contact points form load paths. Accordingly a relatively small number of particles is responsible for the distribution of loads in a track system (Bach, 2013).

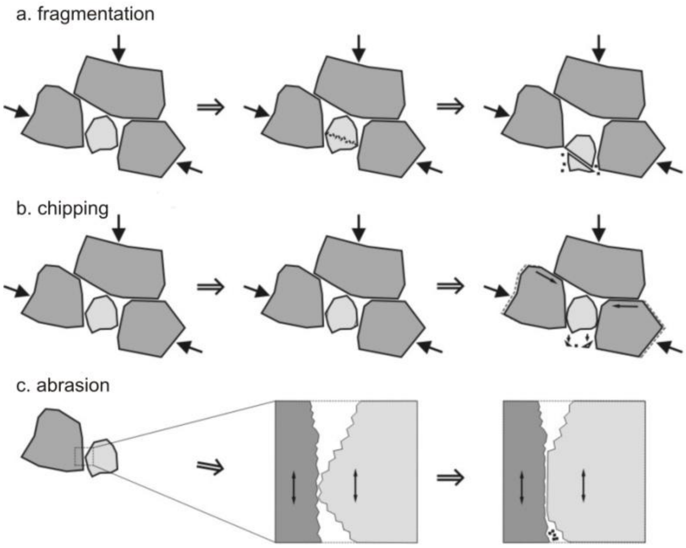


Fig. 3: Main mechanisms of ballast breakdown (Bach, 2013).

Passing trains generate high point loads at the contact points which leads to particle fragmentation (Fig. 3a). The effect of repeated high point loads leads to the development of fatigue fractures. Due to the propagation of such fatigue fractures, a system of interconnected fractures develops and the particle breaks into smaller-sized fragments consequentially.

Chipping or rounding is another mechanism associated with the occurrence of high point loads (Fig. 3b). The breaking off of edges and corners may also be induced by shear stresses. Irrespective of the force, exposed parts of the particle are removed and fine material is generated.

In contrast to chipping, the mechanism of particle abrasion, or particle wear, is solely caused by shear stresses (Fig. 3c). Abrasion of aggregates is also referred to as smoothing of aggregates. Material from the surface of aggregates is removed due to the relative movement of adjacent particles and the resulting friction. This process is accompanied by the generation of a considerable amount of very fine material.

Ballast breakdown as a consequence of particle fragmentation, chipping and particle abrasion is the main reason for the accumulation of fine material within the voids of the unbound aggregate layer (Selig and Waters, 1994). This process may also be referred to as ballast fouling (Huang and Tutumluer, 2011) and has an adverse effect on the performance of the ballast bed. Other reasons for ballast fouling are the infiltration of material from the ballast surface (e.g. spillage from trains), sleeper wear, the infiltration of material from underlying granular layers or the subgrade (Selig and Waters, 1994). The respective shares vary from one railway line to another.

Fine fouling components or fines (particles in the range of silt or clay) may fill the void space until the water drainage is almost stopped. The resulting excess of water causes hydraulic erosion and leads to a loss of stability (Selig and Waters, 1994).

Ballast fouling contributes significantly to the process of track settlement. In the majority of cases, average track settlement as well as differential track settlement is attributed to the settlement of the ballast bed (Selig and Waters, 1994). The quality of the entire track system (interaction of rails, sleepers, fastening system and type of railway ballast) and the service loading (traffic density per year, axle load, train speed) may also contribute to the process of track settlement (Klotzinger, 2007). The context between the track settlement or track quality and the cumulated traffic is depicted in Fig. 4a. High settlement rates in the beginning (< 100,000 gross million tons of traffic) lead to a fast decrease in track quality (phase I). Phase II (> 100,000 gross million tons of traffic) is also characterised by a decrease in quality, but settlement rates are considerably lower (Bach, 2013).

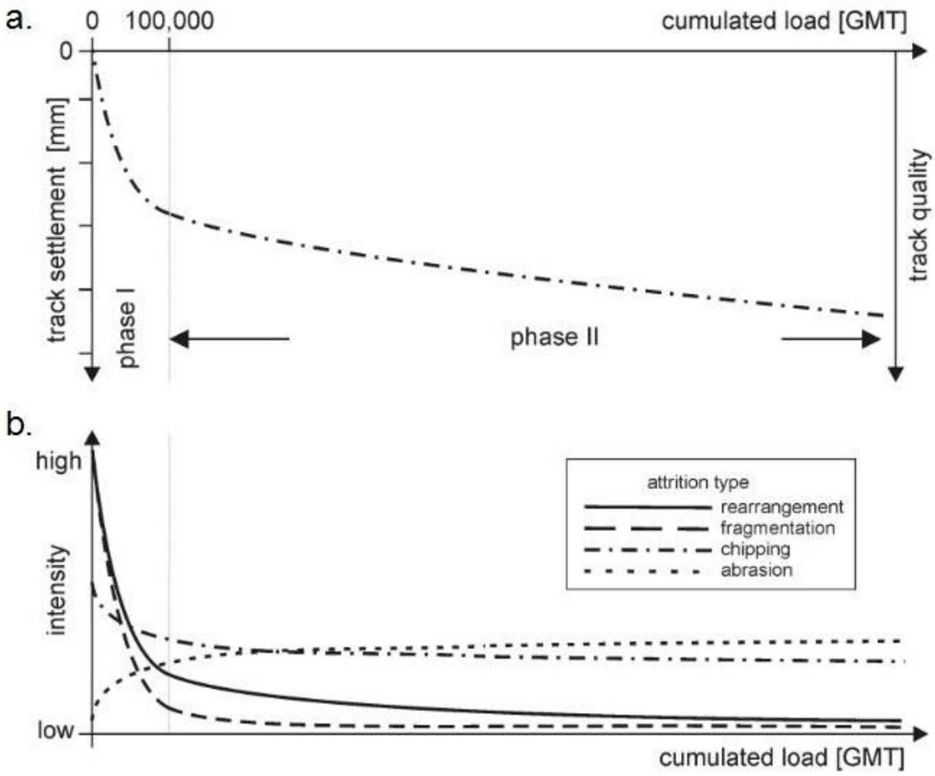


Fig. 4: Impact of traffic load on track settlement and intensity of attrition types (Bach, 2013).

The respective contribution of particle fragmentation, chipping and particle abrasion to track quality varies with time as well (Fig. 4b). High settlement rates in phase I are induced by an extensive fragmentation and rearrangement of particles. Once a more or less stable configuration is established, fragmentation and rearrangement are no longer regarded as the determining mechanisms. Considerably low settlement rates in phase II are induced by other deterioration mechanisms, namely chipping and particle abrasion (Bach, 2013).

Tamping is deemed to be a necessary maintenance operation whenever the track position and the stability reach a critical level; ballast cleaning is performed once the amount of particles with diameters less than 22.4 mm reaches 30 % to 40 %. The frequency of tamping and ballast cleaning processes is affected by the quality of the ballast aggregates. As mechanical properties are of particular importance, the resistance to degradation by fragmentation and / or abrasion represent quality criteria for railway ballast aggregates. Its determination includes three well-established test methods (ÖBB, 2007): (1) Micro-Deval test; (2) Los Angeles test; (3) Impact test. The Micro-Deval test is used to determine resistance to abrasion (Österreichisches Normungsinstitut, 2011). Methods for the determination of resistance to fragmentation are Impact test and Los Angeles test (Österreichisches Normungsinstitut, 2006).

2.2.2 Geometrical properties

Specifications with regard to geometry of railway ballast particles include the particle size distribution, the percentage of fine and finest grains, the length and the length-to-width ratio (ÖBB, 2007).

Grain size distribution and undersize particles

Railway ballast is composed of uniformly-graded aggregates. This term refers to aggregates with a limited range of particle sizes. This lack of diversity of grain sizes has a positive effect on load dispersion, load transfer and drainage capability (Kuttelwascher, 2012). Therefore the grain size distribution and the percentage of undersize particles is specified.

Grain size distribution is determined according to EN 933-1 (Österreichisches Normungsinstitut, 2012a). Austrian Federal Railways distinguish between railway ballast of category I and railway ballast of category II (ÖBB, 2007). Railway ballast of category I comprises aggregates with a gradation of 31.5 / 63 mm and is generally used on tracks in Austria. Its grain size distribution curve is shown in Fig. 5. Railway ballast of category II comprises smaller aggregates with a gradation of 16 / 31.5 mm. It is only used in marshaling yards and parking areas (Kuttelwascher, 2012).

Austrian Federal Railways tolerate only a small amount of undersize particles. Railway ballast with the gradation 31.5 / 50 mm may comprise 3 % by weight of particles with diameters less than 22.4 mm when the sample is taken at the quarry and 5 % by weight when the sample is taken at the worksite. The content of fine grains (diameter < 0.5 mm) and finest grains (diameter < 0.063 mm) must not exceed 1 % by weight in each case (ÖBB, 2007).

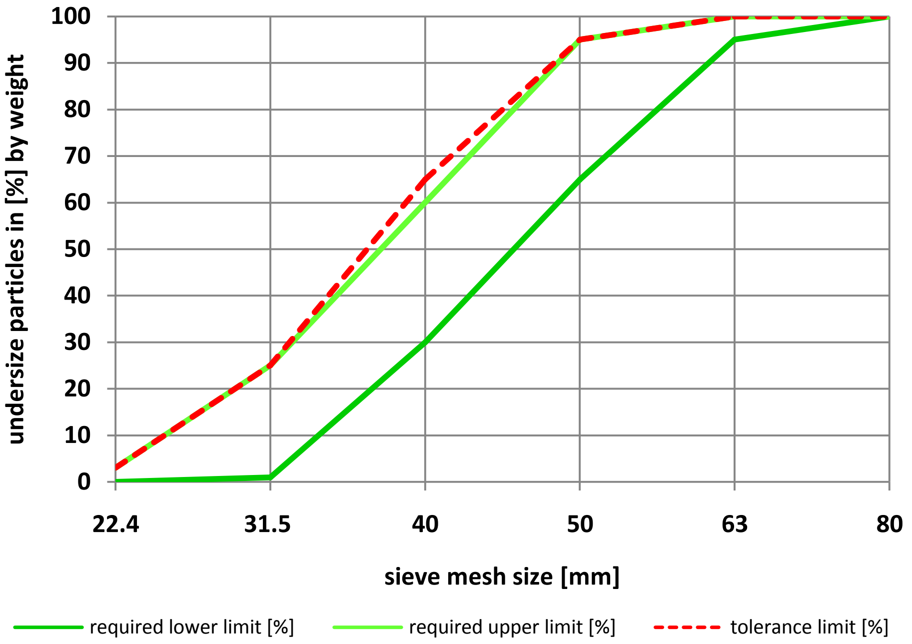


Fig. 5: Grain-size distribution curve of railway ballast category I with a gradation of 31.5 / 63 mm. The solid lines (green) indicate the lower and upper limit; the dashed line (red) delineates the tolerance limit (ÖBB, 2007).

Shape Index and length of particles

In order to achieve efficient interlocking properties, railway ballast aggregates need to be irregularly shaped. Both, cuboidal and non-cuboidal aggregates need to be constituents of the ballast bed (ÖBB, 2007) to ensure stability of the track. The term non-cuboidal refers to particles with a length-to-width ratio exceeding 3:1. Its percentage is expressed by the Shape Index and determined according to EN 933-4 (Österreichisches Normungsinstitut, 2008). Austrian Federal Railways stipulate a Shape Index between 5 % and 30 % by weight (ÖBB, 2007).

As indicated above, the ratio between cuboidal and non-cuboidal particles has an impact on the interlocking properties of the ballast layer and consequently on track stability. More generally speaking, the external expression of an object influences its mechanical properties. For instance, the Los Angeles coefficient increases with an increasing amount of non-cuboidal particles (Röthlisberger, 2005). In particular, flat particles have a negative impact on the resistance to fragmentation (Röthlisberger, 2005).

Additionally, the percentage of particles with a length > 100 mm must not exceed 6 % by weight for railway ballast with a gradation of 31.5 / 50 mm (ÖBB, 2007). This specification is based on the assumption that flat particles with a considerable elongation are likely to have a negative impact on the resistance to fragmentation.

3 Characterisation of railway ballast samples used for test series

3.1 Introduction

The ballast bed in Austria is composed of igneous (granite, granite porphyry, dunite, basalt), metamorphic (granulite, diabase) and sedimentary (dolomite) rocks (ÖBB, 2009). The application of sedimentary rocks is limited due to unfavourable strength properties. Therefore dolomite aggregates are only used in marshalling yards, parking areas and minor lines. Fig. 6 shows the relative delivery quantities of the respective rock types. The colour coding of basalt, granite porphyry, dunite and granulite (see below) will be maintained throughout the entire Master's thesis.

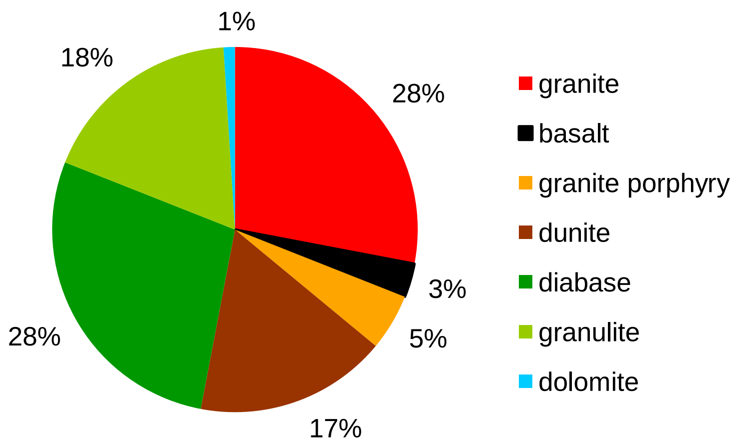


Fig. 6: Delivery quantities of different railway ballast rock types during the year 2008 (ÖBB, 2009).

For the present study railway ballast aggregates originate from four different quarries. Each quarry serves as a supplier of railway ballast in Austria and makes railway ballast aggregates available for testing. Provided railway ballast represents four different rock types: basalt (quarry 02); granite porphyry (quarry 03); dunite (quarry 04); granulite (quarry 10). The name of the respective quarry is replaced by an arbitrarily chosen number.

Railway ballast has to comply with precisely defined quality standards regarding its mechanical, geometrical, physical and chemical properties. The evaluation of properties refers only to a minimum quantity of sample material, therefore the resulting statistical significance is limited. Neither the respective supplier nor Austrian Federal Railways are able to guarantee that railway ballast aggregates are homogeneous in terms of required properties. For this reason the homogeneity of railway ballast aggregates of each rock type and each quarry respectively was examined and, where present, a classification into subclasses was performed. The classification into subclasses was based on macroscopic criteria such as mineralogical composition, colour, fabric, degree of alteration and particle shape. Approximately 500 to 1000 kg of each rock type were sorted manually and grain by grain.

A classification into subclasses was possible in case of granite porphyry (03), dunite (04) and granulite (10). In case of basalt (02), railway ballast aggregates are more or less homogeneous, therefore no classification into subclasses was performed. Tab. 1 shows the percentage of respective subclasses for the different rock types. The letters A, B, C and D mark the subclasses, whereby the letter A represents the most common subclass of each rock type or quarry.

Tab. 1: Percentage of subclasses for granite porphyry (03), dunite (04) and granulite (10).

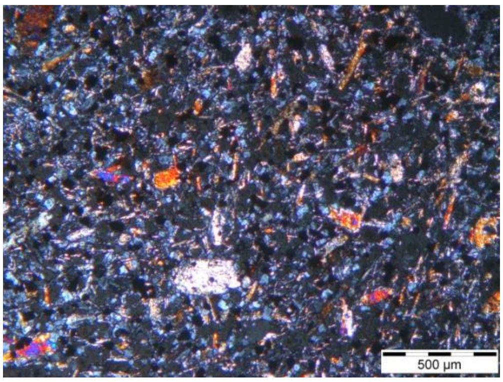
	subclass A	**subclass B**	**subclass C**	**subclass D**
granite porphyry (03)	65%	25%	10% (C+D)	
dunite (04)	60%	39.5%	0.5%	-
granulite (10)	90%	10%	-	-

Within the scope of this study the two most frequent subclasses of rock type granite porphyry (03), dunite (04) and granulite (10) and material without prior selection is taken into account in each case. Samples consisting of material without prior selection (random samples) are marked with the letter M throughout the entire Master's thesis. In case of basalt (02) the determination of mechanical and geometrical properties is restricted to random samples.

3.2 Macroscopic and microscopic characterisation

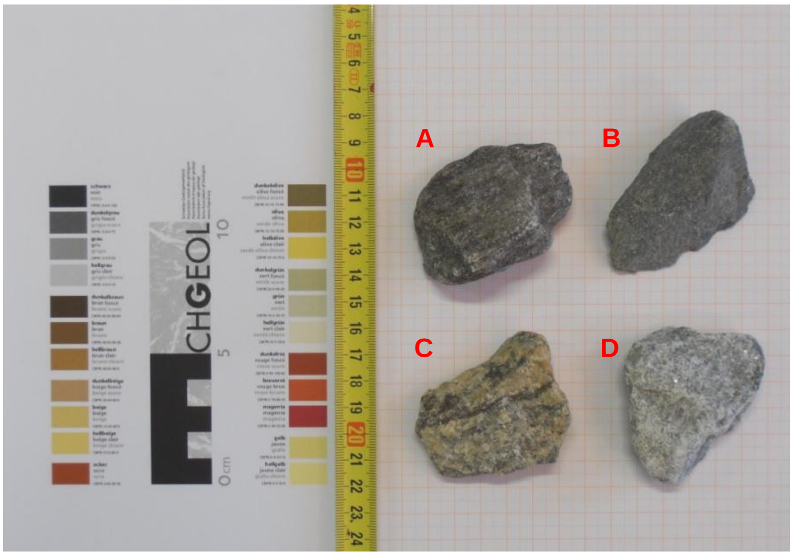
The following tables (Tab. 2, Tab. 3, Tab.4, Tab.5) show a petrographic description of each rock type and the respective subclasses. The mineralogical composition of each subclass was determined by X-ray diffraction on selected, representative particles.

Tab. 2: Petrographic description of railway ballast aggregates of rock type basalt (02).

<table>
<tr><th colspan="2">rock type basalt (02)</th></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">additional information: homogeneous material, no subclasses present</td></tr>
<tr><td>
5 cm</td><td>macroscopic description:
Basalt aggregates are dark grey to dark brown in colour and show an aphanitic texture - individual mineral grains are not distinguishable. Small cavities or vesicles are present.</td></tr>
<tr><td>
</td><td>microscopic description:
The thin section indicates a very fine grained matrix. A few larger crystals are embedded within the fine grained matrix.</td></tr>
<tr><td colspan="2">mineral content: pyroxene, foids, magnetite</td></tr>
</table>

Tab. 3: Petrographic description of railway ballast aggregates of rock type granite porphyry (03).

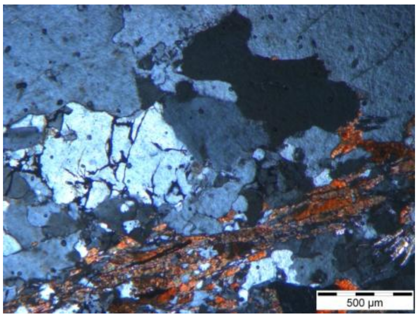
<table>
<tr><th colspan="2">rock type granite porphyry (03)</th></tr>
<tr><td colspan="2">



</td></tr>
<tr><td colspan="2">additional information: very heterogenous material, four subclasses are present (A, B, C, D)</td></tr>
<tr><th>A</th><th>B</th></tr>
<tr><th colspan="2">macroscopic description:</th></tr>
<tr><td>

Aggregates of subclass 03A are dark grey to black in colour due to a relativly high amount of biotite. The presence of garnet is responsible for the purple-coloured spots. Aggregates show a foliation.</td><td>

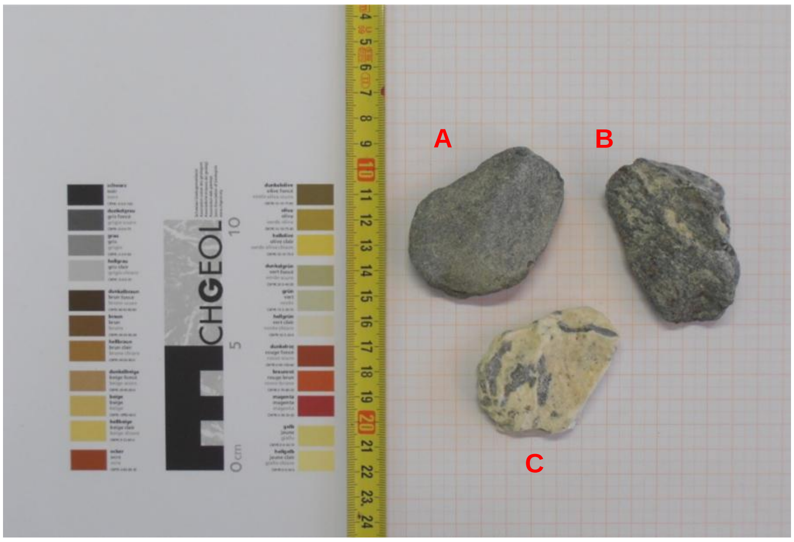
Aggregates of subclass 03B are grey and show a porphyritic texture. The particle shape is a further difference between aggregates of subclass 03A and 03B: Aggregates of subclass B are flat and more angular compared to aggregates of subclass A.</td></tr>
<tr><th colspan="2">microscopic description of thin sections:</th></tr>
<tr><td>



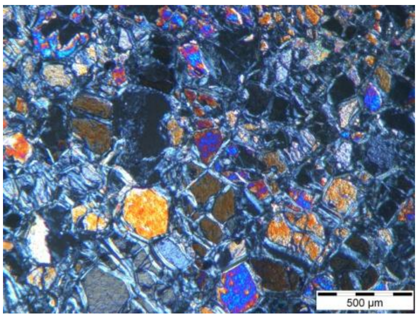
The majority of minerals is medium to coarse grained. Especially garnet crystals are coarse grained. Aligned biotite crystals are the most prominent feature of the foliation.</td><td>

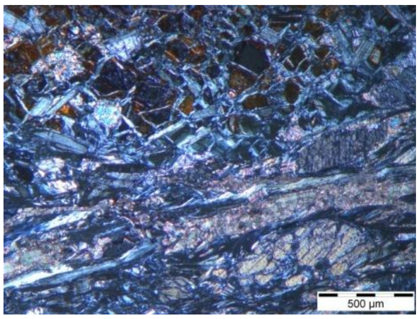
The porhpyritic texture is characterised by a fine grained matrix which exhibits blade-like crystals. Larger crystals (biotite and feldspar) are embedded within the fine grained matrix.</td></tr>
<tr><th colspan="2">mineral content:</th></tr>
<tr><td>quartz, feldspar, amphibole, biotite, garnet</td><td>quartz, feldspar, amphibole, biotite</td></tr>
</table>

Tab. 4: Petrographic description of railway ballast aggregates of rock type dunite (04).

<table>
<tr><th colspan="2">rock type dunite (04)</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">additional information: very heterogenous material, three subclasses are present (A, B, C)</td></tr>
<tr><td>A</td><td>B</td></tr>
<tr><td colspan="2">macroscopic description:</td></tr>
<tr><td>

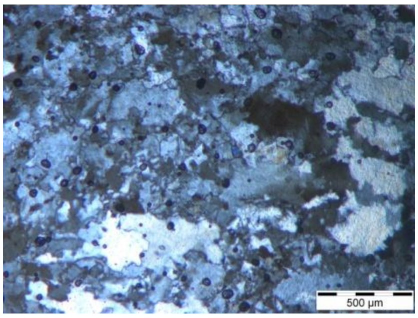
Microcrystalline, greenish aggregates constitute subclass 04A. No foliation is present.</td><td>

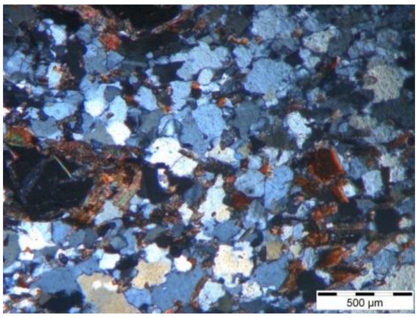
Subclass 04B represents a macrocrystalline, grey variety with reddish to brownish discolourations and numerous thin, white veins or cracks. A slightly preferred orientation is present. Aggregates of subclass 04B are a little bit flatter compared to aggregates of subclass 04A.</td></tr>
<tr><td colspan="2">microscopic description:</td></tr>
<tr><td>

Minerals are similar in size and angular shaped. Aggregates are serpentinised and mesh-textured to a certain degree.</td><td>

The thin section indicates a higher degree of chemical alteration. Serpentinisation and mesh-texturing is more pronounced compared to subclass 04A.</td></tr>
<tr><td colspan="2">mineral content:</td></tr>
<tr><td>serpentine, amphibole, olivine</td><td>serpentine, amphibole, olivine, chlorite</td></tr>
</table>

Tab. 5: Petrographic description of railway ballast aggregates of rock type granulite (10).

<table>
<tr><th colspan="2">rock type granulite (10)</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">additional information: relatively uniform material, two subclasses are present (A, B)</td></tr>
<tr><th>A</th><th>B</th></tr>
<tr><th colspan="2">macroscopic description:</th></tr>
<tr><td>
5 cm
Railway ballast aggregates of subclass 10A are more or less white to light grey in colour. Red garnet crystals are present as well as a foliation.</td><td>
5 cm
Railway ballast aggregates of subclass 10B very similar compared to aggregates of subclass 10A. The differentiation between 10A and 10B is based on the amount of biotite. Due to the higher amount of biotite of subclass 10B, alternating black and white layers are clearly visible.</td></tr>
<tr><th colspan="2">microscopic description:</th></tr>
<tr><td>

Subclass 10A is characterised by medium to fine grained quartz crystals which exhibit a irregular shape (sutured grain boundaries).</td><td>

Biotite is concentrated and forms a linear pattern which reflects the dark layers of the hand specimens. Equidimensional grains form a granoblastic texture.</td></tr>
<tr><th colspan="2">mineral content:</th></tr>
<tr><td>quartz, feldspar, biotite, garnet</td><td>quartz, feldspar, biotite, garnet</td></tr>
</table>

4 Los Angeles test procedure

According to EN 1097-2 (Österreichisches Normungsinstitut, 2006) the Los Angeles test is the reference procedure for the determination of resistance to fragmentation. The performance of the Los Angeles test is based on EN 1097-2 (Österreichisches Normungsinstitut, 2006); its adaptation for railway ballast is specified in Annex C to European Standard EN 13450 (Österreichisches Normungsinstitut, 2004). Both according to EN 1097-2 and EN 13450 the Los Angeles test is referred to as method for the determination of resistance to fragmentation. However, quality standards of Austrian Federal Railways mention the Los Angeles test as method for the determination of resistance to fragmentation and abrasion (ÖBB, 2007). The testing procedure is depicted in Fig. 7 and extensively described in the following paragraph.

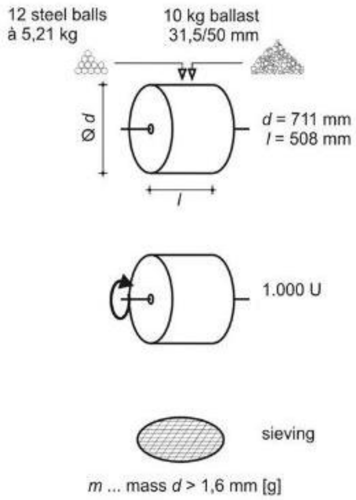


Fig. 7: Los Angeles test procedure according to EN 1097-2 and EN 13450 (Bach, 2013).

Material has to be sieved on 31.5 mm, 40 mm and 50 mm sieves. At the beginning, each grain fraction is washed and subsequently dried at a temperature of 110 ± 5°C in a drying cabinet. The sample material has to cool down to ambient temperature. Twelve steel spheres with a total weight of 5,210 ± 90 g and the sample material consisting of 5,000 ± 50 g of aggregates with a gradation of 31.5 / 40 mm and 5,000 ± 50 g of aggregates with a gradation of 40 / 50 mm are inserted into a standardised drum. A shelf (thickness 25 ± 1 mm, width 90 ± 2 mm) is mounted inside the drum. The drum has to perform 1,000 revolutions at speed of 31 – 33 revolutions per minute. Finally, the sample material is washed and sieved on a 1.6 mm sieve. Aggregates with a diameter > 1.6 mm are dried at a temperature of 110 ± 5°C in a drying cabinet and weighted. When the mass of material m retained on the 1.6 mm sieve in grams has been obtained, the Los Angeles coefficient LA_{RB} is calculated using the equation below:

$$LA_{\mathrm{RB}}\,[\%] = \frac{10{,}000 - m}{100}$$

The more material is retained on the 1.6 mm sieve, the lower the Los Angeles coefficient and the higher the resistance to fragmentation of the tested material. Los Angeles coefficients of railway ballast in Austria must not exceed a maximum value of 22 % by weight (ÖBB, 2007). The maximum value of 22 % by weight may be raised to a level of 24 % by weight if one of the two other tests (either Micro-Deval or Impact test) yield better results than required (ÖBB, 2007).

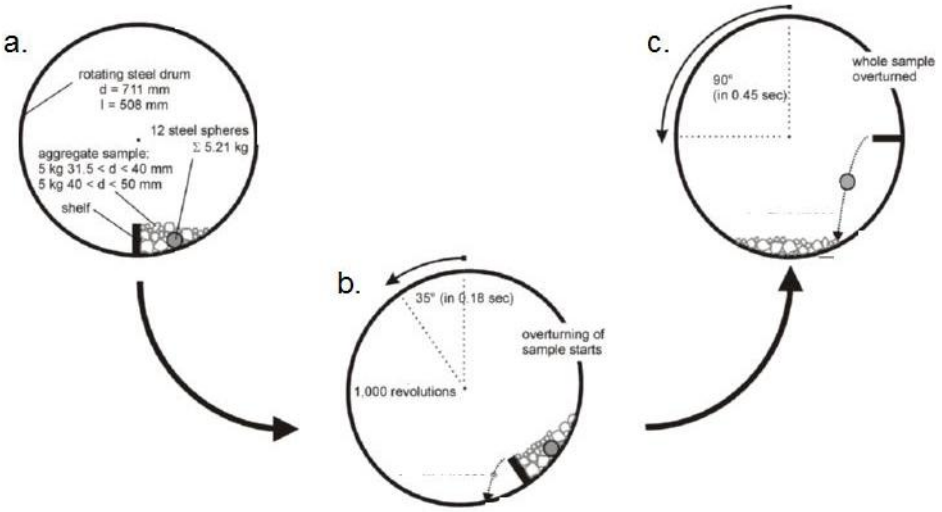


Fig. 8: Schematic cross section of the standardised steel drum during the Los Angeles test including aggregate sample and steel spheres (Bach, 2013).

A cross section of the drum including shelf and the test material is schematically illustrated in Fig. 8a. Within 0.18 seconds, the shelf has lifted up the sample by 35° and the overturning of the sample starts (Fig. 8b). After another 0.27 seconds, a quarter-turn is performed and the whole sample is overturned (Fig. 8c). After the free fall, a particle either collides with the wall of the drum, another particle or a steel sphere. Additionally, the respective particle may be hit by another particle or a steel sphere. Each of these possibilities leads to fragmentation processes. The onward movement of the bulk inside of the rotating drum leads to abrasion processes. Abrasion of particles is induced either by friction between two particles, a particle and a steel sphere or a particle and the inner surface of the drum (Bach, 2013).

5 Measuring device Petroscope 4D®

5.1 Introduction

Austrian Federal Railways need approximately one million tons of ballast aggregates per year (Kuttelwascher, 2012) and although railway ballast is a mass product, the evaluation of geometrical properties is a manual process.

Internal quality controls are performed by the respective supplier of railway ballast material. The inspection of railway ballast aggregates for the grain size distribution and the content of fine and finest grains is performed once a week, whereas the inspection for length and the length-to-width ratio is performed once a month. In addition to internal quality controls, geometrical properties are evaluated by personnel of Austrian Federal Railways every six months. Furthermore, Austrian Federal Railways are allowed to carry out intermediate examinations at the work site or place of installation any time (ÖBB, 2007).

Particle size distribution and the content of fine and finest grains is determined by sieving. The length and the length-to-width ratio of each individual grain is determined by using appropriate particle shape calliper gauges. Even though only a minimum quantity of material is subject to testing at regular intervals, the evaluation is costly in terms of time and labour. Maerz and Zhou (1999) mention a further disadvantage: Gathering data on the basis of manual processes is prone to human subjectivity.

In order to avoid the arduous work related to the determination of geometrical properties of railway ballast aggregates, the application of new technologies such as machine vision has become enhanced in the past few years (Lee et al., 2007). In general, the automation of quality assessment procedures aims at an increase in objectivity, precision and speed of operation. Aggregate characterisation might be more extensive – for example, due to an increase in speed of operation, more than just a minimum quantity of sample material could be subjected to the evaluation of geometrical properties. Thus, the statistical significance would not be limited anymore.

5.2 Functional units and operating principle of Petroscope 4D®

In the present study the determination of geometrical parameters of railway ballast aggregates is assisted by machine vision - the measuring device Petroscope 4D® is used. Petroscope 4D® (patent no. 2006/027802 A1) was developed by an Icelandic company (Petromodel Ltd.) and allows automated measurements of numerous geometrical data with the aid of laser scanning technology, its statistical evaluation and the estimation of the petrographic composition by means of reflectance spectra in visible and infrared light. Three functional units are distinguished: (1) system of feeders; (2) spectrometer; (3) unit for the determination of geometrical properties. The positioning of units is depicted in Fig. 9.

Fig. 9: Functional units of the measuring device Petroscope 4D®.

Petroscope 4D® is an automated measuring device. Aggregates which are to be analysed need to be inserted manually into the first feeder. The first feeder constantly supplies the testing device with aggregates. Following the first feeder, a system of smaller linear feeders aligns the aggregates and ensures that the distance between the individual aggregates is large enough for the analyses. The capacity of transporting is 300 to 600 particles per hour, depending on the size of particles (minimum particle size = 4 mm). Subsequent to the arrangement of aggregates reflectance spectra of particles are evaluated using a spectrometer (Avantes AvaSpec-ULS2048) with a wavelength range of 200 – 1160 nm and thus operating mainly in the visible light range and, to a minor extent, near infrared light range. The evaluation of reflectance spectra is followed by the determination of geometrical properties. The determination of geometrical properties is carried out within the measurement cubicle. Aligned aggregates are transported through the unit on a conveyor belt. The main component of the measurement cubicle is a single line laser (LasirisTM SNF-501L-635-5-15°) which is mounted above the conveyor belt. The laser projects a line onto the conveyor belt, perpendicular to the direction of movement. Two high speed cameras (Jai RM/TM-6740CL) capture images of moving aggregates when intersecting the laser line (Fig. 10) and computer software automatically calculates the geometrical properties. Resolution and accuracy are 0.15 mm in each case (Bach, 2013). A box is situated at the end of the conveyor belt in order to collect the analysed aggregates.

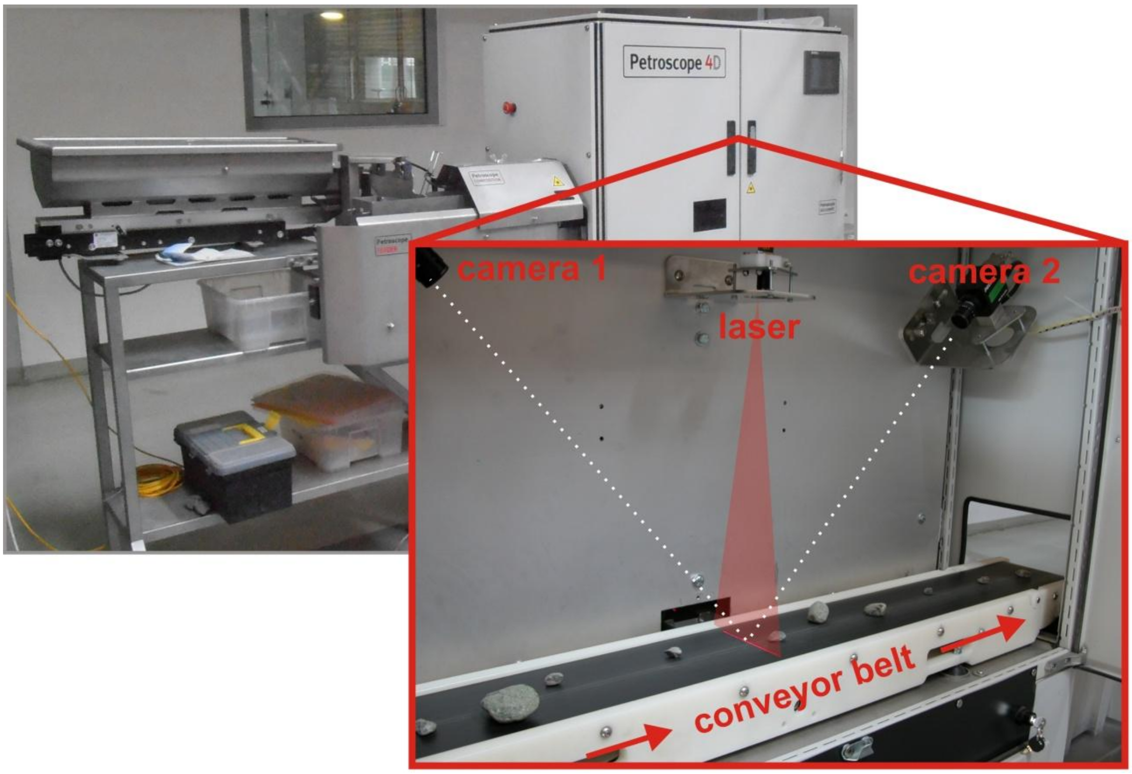


Fig. 10: Detailed view of the measruement cubicle including cameras and laser. The red arrows indicate the working direction of the conveyor belt.

5.3 Determination of geometrical properties using Petroscope 4D®

Railway ballast aggregates are examined regarding the external appearance. The external appearance of an object or rock aggregate is characterised by its surface texture and its shape. Surface texture refers to small-scale aspects, whereas shape refers to large- and medium-scale aspects compared to the overall size of the aggregate. Shape aspects include form, roundness or angularity and sphericity (Blott and Pye, 2008). According to Blott and Pye (2008) sphericity is an independent aspect of shape, even though it has been confused with the two other aspects. The term sphericity refers to the degree to which an aggregate resembles a sphere. Wadell (1932) compares the surface area of a particle to the surface area of a perfect sphere with the same volume. The shape aspects form and roundness or anglularity are briefly explained in the following paragraphs.

5.3.1 Form of aggregates

Zingg (1935) recommends a classification system in order to characterise the form of particles. The classification system is based on the measurement of all three principal axes. The longest dimension L (length), the intermediate dimension I (breadth) and the smallest dimension S (thickness) are taken into account. In doing so, axes need to be perpendicular to each other. In order to allow comparison between aggregates of all sizes, only the ratio between the axes is considered. The elongation ratio ER is calculated as the ratio of breadth I to length L. Particles with an elongation ratio ER < 0.67 are called elongated. The flatness ratio FR is calculated as the ratio of thickness S to breadth I. Particles with a flatness ratio FR < 0.67 are called flat. The combination of elongation ratio ER and flatness ratio FR is used to classify different form classes. In order to distinguish four form classes, a ratio value of 2:3 or 0.67 is selected. Zingg (1935) determined the threshold value empirically. Fig. 11 depicts the classification diagram proposed by Zingg (1935). The English terminology suggests the terms flat, elongated, flat and elongated, and cuboidal in order to differentiate amongst the form classes. Synonyms for the respective form classes exist.

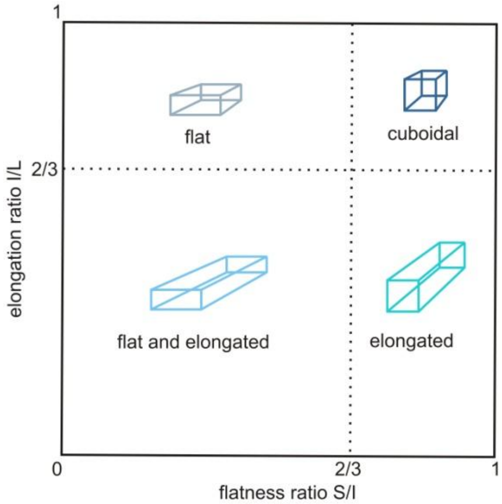


Fig. 11: Zingg's form classes flat, elongated, flat and elongated and cuboidal with corresponding values for flatness ratio and elongation ratio according to Zingg (1935).

5.3.2 Angularity or roundness of aggregates

Angularity or roundness is independent of form classes and refers to the sharpness of particle edges and corners compared to the overall size of the particle. According to Blott and Pye (2008) the angularity or roundness classification scheme, developed by Powers (1953), is most widely used. Powers (1953) distinguishes six classes with regard to angularity: very angular; angular; subangular; subrounded; rounded; well-rounded. Respective classes of angularity are expressed in terms of a numerical value or Powers number. Powers number one represents very angular particles, whereas Powers number six represents well-rounded particles. The distinction is based on the comparison between the radius of the corner r_2 and the radius of the maximum inscribed circle r_1. The smaller the radius of the corner r_2, the higher is the angularity of the particle. Angularity classes and the respective ratios of radii are depicted in Fig. 12.

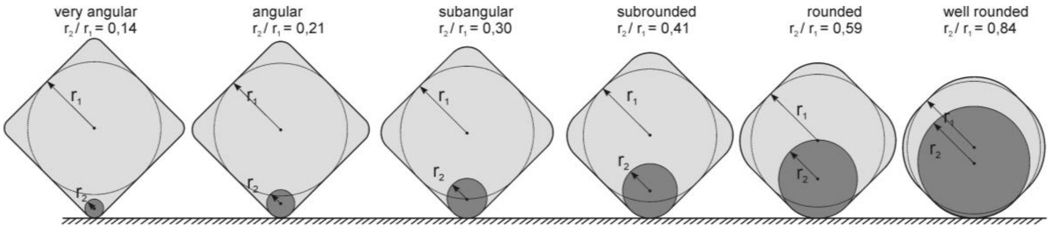


Fig. 12: Powers' angularity classes very angular, angular, subangular, subrounded, rounded and well rounded with corresponding ratios between radius of corner r_2 and radius of maximum inscribed circle r_1 (Bach, 213).

Lee et al. (2005) developed a different mathematical approach to determine the angularity of particles. The approach is also referred to as 'rolling ball transform'. The main principle of this algorithm is based on the fact that a ball rolling over a flat surface or a surface with a low curvature may have contact with the surface at every point. In contrast, the ball is not in touch with the surface at every point if the curvature is high, thus, inaccessible regions arise. Lee et al. (2007) improved the algorithm by replacing the structuring element. Instead of the spherical element an ellipsoid is used. The ellipsoid has the same ratio of principal axes compared to the analysed aggregate, but the absolute values of axes lengths are reduced to one third. The volume of inaccessible regions is compared to the total volume of the aggregate, and the result is expressed as 'volume loss'. The more parts are inaccessible to the ellipsoid, the higher is the volume loss (Fig. 13), thus a high volume loss refers to a high angularity of aggregates.

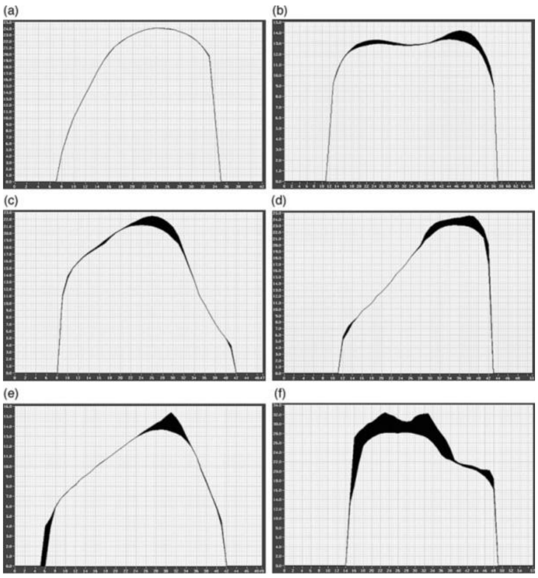


Fig. 13: Volume loss (black areas) of particles with a different degree of angularity. The particle on the bottom right exhibits the highest angularity (Lee, 2007).

5.3.3 Data mining through Petroscope 4D®

Petroscope 4D® calculates the following geometrical properties for each individual particle in order to quantify and characterise its external appearance:

- dimension of long, medium and short axes
- minimum sieve sieze
- elongation ratio, flatness ratio and associated form class according to Zingg (1935)
- angularity class according to Powers (1953)
- volume loss according to Lee et al. (2005, 2007); the volume loss is further denoted as 'volume of angles'
- volume and surface area
- sphericity

The display of data is represented in Fig. 14. For an entire batch of particles, the respective percentage of each form class and angularity class is presented either with regard to the total number of particles or the total volume of particles. Furthermore, the average sphericity is calculated and the analysis of an entire batch of particles contains information on the following parameters:

- particles size distribution according to EN 933-1 (Österreichisches Normungsinstitut, 2012a)
- Flakiness Index according to EN 933-3 (Österreichisches Normungsinstitut, 2012b)
- Shape Index according to EN 933-4 (Österreichisches Normungsinstitut, 2008)

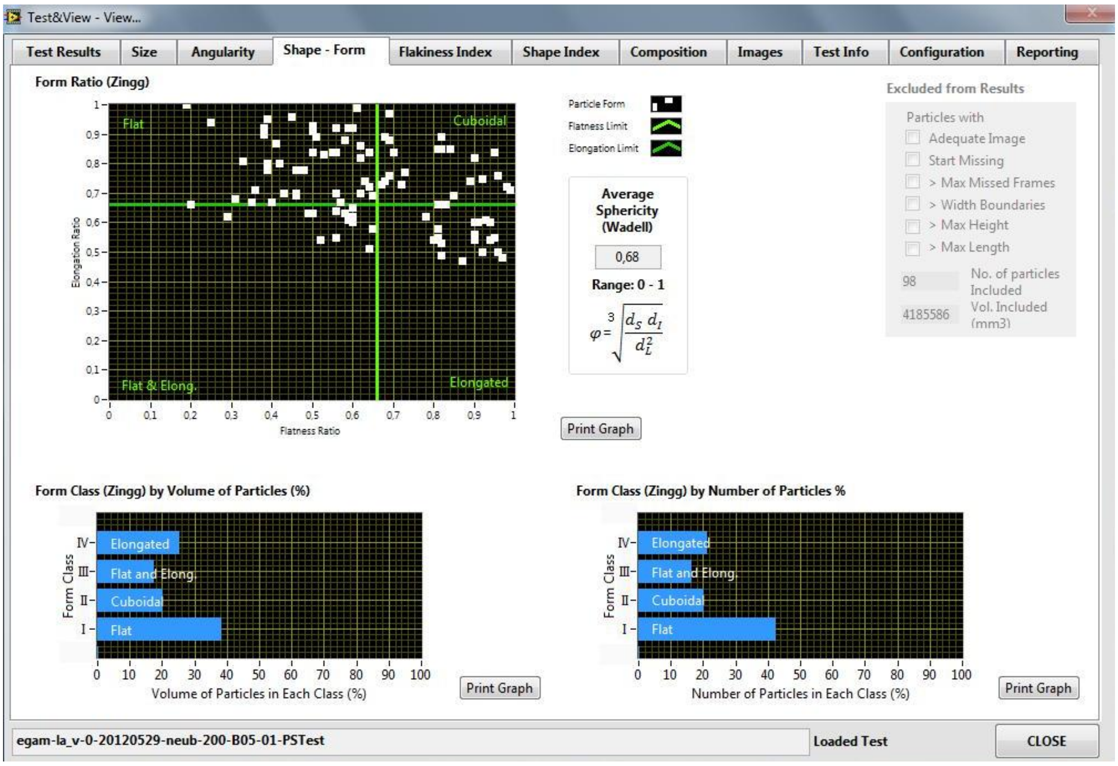


Fig. 14: Screenshot of data display. Form ratios, form classes (by volume and by percentage) and average sphericity of a sample.

Flakiness Index and Shape Index are parameters in order to constitute the ratio between the mass of non-cuboidal particles and the overall mass of particles.

The Flakiness Index is determined according to EN 933-3 (Österreischisches Normungsinstitut, 2012b) and indicates the ratio between the mass of flaky particles and the overall mass of the sample. In order to calculate the Flakiness Index FI of railway ballast with a gradation of 31.5 mm to 63 mm (31.5 represents the lower sieve size d in mm and 63 represents the upper sieve size D in mm) three size fractions (31.5 / 40 mm, 40 / 50 mm, 50 / 63 mm) are important. For each size fraction with the gradation d / D, the amount of material is determined which passes a corresponding bar sieve with a slot width D / 2. The Flakiness Index is calculated as follows:

$$FI\ [\%] = \left(\frac{M_2}{M_1}\right) \times 100$$

where M_2 is the sum of masses passing the respective sieve sizes in grams and M_1 is the total mass of the size fractions in grams. The lower the Flakiness Index FI, the more particles are close to cuboidal form.

The Shape Index is a comparable parameter. Its determination is explained in paragraph 2.2.2 (Geometrical properties).

6 Test results

6.1 Los Angeles test results

A total of 85 Los Angeles tests was performed on railway ballast material. The number of Los Angeles tests is divided as follows: 15 tests were performed on basalt (02) material; 22 tests were performed on granite porphyry (03) material; 27 tests were performed on dunite (04) material; 21 tests were performed on granulite (10) material. In case of granite porphyry, dunite and granulite, separated tests were performed on material of the respective subclass A and subclass B and on material without prior selection. In case of basalt all tests were performed on material without prior selection. Material without prior selection is marked with the letter M and represents a mixture of all subclasses or a random sample respectively. The number of performed tests per subclass is listed in Tab. 6.

Tab. 6: Number of Los Angeles tests per subclass.

	02M	03A	03B	03M	04A	04B	04M	10A	10B	10M
number of tests	15	8	5	9	8	8	11	8	3	10

6.1.1 Basalt

Fig. 15 depicts the Los Angeles test results for rock type basalt (02). LA_{RB} values average out at 12.75 %. Basalt samples are considered to be comparatively homogeneous in terms of macroscopic criteria, however Los Angeles test results show a considerable variation. The lowest LA_{RB} value is 10.44 % (sample number M15), the highest LA_{RB} value is 15.11 % (sample number M7). The difference between the minimum LA_{RB} value and the maximum LA_{RB} value for aggregates of rock type basalt is 4.67 %.

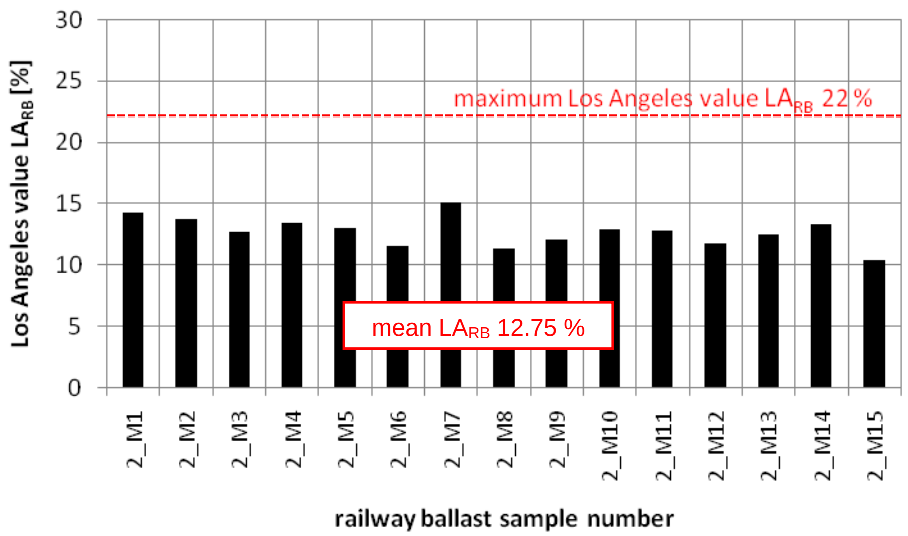


Fig. 15: Results of 15 Los Angeles tests performed on basalt samples (02).

6.1.2 Granite Porphyry

The visual difference within granite porphyry (03) samples is reflected by varying Los Angeles test results (Fig. 16) regarding the subclasses. The average LA_{RB} value for subclass 03A is 20.62 %. The average LA_{RB} value for aggregates of subclass 03B is 11.78 % and hence considerably lower than the average LA_{RB} value for subclass 03A. The difference is 8.84 %. The statistical significance is determined by means of the statistical computing system R (R version 2.11.1) and the so called student's t-test respectively. This test is applicable to compare two sets of data – provided that both sets of data are normally distributed - and determine whether or not the mean or average values show a statistically significant difference. In order to demonstrate statistical significance, the p-value must be lower than 0.05. In case of average LA_{RB} values for aggregates of subclass 03A and 03B, the p-value is 6.809e-06 and hence considerably lower than the threshold value. This means that the difference between the average LA_{RB} values for 03A and 03B is statistically significant. Due to the fact that subclass 03B accounts for only 25 % to samples without prior selection, the minor proportion of subclass B requires a high effort to gain enough material (10 kg per Los Angeles test) through the time-consuming process of manual sorting. This is why less tests are performed on subclass B. Although material of subclass 03A consists of similar aggregates with regard to macroscopic criteria, individual Los Angeles test results show a considerable variation. Whereas the minimum LA_{RB} value is 18.00 % (sample A2), the maximum LA_{RB} value (sample A7) is 25.57 %. Hence, the difference between sample A2 and A7 is 7.57%. Results of sample A7 as well as A8 exceed 22 %, thus two individual results exceed the maximum value allowed for railway ballast. LA_{RB} values for material without prior selection (03M) average out at 17.51 %.

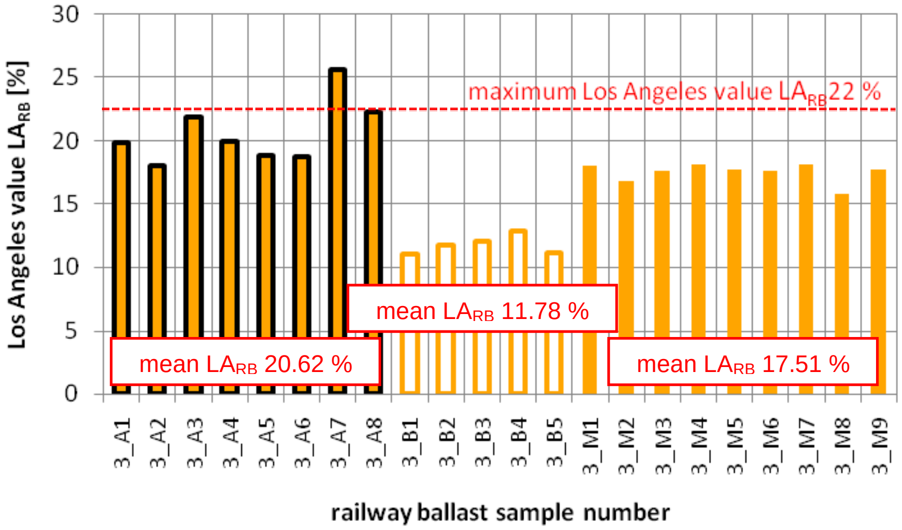


Fig. 16: Results of 22 Los Angeles tests performed on granite porphyry samples (03).

6.1.3 Dunite

Fig. 17 shows the Los Angeles test results for rock type dunite (04). The average LA_{RB} values for subclass 04A and 04B show nearly no difference, although macroscopic criteria indicate the existence of respective subclasses. LA_{RB} values for subclass 04A average out at 24.50 % and LA_{RB} values for subclass 04B average out at 25.18 %. Hence, the difference is 0.68% and fails to demonstrate statistical significance. Almost 40 % of the samples without prior selection are aggregates of subclass 04B - this high proportion allows to perform an equal number of tests on material of subclass A and subclass B. The average LA_{RB} value for material without prior selection (04M) is 25.29 %. Each individual result – regardless whether it belongs to subclass A, subclass B or material without prior selection – exceeds the maximum value allowed for railway ballast (max. LA_{RB} = 22 %).

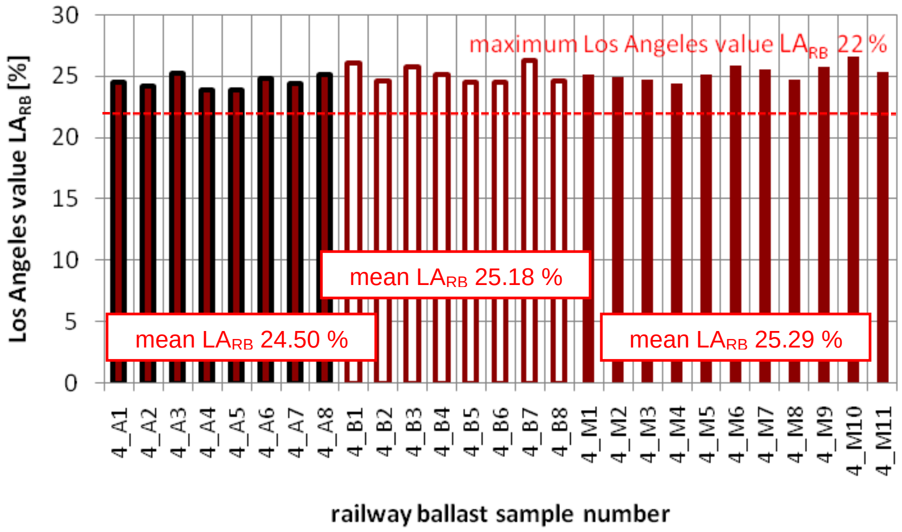


Fig. 17: Results of 27 Los Angeles tests performed on dunite samples (04).

6.1.4 Granulite

Los Angeles test results for rock type granulite (10) are shown in Fig. 18. The average LA_{RB} value for aggregates of subclass 10A is 15.44 %. The average LA_{RB} value for aggregates of subclass 10B is 14.45 % and hence slightly lower than the average LA_{RB} value for aggregates of subclass 10A. Comparable with the student's t-test, the Wilcoxon rank-sum test is used to determine whether or not the Los Angeles test results for subclass A and subclass B show a statistically significant difference. In this case, the Wilcoxon rank-sum test is used because one of the two data sets is not normally distributed. The resulting p-value is 0.04848 and hence lower than the threshold value of 0.05 (statistical computing system R, R version 2.11.1). Only 10 % of the random samples exhibit a high amount of biotite and constitute subclass B. Due to the minor proportion of subclass B it would have been too time-consuming to gain enough material in order to perform more than three Los Angeles tests. LA_{RB} values for random samples (10M) average out at 15.29 %.

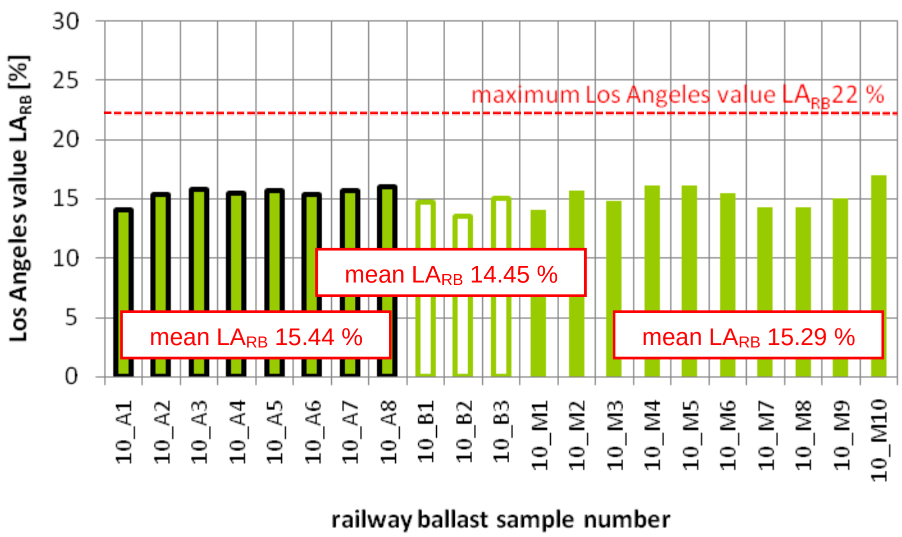


Fig. 18: Results of 21 Los Angeles tests performed on granulite samples (10).

6.2 Results determined by using Petroscope 4D®

Geometrical properties of railway ballast material were analysed by means of the measuring device Petroscope 4D®. Petroscope 4D® calculates geometrical properties for individual particles as well as for an entire batch of particles. A batch of particles corresponds to one sample. One sample, in turn, is composed of 85 to 114 (10,000 ± 100 g) individual particles with a gradation of 31.5 / 50 mm (prior to Los Angeles testing). The differing numbers of individual particles are due to differences in particle shape of the respective rock type or subclass. As previously stated, a total of 85 Los Angeles tests was performed on railway ballast material of different rock types and subclasses respectively. Each of the 85 samples was analysed by means of Petroscope 4D® prior and subsequent to Los Angeles testing.

6.2.1 Particle number ratio (PNR)

Tab. 7 shows the mean number of particles per sample prior and subsequent to the Los Angeles test for each rock type and each subclass respectively. Railway ballast material of rock type dunite (04), in particular subclass 04B and material without prior selection (04M) are characterised by a relatively high number of particles with a diameter exceeding 4 mm after the Los Angeles test.

Tab. 7: Comparison between the number of particles prior the Los Angeles test and the number of particles with a diameter exceeding 4 mm after the Los Angeles test.

	02M	03A	03B	03M	04A	04B	04M	10A	10B	10M
particle number prior test	95	85	101	89	99	96	97	101	103	114
particle number > 4 mm after test	324	445	548	444	598	1530	920	561	491	579

The ratio between the number of particles d > 4 mm after the Los Angeles test and the number of particles prior to the Los Angeles test is called particle number ratio (PNR). The mean particle number ratio for each rock type and each subclass respectively is illustrated in Fig. 19. In case of rock type basalt (02M) the PNR is 3.41 (minimum PNR value), accordingly the number of particles has tripled. Rock type granite porphyry (03) as well as rock type granulite (10) are each characterised by a similar PNR with regard to respective subclasses and random samples. For dunite (04) the PNR allows for a clear distinction between subclass 04A and 04B. The PNR for aggregates of subclass 04A is 6.04, whereas the PNR for aggregates of subclass 04B is 15.96 (maximum PNR value). The number of particles > 4 mm after the Los Angeles test is 16 times the number of particles prior to the Los Angeles test. The PNR for aggregates without prior selection (04M) is 9.48.

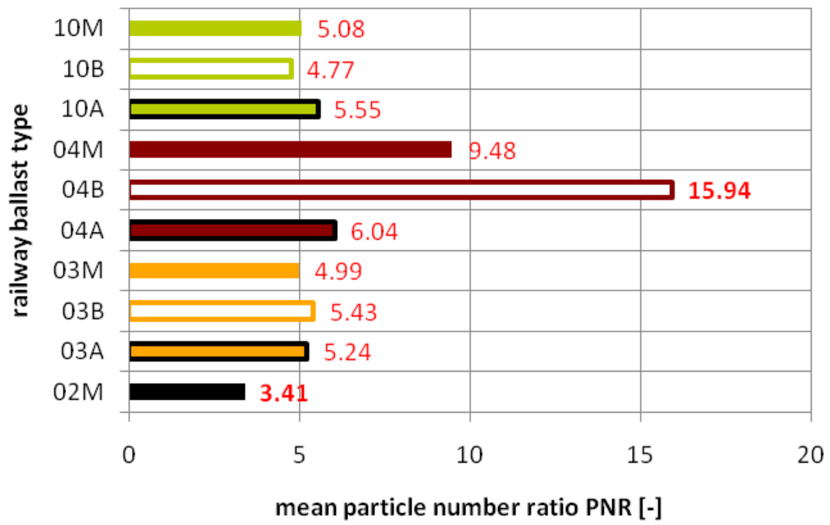


Fig. 19: Mean particle number ratio PNR for each rock type and subclass respectively. Data in bold indicate the minimum and the maximum particle number ratio PNR.

6.2.2 Angularity or roundness

Prior to the Los Angeles test, for all rock types, very angular, angular and subangular particles account for the major share. Rock type granite porphyry (03) exhibits the highest percentage of very angular, angular and subangular particles: Subclass 03A, 03B and the random samples 03M as well contain more than 97.5 % of very angular to subangular particles in each case. The maximum percentage of very angular to subangular particles is 98.06 % (03B). Material of subclass 04A exhibits the minimum percentage of very angular to subangular particles (91.51 %). Tab. 8 shows the mean percentage of very angular, angular and subangular particles prior and after the Los Angeles test for each rock type and subclass respectively.

After the Los Angeles test rounding is reflected in a decrease in the percentage of very angular to subangular particles and in an increase in the percentage of subrounded to well-rounded particles for all rock types. It still remains material of subclass 03B which exhibits the largest percentage of very angular to subangular particles (87.75 %) and it still remains material of subclass 04A which exhibits the least percentage of very angular to subangular particles (59.01 %).

Tab. 8: Mean percentage of very angular, angular and subangular particles prior and after the Los Angeles test.

	02M	03A	03B	03M	04A	04B	04M	10A	10B	10M
very angular to subangular particles prior test [%]	96.77	97.54	98.06	97.85	91.51	96.04	96.28	94.93	96.80	95.78
very angular to subangular particles after test [%]	81.12	77.39	87.75	79.51	59.01	80.61	70.86	80.03	79.10	78.85

The decrease in angularity, here expressed as volume of angles, is illustrated in Fig. 20. Comparing the pre-test and the post-test configuration, the decrease in angularity is most pronounced for rock type dunite (04). For subclass 04A, subclass 04B and random samples (04M), the difference between the mean volume of angles prior to the test and the mean volume of angles after the test exceeds 4 % in each case. For random samples (04M), the decrease in angularity is 5.18 % (maximum value). The decrease in angularity is least pronounced for rock type granulite (10). The decrease in angularity for subclass 10A and 10B as well as for random samples (10M) is below 3 %. The minimum value is 2.47 % (10B). Prior to the Los Angeles test, the range between the most rounded rock type and the most angular rock type is between 7.3 % and 10.2 % (Δ = 2.9 %). After the Los Angeles test, the range is between 3.1 % and 6.3 % (Δ = 3.2 %), hence it has increased by 0.3 %. All data depicted in Fig. 20 are mean values of the pre-test or post-test angularity which refers to 50 % of the respective sample volume (VA_{50}).

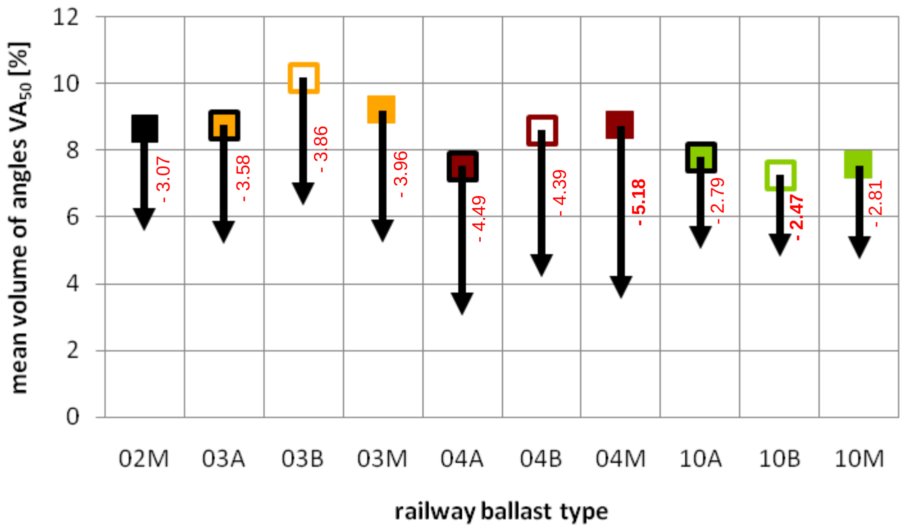


Fig. 20: Decrease in mean volume of angles VA_{50} (red). Data in bold indicate the minimum and maximum value with reference to the difference in angularity. The origin of arrows corresponds to the mean value of angles VA_{50} prior to the Los Angeles test and the arrowhead symbol corresponds to the respective mean value of angles VA_{50} after the Los Angeles test.

6.2.3 Elongation ratio, flatness ratio and form class

Tab. 9 shows the mean flatness ratio and the mean elongation ratio for each rock type and the respective subclasses prior to the Los Angeles test as well as after the Los Angeles test. Additionally the difference between the pre-test and the post-test value for flatness and elongation ratio is given. A negative algebraic sign indicates an increase in flatness and elongation.

Tab. 9: Mean flatness ratio (FR) and mean elongation ratio (ER) prior and after the Los Angeles test for all rock types and subclasses respectively. Difference between post-test and pre-test values is expressed as Δ FR and Δ ER.

	FR prior [-]	FR after [-]	Δ FR [-]	ER prior [-]	ER after [-]	Δ ER [-]
02M	0.67	0.72	0.04	0.76	0.78	0.02
03A	0.61	0.62	0.01	0.71	0.72	0.00 (0.0027)
03B	0.60	0.65	0.05	0.73	0.74	0.01
03M	0.63	0.67	0.04	0.72	0.72	0.00 (0.0005)
04A	0.68	0.67	-0.01	0.75	0.77	0.01
04B	0.65	0.59	-0.06	0.73	0.72	0.00 (-0.0044)
04M	0.68	0.67	-0.01	0.75	0.73	-0.02
10A	0.66	0.67	0.02	0.75	0.78	0.03
10B	0.65	0.67	0.03	0.78	0.77	-0.01
10M	0.66	0.71	0.05	0.76	0.76	0.00 (0.0024)

The differences between the pre-test and post-test values for flatness ratio and elongation ratio are very small. This can be attributed to the fact that Tab. 8 shows only the mean values. Comparing the mean flatness ratio prior to the Los Angeles test with the mean flatness ratio after the Los Angeles test, a decrease in flatness ratio can be observed for subclass 04A and subclass 04B as well as for random samples 04M. For material of subclass 04B, the decrease in flatness ratio and hence the increase in flatness is most pronounced. For material of any other rock type (02, 03, 10), the flatness ratio increases and hence the flatness decreases.

A decrease in elongation ratio can be observed in case of subclass 04B, in case of random samples 04M and in case of subclass 10B. In all three cases the elongation ration decreases and hence the elongation increases. For material of any other rock type and subclass (02M, 03A, 03B, 03M, 04A, 10A, 10M), the results are completely reversed and the elongation ratio increases and hence the elongation decreases.

The flatness ratio and the elongation ratio for all individual samples and rock types prior and after the Los Angeles test are illustrated in Fig. 21. Each single value for the form class is either within the sector of form class flat or within the sector of form class cuboidal. The pre-test configuration of rock type 03A represents the sole exception, because sample A7 exhibits an elongation ratio of 0.66, hence the respective value is within the sector of form class flat and elongated.

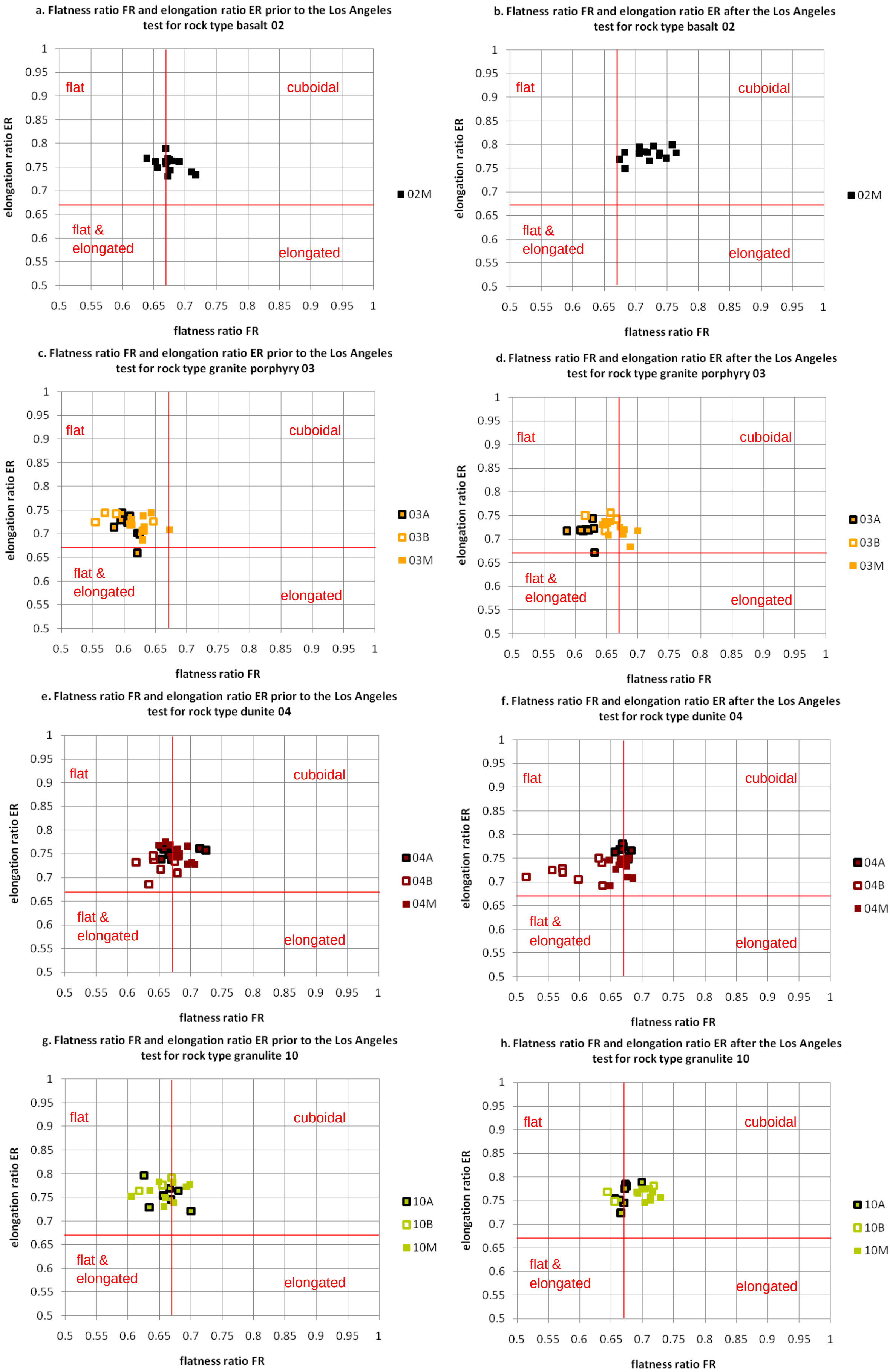


Fig. 21: Distribution of individual samples across the four different form classes for each rock type and subclass respectively prior to the Los Angeles test (left) and after the Los Angeles test (right). Elongation ratio ER and flatness ratio FR are dimensionless.

The change of the mean flatness ratio or the mean elongation ratio and mean form class is illustrated in Fig. 22. Due to the fact that each individual sample (exception 03A_A7) is within the sector of form class flat or within the sector of form class cuboidal, the same applies for the mean values. The origin of an arrow corresponds to the mean value of flatness ratio and elongation ratio prior to the Los Angeles test, whereas the arrowhead symbol corresponds to the mean value of flatness ratio and elongation ratio after the Los Angeles test. Only in the case of rock type dunite (04), the arrowhead symbol is pointing to the left, indicating a decrease in flatness ratio and an increase in flatness. For material of subclass 04B, the change in flatness ratio is most pronounced (maximum value of change in flatness ratio = -0.06). The mean form class of rock type granite porphyry (03) as well as rock type basalt (02) does not change as a consequence of the Los Angeles test. Both prior the Los Angeles test and after the Los Angeles test, mean values for rock type 03A, 03B and 03M are within the sector of form class flat. In case of rock type basalt (02), the origin of the arrow as well as the arrowhead symbol are within the sector of form class cuboidal. Due to the Los Angeles test, the mean values for rock type 10A, 10B and 10M shift from form class flat to form class cuboidal. For material of subclass 10A, the change in elongation ratio is most pronounced (maximum value of change in elongation ratio = 0.03). For rock type 02M, 03A, 03B, 03M, 04B, 10B and 10M the change in flatness ratio exceeds the change in elongation ratio. In contrast the change in elongation ratio exceeds the change in flatness ratio for rock type 04M and 10A. The change in flatness ratio and elongation ratio exhibits the same magnitude but a different direction for rock type 04A.

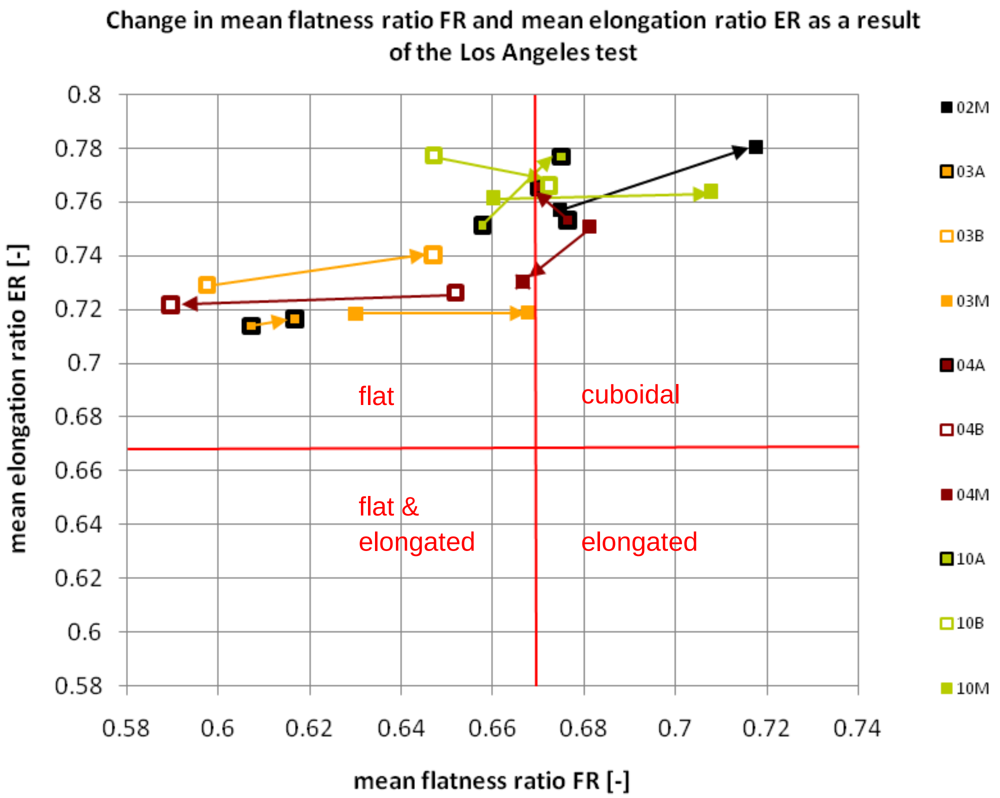


Fig. 22: Mean flatness ratio FR and mean elongation ratio ER before and after the Los Angeles test as well as the related change in mean form class for all rock types and subclasses respectively.

The behaviour of rock type dunite (04) differs significantly from the behaviour of all other rock types. Subclass 04A and subclass 04B and random samples 04M as well show an increase in flatness - the increase in flatness is most pronounced for subclass 04B. This may be explained by its geological appearance. Detailed information about individual characteristics can be found in paragraph 3.2 (Macroscopic and microscopic characterisation). Fig. 23 depicts polished sections of rock type 04A and 04B. Subclass B is characterised by numerous veins or cracks which are aligned approximately parallel. Veins or cracks may form predetermined lines of breakage and lead to the formation of flat particles.

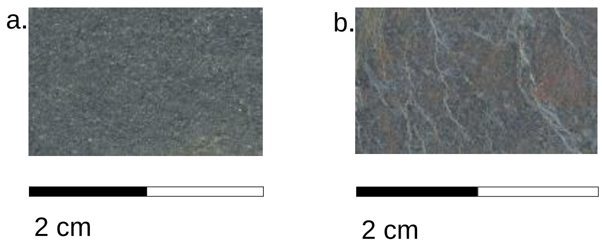


Fig. 23: Polished sections of rock type 04A (a.) and 04B (b.).

6.2.4 Flakiness Index and Shape Index

Fig. 24 shows the Flakiness Indices as well as the Shape Indices for all rock types and respective subclasses. Railway ballast material of rock type granite porphyry (03) exhibits the maximum values for Flakiness Index (FI) and for Shape Index (SI). FI values for subclass 03A average out at 26 %; FI values for subclass 03B average out at 33.2 %. The average SI value is 25 % and 23.2 % respectively. Railway ballast of rock type dunite and subclass 04A exhibits the minimum values for the Flakiness Index as well as for the Shape Index. It includes the highest number of particles which are close to cuboidal form. The mean FI value is 7.88 %; the mean SI value is 12.63 %. In contrast to the particle number ratio PNR (maximum value compared to all other rock types) and the change if form (maximum value for change in flatness ratio compared to all other rock types), FI and SI for rock type 04B don't show unusual results. The mean FI value and the mean SI value for subclass 04B are much higher. The differences between the subclasses are negligible within material of rock type granulite (10). Subclass 10B exhibits both the smaller mean value for the Flakiness Index and the smaller mean value for the Shape Index. Material of rock type basalt (02M) exhibits a small mean value with regard to the Flakiness Index and the Shape Index. The mean Shape Index is between 5 % and 30 % for all rock types, hence the requirements of Austrian Federal Railways with regard to length-to-width ratio are met in each case.

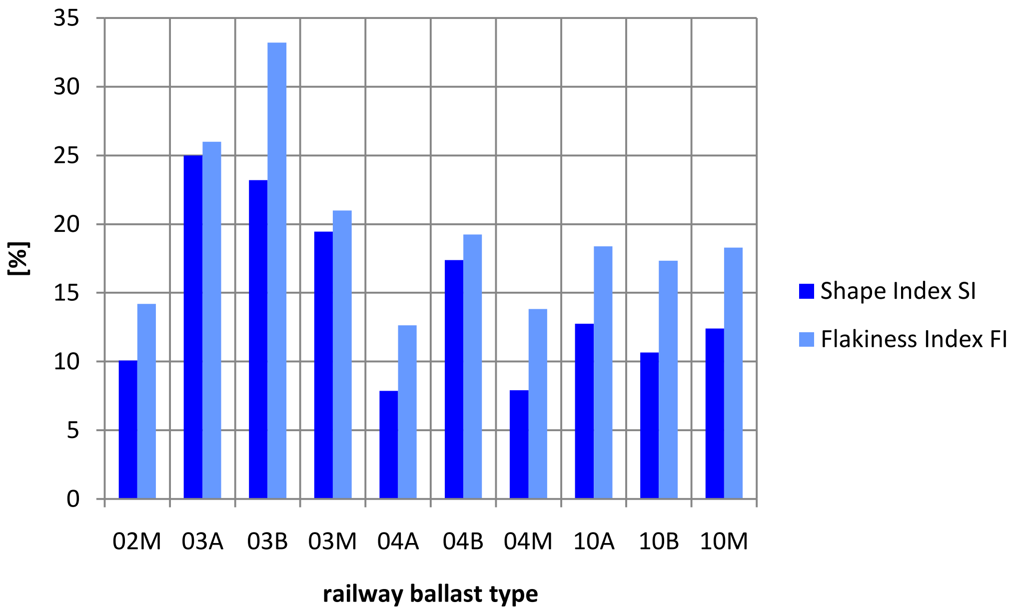


Fig. 24: Shape Index SI and Flakiness Index FI for all rock types and subclasses respectively prior to the Los Angeles test.

7 Evaluation of test results

7.1 Evaluation of Los Angeles test results

A total of 85 Los Angeles tests was performed, whereby the maximum number of tests (15 tests) was carried out on material of rock type basalt (02) and the minimum number of tests (three tests) was carried out on subclass B of rock type granulite (10). Rock type granulite (10) comprises varying proportions of subclass A and subclass B: Material of subclass A accounts for approximately 90 % and material of subclass B accounts for approximately 10 % of the total quantity. Due to the minor proportion of subclass B, further sorting would have been disproportional work. In the specific case of rock type 10B the number of tests is very small. Because of the fact that the number of tests per subclass is generally rather small, the question arises whether the results are sufficient in order to reach a particular precision at an acceptable confidence limit. Tab. 10 shows the mean Los Angeles values LA_{RB}, the mean standard deviations, the actual numbers of tests and the required numbers of tests in order to achieve a precision of ± 0.5 at a confidence level of 0.95 (95 %). Only for rock type 04A, 04M and 10A, the actual number of tests exceeds the required number of tests. For rock type 04B the actual number of tests is equal to the required number of tests. For rock type 03A, the high variation of tests results is reflected in a high standard deviation and therefore an extremely high number of tests (96 tests) is required in order to reach a precision of ± 0.5 at a confidence level of 0.95 (95 %). The minimum number of tests n in order to reach a precision of ± 0.5 at a confidence level of 95 % is calculated as follows:

$$n \geq \frac{z^2 \times \sigma^2}{d^2}$$

where z equals 1.96, σ is the respective standard deviation and d equals 0.5.

Tab. 10: Mean Los Angeles value, standard deviation, number of performed and required tests as well as the difference between performed and required tests for each subclass. The number of required tests refers to a precision of ± 0.5 at a confidence level of 0.95 (95 %).

rock type	mean LA_{RB} [%]	standard deviation [%]	number of tests performed (per.)	number of tests required (req)	difference per-req
02M	12.75	1.20	15	22	-7
03A	20.61	2.50	8	96	-88
03B	11.78	0.76	5	9	-4
03M	17.51	0.79	9	10	-1
04A	24.51	0.54	8	4	4
04B	25.19	0.74	8	8	0
04M	25.29	0.62	11	6	5
10A	15.43	0.59	8	5	3
10B	14.45	0.81	3	10	-7
10M	15.29	0.94	10	14	-4

Austrian Federal Railways evaluate the Los Angeles value LA_{RB} of railway ballast aggregates every six months – during the first and the second half of the year (ÖBB, 2007). The results for the time period from 2004 to 2008 reveal variations for all four rock types (Fig. 25). For rock type 02, 03 and 04, the difference between the maximum LA_{RB} and the minimum LA_{RB} is 6 % in each case. For rock type 10, the difference is higher and accounts for 10 %.

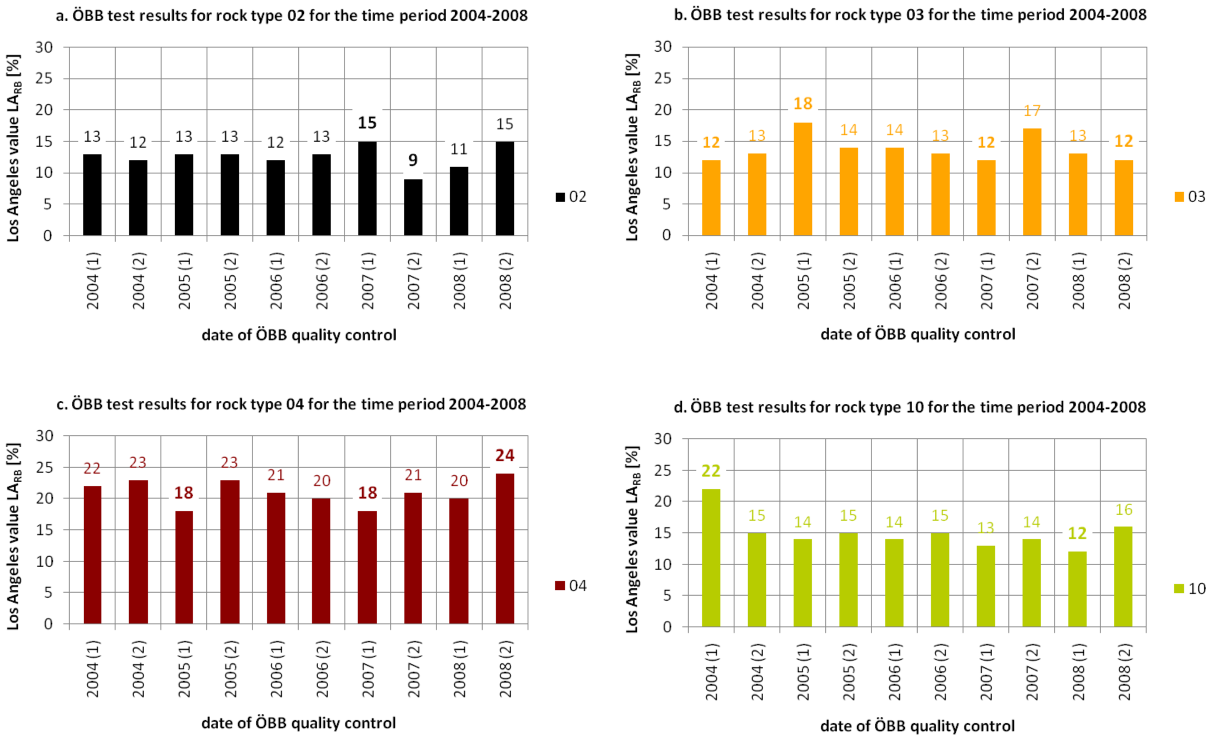


Fig. 25: Los Angeles test results of biannual external quality controls performed by Austrian Federal Railways (ÖBB) for a time period from 2004 to 2008. Data in bold indicate the maximum and minimum LA_{RB} values.

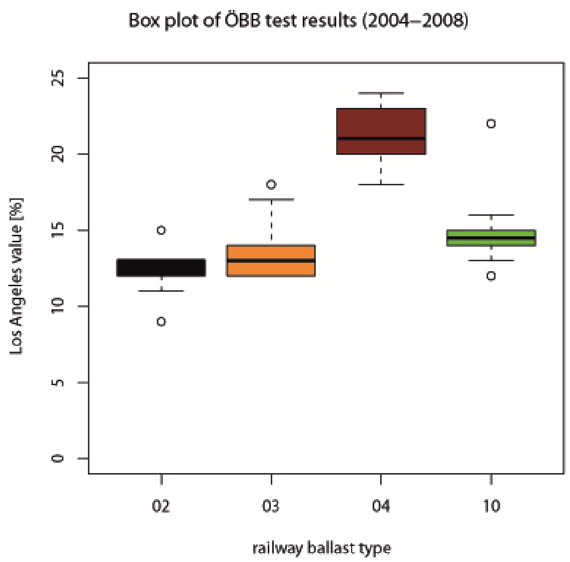


Fig. 26: Box plot of ÖBB test results for all rock types for a time period from 2004 to 2008.

Within the course of this Master's thesis material without prior selection (samples marked with the letter M) correspond to the original composition of railway ballast material. Test results of rock type 02M, 03M, 04M and 10M are comparable with test results of Austrian Federal Railways (ÖBB) exclusively. Both TU test results and ÖBB test results indicate that rock type 02 exhibits a very high resistance to fragmentation and abrasion (low Los Angeles values) and rock type 04 exhibits a very low resistance to fragmentation and abrasion (high Los Angeles values). Fig. 26 shows a box plot of ÖBB test results for the time period from 2004 to 2008. Comparing the results of this Master's thesis with the results determined by personnel of Austrian Federal Railways, it becomes apparent that the mean Los Angeles value LA_{RB} for rock type 03 and 04 differ by approximately 4 % in each case (Fig. 27). This may be attributed to the heterogeneity of materials or varying proportions of subclasses. For rock type 02 and 10 the difference is much smaller. For all rock types ÖBB test results exhibit lower mean LA_{RB} values.

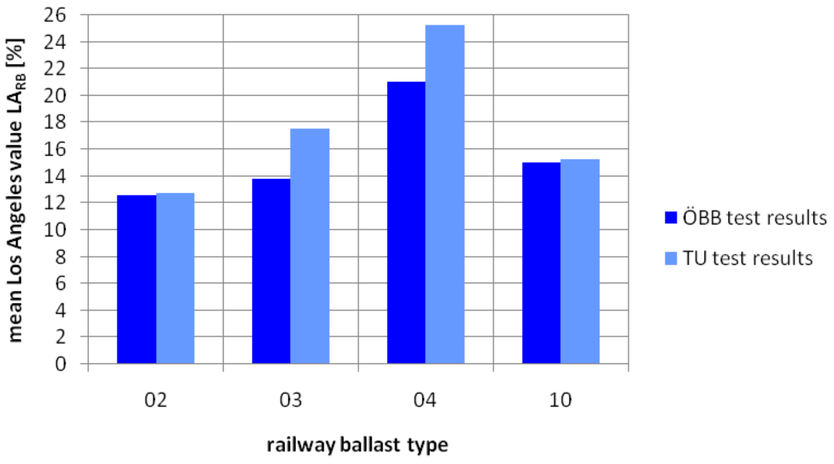


Fig. 27: Mean Los Angeles values for tests performed by Austrian Federal Railways (ÖBB test results) and tests performed within the course of this Master's thesis (TU test results).

7.2 Evaluation of petrography and its effects on the mechanical properties

7.2.1 Basalt

Railway ballast of rock type basalt (02) has an exceptional character because no subclasses are present. Although aggregates appear to be homogeneous in terms of mineral content, test results of rock type 02M indicate high variation. Considering the test results (TU test results) of samples without prior selection (02M, 03M, 04M, 10M), results of rock type 02M show the highest variation with regard to the Los Angeles value LA_{RB} (mean LA_{RB} = 12.75 %; standard deviation 02M = 1.20 %; 15 tests). This raises the question whether slight variations concerning shape aspects (form or angularity of particles) are responsible for the differing mechanical properties. Biannual test results by Austrian Federal Railways (ÖBB test results) indicate a variation as well. But it must be noted that TU tests were performed on material of a single batch, whereas ÖBB tests were performed on material of different batches. Compared to ÖBB test results for 03, 04 and 10, results for rock type 02 show the lowest variation with regard to the Los Angeles value LA_{RB} (mean LA_{RB} = 12.60 %; standard deviation = 1.78 %; ten tests).

7.2.2 Granite porphyry

A total of 22 tests was performed on railway ballast material of rock type granite porphyry (03) within the course of this Master's thesis. Eight tests were performed on rock type 03A, five tests were performed on rock type 03B and nine tests were performed on rock type 03M. The mean LA_{RB} value for subclass A is 20.62 %, whereas the mean LA_{RB} value for subclass B is 11.78 %. This significant difference in the mean Los Angeles value LA_{RB} is owed to the fact that aggregates of subclass A differ from aggregates of subclass B in terms of respective petrographic characteristics: Railway ballast aggregates of subclass 03A contain coarse-grained minerals of quartz, feldspar, amphibole, biotite and garnet. Furthermore a prominent foliation is present. On the contrary, railway ballast aggregates of subclass B have a completely different rock fabric. Subclass B exhibits a porphyritic texture - a few large crystals are embedded in a microcrystalline matrix of quartz, feldspar, amphibole and biotite. Garnet is not present at all. The LA_{RB} value for samples without prior selection 03M averages out at 17.51 % (standard deviation 03M = 0.79 %, nine tests) and is between the test results of subclass A and subclass B. Actually it is much closer to the mean Los Angeles value LA_{RB} for rock type 03A. This may be attributed to the fact that subclass A accounts for the largest share of samples without prior selection. Subclass A accounts for 65 % to samples without prior selection and subclass B accounts for 25 % to samples without prior selection. The remaining 10 % are allocated to subclass C and D. Analysed railway ballast samples originate from a single day's production, therefore, the share of respective subclasses is considered to be relatively similar throughout all of the nine samples of rock type 03M. This particular situation is the opposite for Los Angeles test results by Austrian Federal Railways because the samples originate from ten different production days. The minimum LA_{RB} value

(ÖBB test results) was 12 % and the maximum LA_{RB} was 18 % (mean LA_{RB} = 13.80 %; standard deviation = 2.10 %; ten tests). This variation may be explained by varying proportions of subclasses. High LA_{RB} values may indicate a higher share of subclass A, whereas low LA_{RB} values may indicate a higher share of subclass B. Within the course of this Master's thesis no Los Angeles test was performed on material of subclass C or D of rock type 03, therefore its mechanical behaviour is not known but may also come into question in order to explain the variation of ÖBB test results.

7.2.3 Dunite

The maximum number of Los Angeles tests was performed on railway ballast material of rock type dunite (04). Eight tests were performed on rock type 04A, eight tests were performed on rock type 04B and eleven tests were performed on rock type 04M. Aggregates of subclass A and subclass B of rock type 04 differ in terms of mineral content, fabric and degree of alteration. Subclass A contains fine-grained serpentine, olivine and amphibole, whereas subclass B contains coarse-grained minerals of serpentine, olivine, amphibole and chlorite. Compared to subclass A aggregates of subclass B are characterised by a slight foliation and a very prominent chemical alteration or metasomatosis. Differences between subclass A and subclass B are present, nevertheless the mean Los Angeles values LA_{RB} show hardly any difference. LA_{RB} values for subclass 04A average out at 24.50 % and LA_{RB} values for subclass 04B average out at 25.18 %. The mean LA_{RB} value for random samples M of rock type 04 is 25.29 % (standard deviation 04M = 0.62 %, eleven tests) and thus slightly higher. Rock type 04M does not only consist of subclass A (60 %) and subclass B (39.5 %), but also of subclass C. Although subclass C is only present in very small quantities (0.5 %), it may affect the result of the Los Angeles test. According to Röthlisberger (2005) one weak particle such as a carbonate may lead to an increase of the LA_{RB} value by 1 % already. Subclass C is represented by magnesite or magnesium carbonate aggregates. Due to the unfavourable strength properties ascribed to carbonates in general, subclass C may adversely affect the LA_{RB} value for random samples M of rock type 04. ÖBB test results for dunite average out at 21 % (standard deviation = 2.05 %, ten tests). This variation may also be explained by a varying amount of magnesite particles within the ÖBB test samples.

7.2.4 Granulite

A total of 21 tests was performed on railway ballast material of rock type granulite (10) within the course of this Master's thesis. Eight tests were performed on rock type 10A, only three tests were performed on rock type 10B and ten tests were performed on rock type 10M. For rock type granulite (10) consecutive material inspections by Austrian Federal Railways demonstrate the highest variation (standard deviation = 2.71 %, ten tests) of results – the minimum LA_{RB} value is 12 % and the maximum LA_{RB} value is 22 %. Within the course of this Master's thesis results of Los Angeles tests for rock type 10M do not show such a high variation. Rock type granulite comprises two subclasses – the difference between subclass A (90 %) and subclass B (10 %) is only based on the amount of biotite. Both varieties are coarse-grained and exhibit a foliation. The slight difference with regard to the mineral content is reflected by a slight difference in LA_{RB} values. The average LA_{RB} value for aggregates of subclass 10A is 15.44 % and the average LA_{RB} value for aggregates of subclass 10B is 14.45 %. LA_{RB} values for random samples (10M) average out at 15.29 % (standard deviation = 0.94 %, ten tests) - this result is closer to the result of subclass A.

7.3 Evaluation of geometry and its effects on the mechanical properties

According to Selig and Boucher (1990) the mechanical properties of railway ballast aggregates (e.g. Los Angeles value LA_{RB}) are influenced by the sample petrography (rock type), the sample geometry (particle shape) and the particle size distribution of the sample. The gradation is standardised for the Los Angeles test (railway ballast aggregates with a gradation of 31.5 / 50 mm are used). Therefore test results are exclusively influenced by rock type and particle shape. This raises the question whether the influence of petrography or geometry is more decisive for the Los Angeles value LA_{RB}. Within the course of this Master's thesis the sample geometry or particle shape is discussed in more detail compared to the petrography of railway ballast material. This is mainly due to the fact that geometrical properties are easier to quantify.

Fig. 28 shows a scatterplot (conceptualised by means of the statistical computing system R, R version 2.11.1) matrix of seven pre-test geometrical properties and the Los Angeles values for all rock types. The column on the extreme right and the bottom row indicate that no linear relationship between the pre-test geometrical properties and the Los Angeles values exists for the entire range of railway ballast aggregates. Correlations can be observed among individual pre-test geometrical properties. Correlation coefficients (computed by means of the statistical computing system R, R version 2.11.1) are listed in Tab. 11. Lee's volume of angles VA_{50} and Powers' angularity classes are different mathematical approaches in order to determine the same property.

Already Lee et al. (2005) described an almost linear relationship between the volume of angles VA_{50} and the angularity classes. The computed correlation coefficient (0.877) is statistically significant at a confidence level of almost 100 % (p-value < 2.2e-16).

Five out of seven pre-test geometrical parameters refer to the form of particles. This explains why diagrams in Fig. 28 show partially very high correlation coefficients between the Flakiness Index FI, the Shape Index SI, the volume of cuboidal particles (cuboidal), the flatness ratio FR and the elongation ratio ER. The Pearson's product-moment correlation is most pronounced for the relationship between FI and FR as well as SI and FR. In both cases the computed correlation coefficients are statistically significant at a confidence level of almost 100 % (p-value < 2.2e-16).

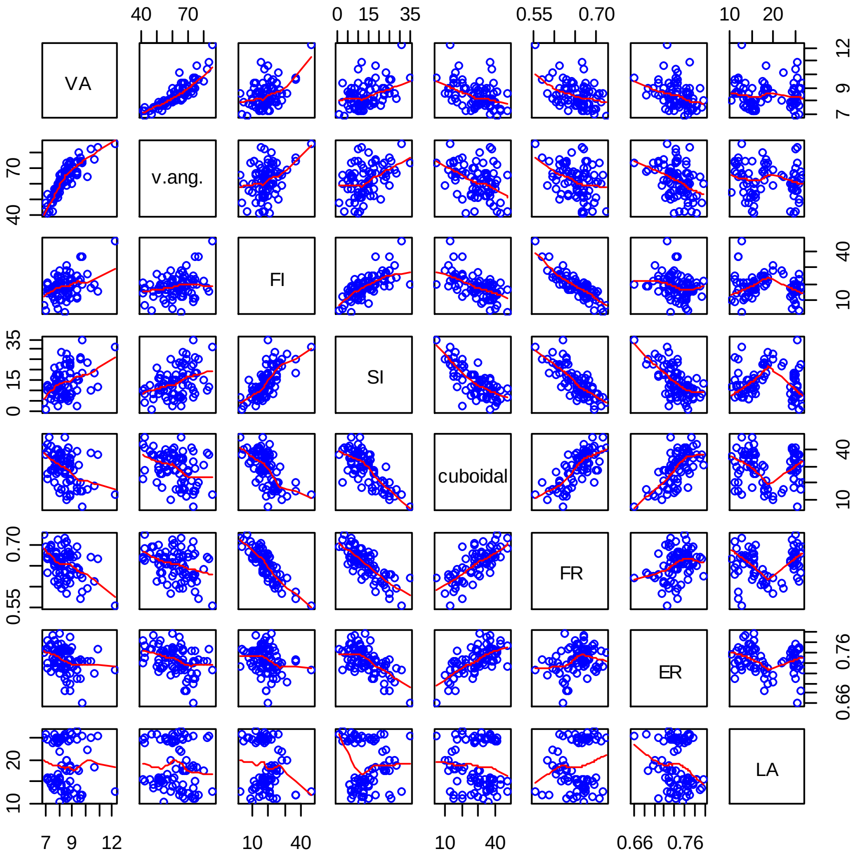


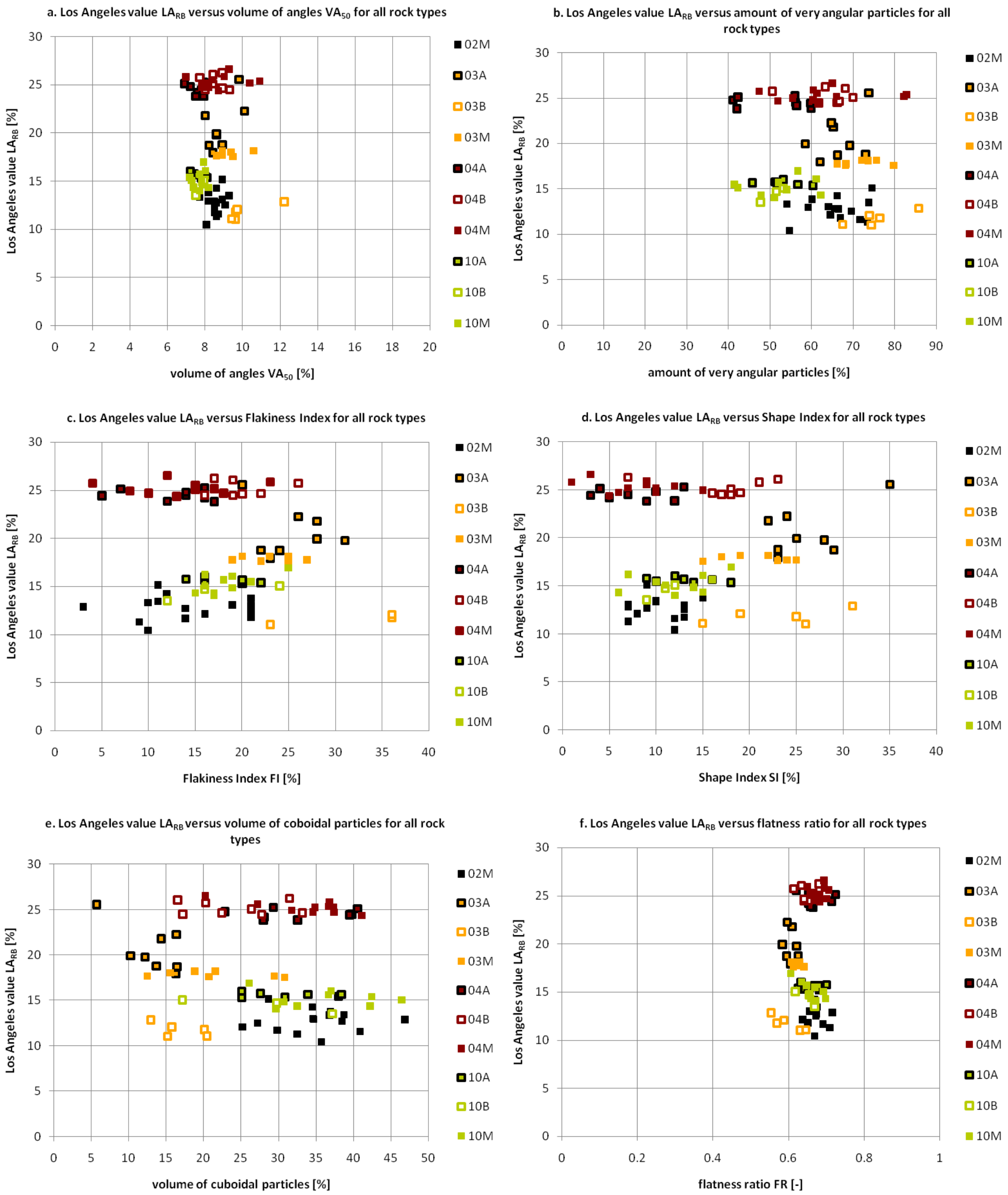
Fig. 28: Scatterplot matrix including the pre-test geometrical properties volume of angles VA_{50} (VA), amount of very angular particles (v.ang.), Flakiness Index FI, Shape Index SI, volume of cuboidal particles (cuboidal), flatness ratio (FR), elongation ratio (ER) and the Los Angeles value (LA) for the entire range of railway ballast material.

Tab. 11: Pearson's product moment correlation for a linear relationship between the following properties: volume of angles VA_{50} (VA), amount of very angular particles (v.ang.), Flakiness Index FI, Shape Index SI, volume of cuboidal particles (cuboidal), flatness ratio (FR), elongation ratio (ER) and the Los Angeles value (LA). Computations include the entire range of railway ballast material.

Pearson's product-moment correlation

	VA	v. ang.	FI	SI	cuboidal	FR	ER	LA
VA		0.87707	0.46451	0.42297	-0.40857	-0.42794	-0.34287	-0.04623
v. ang.	0.87707		0.35197	0.41157	-0.38013	-0.36080	-0.39573	-0.08147
FI	0.46451	0.35197		0.72911	-0.62082	-0.85161	-0.26980	-0.19071
SI	0.42297	0.41157	0.72911		-0.75660	-0.80471	-0.62652	-0.07675
cuboidal	-0.40857	-0.38013	-0.62082	-0.75660		0.75091	0.69857	-0.09096
FR	-0.42794	-0.36080	-0.85161	-0.80471	0.75091		0.32994	0.13926
ER	-0.34287	-0.39573	-0.26980	-0.62652	0.69857	0.32994		-0.21497
LA	-0.04623	-0.08147	-0.19071	-0.07675	-0.09096	0.13926	-0.21497	

Fig. 29 shows the relation between the Los Angeles value LA_{RB} and pre-test geometrical properties for all rock types including the characteristic colour coding. In each case the respective geometrical properties are plotted against the Los Angeles value LA_{RB}. For the volume of angles VA_{50}, the flatness ratio FR and the elongation ratio ER the range of results is relatively small. The amount of very angular particles, the Flakiness Index FI, the Shape Index SI and the volume of cuboidal particles deliver a wide range of results. No linear relationship between the pre-test geometrical properties and the Los Angeles values exists for the entire range of railway ballast aggregates. Different rock types show a different mechanical behaviour with regard to the Los Angeles value and thus the petrography of samples has a larger influence on the Los Angeles test results compared to the geometry of samples. It should be also noted that the geometry in itself is influenced by the petrography (e.g. foliation planes are mechanical discontinuities or planes of weakness and thus foliated metamorphic rocks tend to break along such foliation planes).



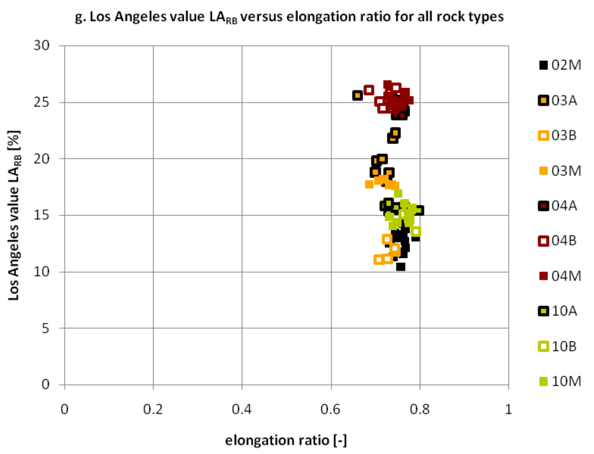


Fig. 29: Range of results for volume of angles VA_{50}, amount of very angular particles, Flakiness Index FI, Shape Index SI, volume of cuboidal particles, flatness ratio FR and elongation ratio ER compared to the respective Los Angeles value for all rock types.

7.3.1 Relation between the Los Angeles value LA_{RB} and pre-test geometrical properties

The angularity and the form of railway ballast particles may influence the Los Angeles value LA_{RB}. Due to this reason the following section will focuses on the relation between the Los Angeles value LA_{RB} and pre-test properties with regard to the angularity or form. A linear regression line is graphically presented if the coefficient of determination R^2 exceeds a value of 0.4 or if the statistical model (linear regression line) explains at least 40 % of the variance of data points. For this purpose, a distinction is made between three different levels: The first level takes linear regression lines into consideration which fit data including the entire range of railway ballast material. The second level takes linear regression lines into consideration which fit data including either rock type basalt (02), rock type granite porphyry (03), rock type dunite (04) or rock type granulite (10). The third and last level takes linear regression lines into correlation which fit data including individual subclasses (subclass A or B, or random samples M). If we consider only the third level, it is important to be aware of the fact that the number of tests per subclass is very small. Due to the small sample size (three tests) of rock type 10B no linear relationship is taken into account. The actual number of tests is larger than or at least equal to the number of tests which is required in order to reach a precision of ± 0.5 at a confidence level of 95 % only for rock type 04A, 04B, 04M and rock type 10A.

With the help of two box-and-whisker plots or box plots, three outliers or extreme values regarding the Los Angeles value LA_{RB} could be identified. Due to this reason Los Angeles test results for two samples of rock type 03M and one sample of rock type 10A are not taken into consideration (Fig. 30). Outliers or extreme values exceed the interquartile range (corresponds to the length of the respective boxes below) by a factor of 1.5 (Liu, 2010) and are plotted as individual points (see below). In case of rock type 10A the number of actual tests still exceeds the required number of tests in order to reach a precision of ± 0.5 at a confidence level of 95 %.

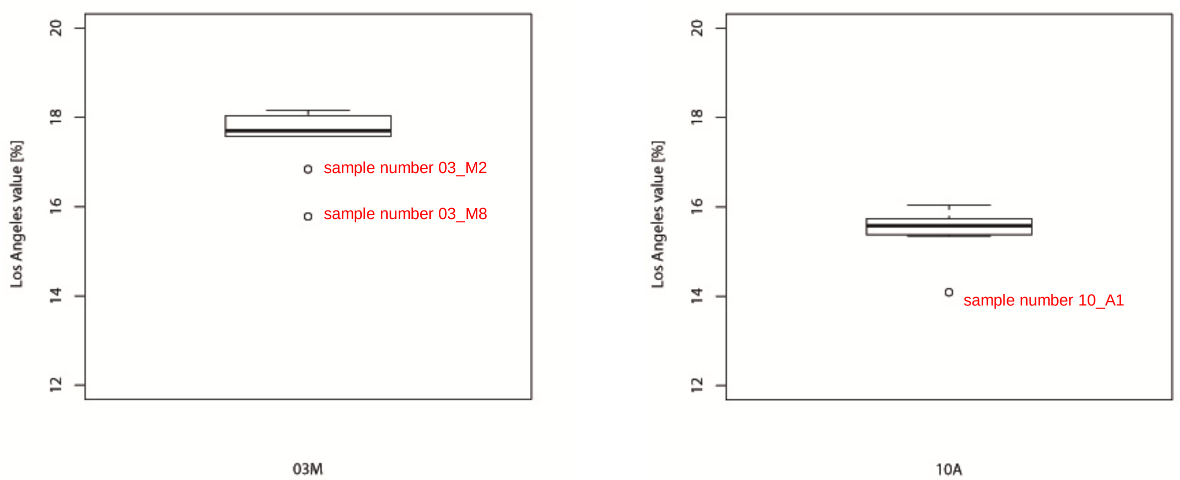


Fig. 30: Box plot and graphical representation of Los Angeles test results for rock type 03M and 10A including outliers.

Los Angeles value LA_{RB} versus angularity or roundness of aggregates

According to Descantes (2006), recycled railway ballast aggregates yield better results with respect to the Los Angeles value LA_{RB} compared to new railway ballast aggregates. Better results and thus lower Los Angeles values LA_{RB} are due to the fact that recycled railway ballast aggregates have more rounded edges and as a consequence produce less fragments during the testing procedure. No linear relationship (linear regression line with a coefficient of determination $R^2 > 0.4$) between the volume of angles VA_{50} per particle and the Los Angeles value LA_{RB} is observed, which fits data including the entire range of railway ballast aggregates or one rock type. In case of subclass A and subclass B of rock type granite porphyry (03), a higher volume of angles VA_{50} per particle corresponds to a higher Los Angeles value LA_{RB}. Subclass A of rock type granulite (10) shows a quite different behaviour: The relationship is negative, thus a lower volume of angles VA_{50} per particle corresponds to a higher Los Angeles value LA_{RB}. The results of individual subclasses are depicted in Fig. 31. All coefficients of determination R^2 are listed in Tab. 12.

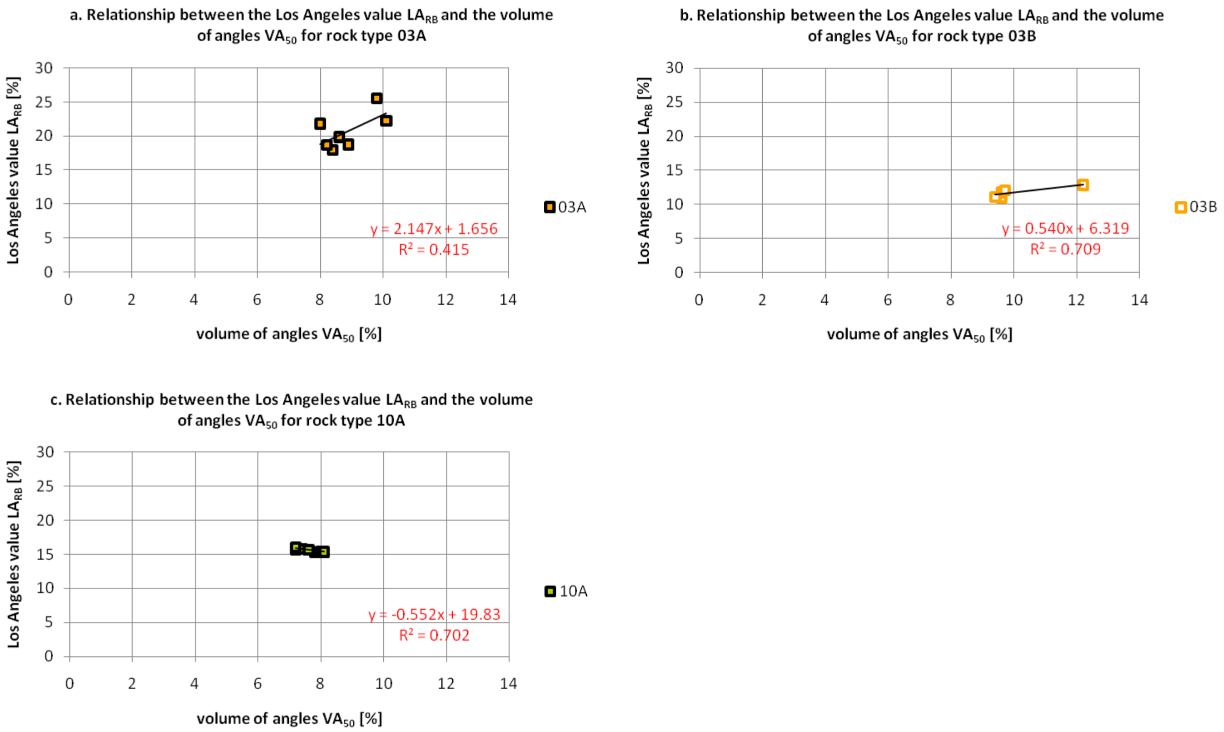


Fig. 31: Relation between the Los Angeles value and the volume of angles for three subclasses. The equation for the linear regression line and the coefficient of determination R^2 are displayed on the bottom right (red) in each case.

Tab. 12: Coefficients of determination R^2 for the entire range of railway ballast aggregates, each rock type and the respective subclasses regarding the relation between the Los Angeles value and the volume of angles. Data in bold refers to R^2 values exceeding 0.4.

	all	02	03	04	10	03A	03B	03M	04A	04B	04M	10A	10B	10M
R^2	0.002	0.039	0.104	0.072	0	**0.415**	**0.709**	0.265	0.116	0.062	0.03	**0.702**	-	0.018

The degree of angularity might be an important factor regarding the Los Angeles value LA_{RB} – this raises the question whether the amount of very angular particles is of importance too. In Fig. 32, the amount of very angular particles is plotted on the horizontal axis, and the Los Angeles values LA_{RB} is plotted on the vertical axes. Similar to the previous example, there is no linear relationship (linear regression line with a coefficient of determination $R^2 > 0.4$) between the amount of very angular particles and the Los Angeles value LA_{RB} which fits data including the entire range of railway ballast aggregates or to one rock type. Not only the degree of angularity, but also the amount of very angular particles might be a determining factor for rock type 03B. In case of rock type 03B approximately 73 % of the variance of data points can be explained by a linear regression line. A higher amount of very angular particles corresponds to a higher Los Angeles value LA_{RB}. All coefficients of determination R^2 are listed in Tab. 13.

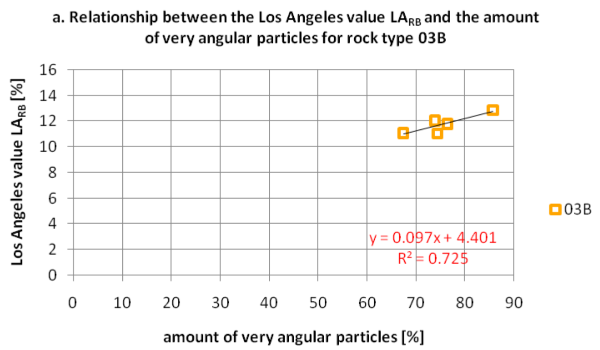


Fig. 32: Relation between the Los Angeles value and the amount of very angular particles for one subclasses. The equation for the linear regression line and the coefficient of determination R^2 are displayed on the bottom right (red).

Tab. 13: Coefficients of determination R^2 for the entire range of railway ballast aggregates, each rock type and the respective subclasses regarding the relation between the Los Angeles value and the amount of very angular particles. Data in bold refers to one single R^2 value exceeding 0.4.

	all	02	03	04	10	03A	03B	03M	04A	04B	04M	10A	10B	10M
R^2	0.006	0.029	0.153	0.042	0.043	0.195	**0.725**	0.045	0.046	0.067	0.004	0.148	-	0.031

Hofer et al. (2013) and Bach (2013) analysed the same railway ballast aggregates and identified a correlation between the initial angularity of a sample and the amount of fines which originate from rounding: Particles with a high angularity are more subject to rounding than particles with a low angularity. According to EN 1097-2 the Los Angeles test is the reference procedure for the determination of resistance to fragmentation. During the test procedure samples are not only subject to fragmentation but also to rounding. For this reason the test declaration is insufficient.

Los Angeles value LA_{RB} versus form of aggregates

Non-cuboidal particles may adversely affect mechanical properties of railway ballast aggregates, this applies in particular for the resistance to fragmentation. Röthlisberger (2005) investigated the influence of non-cuboidal particles on the Los Angeles value LA_{RB} and found out that a linear relationship between particles with a length-to-width ratio of 1:2.5 and the Los Angeles value LA_{RB} as well as between particles with a length-to-width ratio of 1:3 and the Los Angeles value LA_{RB} exists. In both cases the Los Angeles value LA_{RB} increases with an increasing amount of non-cuboidal particles. Not only the amount of non-cuboidal particles is considered to be a relevant factor. Particles with a length-to-width ratio of 1:3 wield more influence on the Los Angeles value LA_{RB} than particles with a length-to-width ratio of 1:2.5. According to Röthlisberger (2005) both the amount of non-cuboidal particles as well as the ratio between the axes are of importance with regard to the Los Angeles value LA_{RB}.

Within this study there is no linear relationship with a coefficient of determination $R^2 > 0.4$ between the Flakiness Index and the Shape Index respectively which applies on the first or on second level. On the third level, particularly between the Flakiness Index and the Los Angeles value LA_{RB}, an appropriate relation is present (Fig. 33). Looking at subclass B of rock type granite porphyry (03) and random samples M of rock type granulite (10), the Flakiness Index FI is related to the Los Angeles value LA_{RB}. In all two cases the linear relation between the amount of flaky or unfavourable shaped particles and the Los Angeles value LA_{RB} is positive. Accordingly, the higher the Flakiness Index, the higher the Los Angeles value LA_{RB}. The sole exception is subclass A of rock type granulite (10) because the relation is negative, indicating that a high Flakiness Index corresponds to a low Los Angeles value LA_{RB}. All coefficients of determination R^2 for the Flakiness Index FI are listed in Tab. 14. A linear relationship with a coefficient of determination $R^2 > 0.4$ between the Shape Index and the Los Angeles value LA_{RB} is not present at all.

According to Röthlisberger (2005) the amount of cuboidal particles should have positive effects on the Los Angeles value LA_{RB}. Fig. 34 shows the volume of cuboidal particles plotted against the Los Angeles value LA_{RB}. Similar to the previous examples, a linear regression line ($R^2 > 0.4$) explains the variance of data points only on the third level. The respective coefficients of determination R^2 for different subclasses are as follows: R^2 for random samples M of rock type dunite (04) is 0.4510; R^2 for subclass A of rock type granite porphyry (03) is 0.4313. For all two cases applies: A higher volume of cuboidal particles corresponds to a lower Los Angeles value LA_{RB}. All coefficients of determination R^2 are listed in Tab. 15.

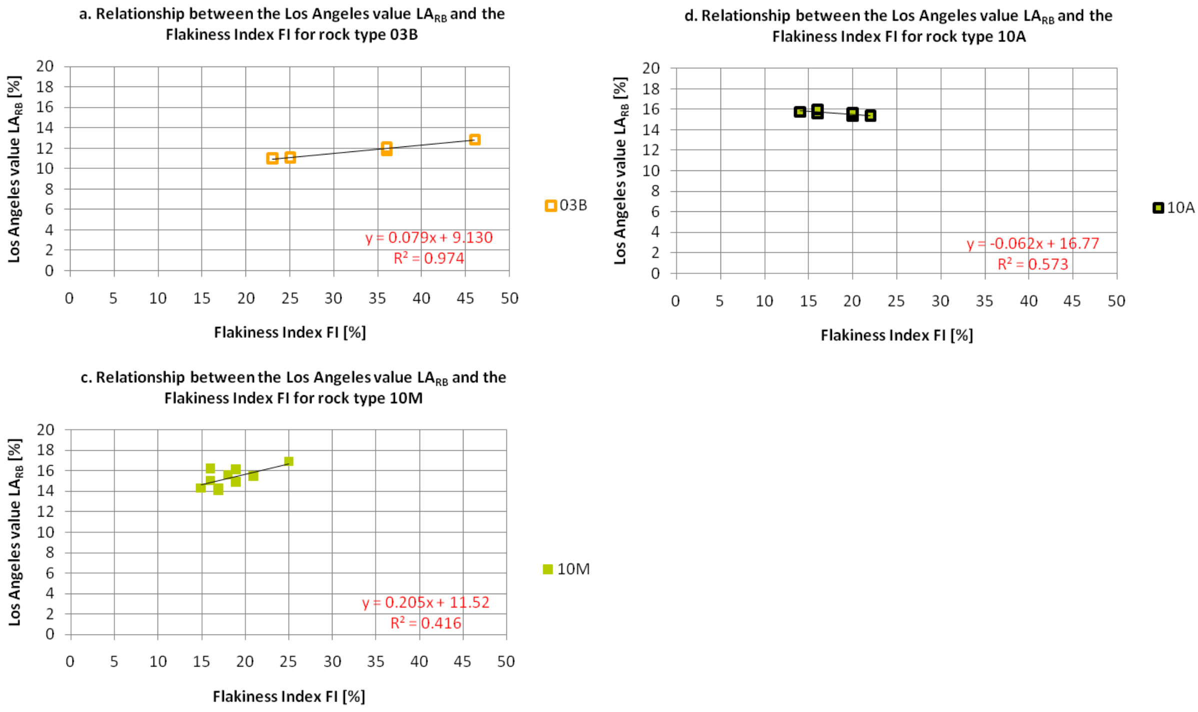


Fig. 33: Relation between the Los Angeles value and Flakiness Index for three subclasses. The equation for linear regression line and the coefficient of determination R^2 are displayed on the bottom right (red) in each case.

Tab. 14: Coefficients of determination R^2 for the entire range of railway ballast aggregates, each rock type and the respective subclasses regarding the relation between the Los Angeles value and the Flakiness Index. Data in bold refers to R^2 values exceeding 0.4.

	all	02	03	04	10	03A	03B	03M	04A	04B	04M	10A	10B	10M
R^2	0.035	0	0.201	0.013	0.221	0.046	**0.974**	0.025	0.044	0.014	0	**0.573**	-	**0.416**

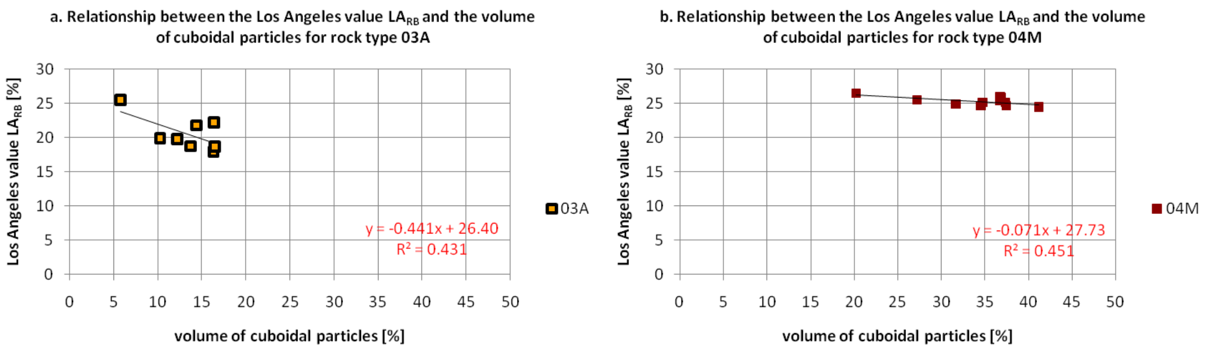


Fig. 34: Relation between the Los Angeles value and the volume of cuboidal particles for two subclasses. The equation for linear regression line and the coefficient of determination R^2 are displayed on the bottom right (red) in each case.

Tab. 15: Coefficients of determination R^2 for the entire range of railway ballast aggregates, each rock type and the respective subclasses regarding the relation between the Los Angeles value and the volume of cuboidal particles. Data in bold refers to R^2 values exceeding 0.4.

	all	02	03	04	10	03A	03B	03M	04A	04B	04M	10A	10B	10M
R^2	0.008	0	0.093	0.049	0.036	**0.431**	0.336	0.152	0.019	0.008	**0.451**	0.05	-	0.031

Wieden et al. (1977) already investigated the influence of breadth-to-thickness ratios of loose chippings (gradation 2 / 10 mm) on the Los Angles value LA_{RB}. Therefore Wieden et al. (1976) distinguished between loose chippings of group I to V with the following breadth-to-thickness ratio: 1:1-1.5:1 (group I); 1.5:1-2:1 (group II); 2:1-2.5:1 (group III); 2.5:1-3:1 (group IV) and > 3:1 (group V). The greater the difference between breadth and thickness of particles and the flatter the particles, the higher the Los Angles value LA_{RB}. Within the course of this Master's thesis there is no linear relationship with a coefficient of determination R^2 exceeding 0.4 between the Los Angeles value LA_{RB} and the flatness ratio FR that applies to the entire range of railway ballast material or to one rock type. But such a relationship is present in case of subclass B of rock type granite porphyry (03): A linear regression line explains approximately 82 % of variance of data points. The coefficient of determination R^2 for random samples M of rock type granulite (10) is 0.6147 (Fig. 35). Thus the Los Angeles value LA_{RB} increases with decreasing flatness ratio and increasing flatness. All coefficients of determination R^2 are listed in Tab. 16.

Fig. 35: Relation between the Los Angeles value and the flatness ratio for two subclasses. The equation for the linear regression line and the coefficient of determination R^2 are displayed on the bottom right (red) in each case.

Tab. 16: Coefficients of determination R^2 for the entire range of railway ballast aggregates, each rock type and the respective subclasses regarding the relation between the Los Angeles value and the flatness ratio. Data in bold refers to R^2 values exceeding 0.4.

	all	02	03	04	10	03A	03B	03M	04A	04B	04M	10A	10B	10M
R^2	0.19	0.001	0.02	0	0.195	0.038	**0.823**	0.302	0.106	0.005	0	0.101	-	**0.614**

Besides flat particles, particles with a considerable elongation may adversely affect the Los Angles value LA_{RB} because, according to Maerz and Zhou (1999), elongated particles tend to break more easily. The assumption that the Los Angles value LA_{RB} increases with decreasing elongation ratio does not apply to the entire range of railway ballast material or to one rock type or subclass.

As described, no linear relationship ($R^2 > 0.4$) between the Los Angeles value LA_{RB} and pre-test geometrical properties exists for the entire range of railway ballast material or one rock type (02, 03, 04 or 10). Linear relationships between the Los Angles value LA_{RB} and pre-test geometrical properties with regard to angularity and form of particles and a coefficient of determination $R^2 > 0.4$ refer only to railway ballast material of individual subclasses.

Each linear relationship between the Los Angeles value LA_{RB} and pre-test geometrical properties with a coefficient of determination $R^2 \geq 0.4$ and a sample size ≥ 5 is graphically presented. The following table (Tab. 17) lists the findings.

Tab. 17: Coefficients of determination R^2 for the linear relationship between the Los Angeles value LA_{RB} and various pre-test geometrical properties for relevant subclasses. Data is ranked by R^2.

	rock type	R^2
LA_{RB} versus Flakiness Index FI	03B	0.974
LA_{RB} versus flatness ratio FR	03B	0.823
LA_{RB} versus amount of very angular particles	03B	0.725
LA_{RB} versus volume of angles VA_{50}	03B	0.709
LA_{RB} versus volume of angles VA_{50}	10A	0.702
LA_{RB} versus flatness ratio FR	10M	0.614
LA_{RB} versus Flakiness Index FI	10A	0.573
LA_{RB} versus volume of cuboidal particles	04M	0.451
LA_{RB} versus volume of cuboidal particles	03A	0.431
LA_{RB} versus Flakiness Index FI	10M	0.416
LA_{RB} versus volume of angles VA_{50}	03A	0.415

For eleven linear relationships the coefficient of determination R^2 exceeds a value of 0.4, to be precise, for eleven linear relationships between the Los Angeles value LA_{RB} and pre-test geometrical properties, a linear regression line explains 41.5 % to 97.4 % of the variance of data points. By means of the statistical computing system R (R version 2.11.1) in each case a correlation test was performed, a correlation coefficient was computed and the associated significance of the statistical model (p-value) was tested. Tab. 18 lists the correlation coefficients if whether the statistical model is significant (p-value < 0.05) for the respective relationship and rock type.

Tab. 18: Pearson's product-moment correlation for a linear relationship between the Los Angeles value LA_{RB} and pre-test geometrical properties for relevant subclasses at a minimum confidence level of 95%. Data is ranked by p-value.

	rock type	Pearson's product-moment correlation	p-value
Los Angeles value LA_{RB} versus Flakiness Index FI	03B	0.9872341	0.001728
Los Angeles value LA_{RB} versus flatness ratio FR	10M	-0.7840673	0.01238
Los Angeles value LA_{RB} versus volume of angles VA_{50}	10A	-0.8383472	0.01846
Los Angeles value LA_{RB} versus flatness ratio FR	03B	-0.9076205	0.03323
Los Angeles value LA_{RB} versus Flakiness Index FI	10M	0.6450933	0.044
Los Angeles value LA_{RB} versus Flakiness Index FI	10A	-0.7572324	0.04869

Comparing Tab. 17 with Tab. 18, the number of listed linear relationships is reduced. Tab. 17 lists linear relationships between the Los Angeles value LA_{RB} and various pre-test geometrical properties with a coefficient of determination R^2 exceeding 0.4. The coefficient of determination R^2 explains the variance of data points but is an inadequate measure to draw conclusions about the statistical significance. Only six out of eleven linear relationships (Fig. 18) are statistically significant at a very high confidence level of at least 95 %. The higher the confidence level, the lower the number of statistical significant correlations.

In case of rock type 03B the computed correlation coefficient between the Los Angeles value LA_{RB} and the Flakiness Index FI is statistically significant at a confidence level of 99.8 %, whereas the correlation coefficient between the Los Angeles value LA_{RB} and the flatness ratio FR is statistically significant at a confidence level of 96.7 %.

In case of rock type 10M the computed correlation coefficient between the Los Angeles value LA_{RB} and the flatness ratio FR is statistically significant at a confidence level of 98.8 %, whereas the correlation coefficient between the Los Angeles value LA_{RB} and the Flakiness Index FI is statistically significant at a confidence level of 95.6 %.

In case of rock type 10A Los Angeles test results are correlated with the volume of angles VA_{50} and the Flakiness Index FI: The computed correlation coefficient between the Los Angeles value LA_{RB} and the volume of angles VA_{50} is statistically significant at a confidence level of 98.2 %, whereas the correlation coefficient between the Los Angeles value LA_{RB} and the Flakiness Index FI is statistically significant at a confidence level of 95.1 %.

7.3.2 Relation between the Los Angeles value LA_{RB} and the particle number ratio PNR

In addition to the Los Angeles value LA_{RB}, the particle number ratio PNR may also be used to describe the mechanical behaviour aggregates. In Fig. 36 the particle number ratio PNR is plotted on the horizontal axis and the Los Angeles value LA_{RB} on the vertical axes. Although the Los Angeles values LA_{RB} for rock type 03A and 03B differ significantly, no separation between 03A and 03B on the basis of particle number ratio PNR is possible. For rock type dunite (04) the situation is different: The Los Angeles values LA_{RB} for 04A and 04B do not differ significantly, but a separation between 04A and 04B on the basis of particle number ratio PNR is possible. The mean PNR for aggregates of subclass 04A is approximately 6, whereas the mean PNR for aggregates of subclass 04B is approximately 16. The reason for this remarkable difference in PNR might be due to a difference in rock fabric in this case. The thin section of rock type 04B indicates a higher degree of chemical alteration compared to the thin section of rock type 04A (see Tab. 4). 04B exhibits a pronounced mesh-texturing caused by serpentinisation. The mesh-textured fabric weakens the strength properties and is responsible for such a high particle number ratio PNR. As ballast fouling contributes significantly to the process of track settlement, a high particle number ratio may cause an adverse effect on the quality of the entire track system.

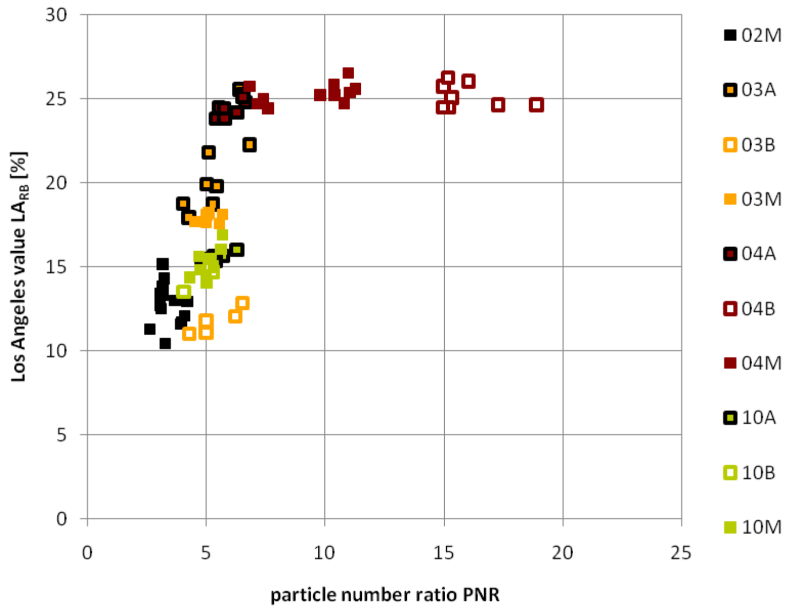


Fig. 36: Relation between the Los Angeles value and the particle number ratio for all rock types.

7.3.3 Prediction of mechanical properties

Petroscope 4D® aims at offering an appropriate hardware and software system in order to improve the quality of construction aggregates. The basic idea behind the development of Petroscope 4D® is a hypotheses stated by Griffiths (1967). Griffiths (1967) introduced the 'concept of properties' and hypothesised that it is possible to predict the behaviour of sedimentary rocks (e.g. engineering properties), provided that the fundamental properties of aggregates are known. The behaviour of aggregates - also termed derived properties - is a function of five fundamental properties and is summarized in a mathematical sense:

$$P = f(m, s, sh, o, p)$$

where P refers to the behaviour of properties. The fundamental properties are the kinds and proportions of elements m (e.g. roughly corresponds to the petrographic composition), the size s, the shape sh, the orientation o and the packing p. As railway ballast represents loose material, unlike sedimentary rocks, orientation and packing are excluded from the equation. The equation is reduced to:

$$P = f(m, s, sh)$$

The fundamental properties of aggregates such as railway ballast are therefore characterised by petrographic composition, size and shape. Petroscope 4D® allows the identification of all three fundamental properties, so in accordance with the hypotheses stated by Griffiths, it should be theoretically possible to predict the engineering behaviour of railway ballast or related construction materials. The assessment of engineering properties solely based on the determination of fundamental properties could be referred to as 'soft testing' or 'virtual testing' (Helgason and Fuxén, 2002).

Hofer and Bach (2012) provide detailed information on the attempts to predict mechanical properties of railway ballast (e.g. resistance to wear and abrasion) based on fundamental properties determined by Petroscope 4D®. The authors used spectral and geometrical data of the 85 Los Angeles tests and developed a statistical model for the prediction of the Los Angeles value LA_{RB}. Predicted values deviate only slightly from the measured values.

8 Discussion and conclusion

Railway ballast material representing four different rock types and originating from just as many quarries was analysed with regard to the petrographic, mechanical and geometrical properties. In 2012, an extensive test series of 85 Los Angeles tests was carried out in order to determine the mechanical properties of railway ballast aggregates. Prior as well as subsequent to the Los Angeles tests, the geometrical properties (e.g. size, form, angularity) of railway ballast aggregates were determined using the measuring device Petroscope 4D. In each case of rock type granite porphyry (03), dunite (04) and granulite (10), the Los Angeles tests as well as the Petroscope 4D tests were performed on the two most frequent subclasses (subclass A and subclass B) and on material without prior selection (marked with the letter M). The division into subclasses was based on macroscopic criteria such as mineralogical composition, colour, fabric, degree of alteration and particle shape. In each case of rock type granite porphyry and dunite, railway ballast is composed of very heterogeneous aggregates. Railway ballast aggregates of rock type granulite are heterogeneous as well but the differences between subclass A and subclass B are very small. Polished sections of each rock type and subclass are depicted in Fig. 37 and associated distinguishing features are listed in Tab. 19. Rock type basalt (02) was regarded to be homogenous and all the tests were performed on material without prior selection.

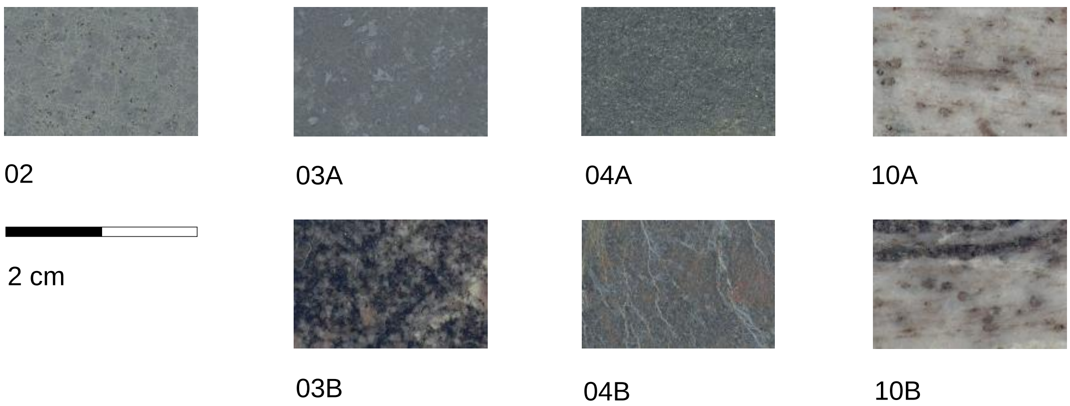


Fig. 37: Polished sections of rock type basalt (02), granite porphyry (03), dunite (04) and granulite (10).

Tab. 19: Distiguishing features composition (mineralogical composition), colour, fabric, alteration (degree of alteration) and shape (particle shape) between subclass A and subclass B for rock type granite porphyry (03), dunite (04) and granulite (10).

	composition	colour	fabric	alteration	shape
granite porphyry (03)	yes	yes	yes	no	yes
dunite (04)	yes	yes	yes	yes	yes
granulite (10)	yes	yes	no	no	no

Test results suggest that the visual difference within granite porphyry samples is reflected by significantly varying Los Angeles values. The situation is different for rock type dunite. Although two varieties exist, the resulting Los Angeles values show hardly any difference. Los Angeles tests performed on subclass 10A and 10B reveal only minor differences of results. Based on the homogeneous appearance of basalt aggregates no subdivision was considered, nevertheless a considerable variation of Los Angeles test results is observed. The mean Los Angeles values for each subclass are listed in Tab. 20. However, it must be kept in mind that only for rock type 04A, 04B, 04M and 10A the number of tests is sufficient in order to guarantee that test results reach a precision of ± 0.5 at a confidence level of 95 %. In order to obtain statistically significant information on the mechanical properties of rock type 02M, 03A, 03B, 03M, 10B and 10M, an increase in the number of performed tests is necessary.

Tab. 20: Mean Los Angeles value and associated statistical significance for each subclass. The statistical significance refers to to a precision of ± 0.5 at a confidence level of 0.95 (95 %).

rock type	mean LA_{RB} [%]	statistical significance of test results
02M	12.75	no
03A	20.61	no
03B	11.78	no
03M	17.51	no
04A	24.51	yes
04B	25.19	yes
04M	25.29	yes
10A	15.43	yes
10B	14.45	no
10M	15.29	no

The impact of geometry on the mechanical properties of railway ballast aggregates is limited to subclass 03B, 10A and 10M. The form of particles (Flakiness Index and flatness ratio) influences the Los Angeles value in case of subclass 03B and 10M, whereas the form (Flakiness Index) as well as the angularity (volume of angles) influence the Los Angeles value in case of subclass 10A. The computed correlation coefficients are statistically significant at a confidence level of 95.1 % to 99.8 % in each case.

Rock type 02M, 03B and 10A, 10B and 10M are the most appropriate railway ballast materials if only the mechanical properties are considered. Rock type 02M and 10A, 10B and 10M are still appropriate if the mechanical properties as well as the geometrical properties are taken into account. Rock type 04 (in particular rock type 04B and 04M) is of inferior quality in terms of the Los Angeles value and the particle number ratio.

The aim of this Master's thesis was to evaluate the influence of the petrographic composition of railway ballast on the Los Angeles test and answer the question whether the influence of petrographic composition or the particle geometry is more decisive for the Los Angeles test results: Different rock types show a different mechanical behaviour with regard to the Los Angeles value – the petrography of samples (mineral content, fabric) has very large influence on the Los Angeles test results. The geometry (form, angularity) is of importance, but to a lesser extent.

List of Tables

List of Figures

References

Aikawa, A, 2009, Techniques to Measure Effects of Passing Trains on Dynamic Pressure Applied to Sleeper Bottoms and Dynamic Behavior of Ballast Stones, Quarterly Report of Railway Technical Research Institute, vol. 50, no. 2, pp. 102-109.

Bach, H., 2013, Evaluation of attrition tests for railway ballast, Dissertation, TU Graz.

Bach, H., Kuttelwascher, C., Latal, C., 2012, Alternative Prüfverfahren zur Qualitätssicherung von Gleisschotter, ZEVrail, vol. 136, pp. 76-85.

Blott, S. J. and Pye, K., 2008, Particle shape: a review and new methods of characterization and classification, Sedimentology, vol. 55, pp.31-63.

Descantes Y. Fosse, Y., Milcent, F., 2006, Automated Measurement of Railway Ballast Angularity, Journal of materials in civil engineering, vol. 18, no. 4, pp. 612-618.

Griffiths, J. C., 1967, Scientific method in analysis of sediments, McGraw-Hill, New York, 508 p.

Helgason, T. S. and Fuxén, S., 2002, Testing and conformity assessment of construction aggregates using the PM Techmodel Software, 9th Nordic Aggregate Research Conference, Reykjavik, Iceland.

Hofer, V., 2011, Functional Methods for Classification of Different Petrographic Varieties by Means of Reflectance Spectra, Mathematical Geosciences, vol. 43, pp. 165-181.

Hofer, V. and Bach, H., 2012, Statistical monitoring for continuous quality control of railway ballast, European Journal of Operational Research, preprint.

Hofer, V., Bach, H., Latal, C., Neubauer, A.-C., 2013, Impact of Geometric and Petrographic Characteristics on the Variability of LA Test Values for Railway Ballast, Mathematical Geosciences, vol. 45, pp. 727-752.

Huang, H. and Tutumluer, E., 2011, Discrete Element Modelling for fouled railroad ballast, Construction and Buildings Materials 25, pp. 3306-3312.

Klotzinger, E., March 2007, Der Oberbauschotter Teil 2: Qualitätsverlauf und Eingriffsschwellen, Eisenbahntechnische Rundschau, no. 3, pp. 120-125.

Kuttelwascher, C., 2012, Track ballast in Austria: Part 3., Rail Infrastructure, Nr. 88.

Lee, J.R.J., Smith, M.L., Smith, Midha, P.S., 2005, A mathematical morphology approach to image based 3D particle shape analysis, Machine Vision and Applications, vol. 16, no. 5, pp. 282-288.

Lee, J.R.J., Smith, M.L., Smith, L.N., 2007, A new approach to the three-dimensional quantification of angularity using image analysis of the size and form of coarse aggregates, Engineering Geology, vol. 91, pp. 254-264.

Liu, Q., Statistical Methods: Statistical Computing Using R System in Earth Sciences (GEO.730), course documents.

Maerz, N.H. and Zhou, W., 1999, Flat and elongated: Advances using digital image analysis, in Proc., 7th Annual ICAR Symp. Austin, Tex., pp. B1-4-1-B1-4-12.

ÖBB (Österreichische Bundesbahnen),´2007, BH 700, Technische Lieferbedingungen für Oberbauschotter, Wien.

ÖBB (Österreichische Bundesbahnen), 2009, Optimierung der Schotterqualität, Sondersitzung, Ergänzung zur 10. Sitzung Erhaltungsstrategie / LCC, Matthä, Wiltberger, Wien.

Österreichisches Normungsinstitut, 2004, EN 13450 Gesteinskörnungen für Gleisschotter, Wien.

Österreichisches Normungsinstitut, 2006, EN 1097-2 Prüfverfahren für mechanische und physikalische Eigenschaften von Gesteinskörnungen - Teil 2: Verfahren zur Bestimmung des Widerstandes gegen Zertrümmerung, Wien.

Österreichisches Normungsinstitut, 2008, EN 933-4 Prüfverfahren für geometrische Eigenschaften von Gesteinskörnungen - Teil 4: Bestimmung der Kornforn - Kornformkennzahl, Wien.

Österreichisches Normungsinstitut, 2011, EN 1097-1 Prüfverfahren für mechanische und physikalische Eigenschaften von Gesteinskörnungen - Teil 1: Verfahren zur Bestimmung des Widerstandes gegen Verschleiß (Micro-Deval), Wien.

Österreichisches Normungsinstitut, 2012a, EN 933-1 Prüfverfahren für geometrische Eigenschaften von Gesteinskörnungen - Teil 1: Bestimmung der Korngrößenverteilung - Siebverfahren, Wien.

Österreichisches Normungsinstitut, 2012b, EN 933-3 Prüfverfahren für geometrische Eigenschaften von Gesteinskörnungen - Teil 3: Bestimmung der Kornforn - Plattigkeitskennzahl, Wien.

Powers, M.C. 1953, A new Roundness Scale for Sedimentary Particles, Journal of Sedimentary Petrology, vol. 23, no. 2, pp. 117-119.

Raymond, G.P., 1985, Higher Standards for Track Ballast, Progressive Railroading, pp. 51-56.

Röthlisberger, F., Däppen, J., Kurzen, E., Würsch, E., 2005, Los Angeles-Prüfung für Gleisschotter - Aussagekraft und Folgerung, vol. 54. no. 6, pp. 355-361.

Selig, E.T. and Boucher, D.L., 1990, Abrasion Tests for Railroad Ballast, Geotechnical Testing Journal, vol. 13, pp. 301-311.

Selig, E.T. and Waters, J.M., 1994, Track Geotechnology and Substructure Management, 4th edn., Thomas Telford Services Ltd., London.

Wadell, H. 1932, Volume, shape and roundness of rock particles, Journal of Geology, vol. 40, pp. 443-451.

Wieden, P., Augustin, H., Zieger, M., 1977, Versuche zur Verbesserung des Los Angeles-Tests, Straßenforschung, Heft 86, Bundesministerium für Bauten und Technik, Wien.

Zingg, T., 1935, Beitrag zur Schotteranalyse - Die Schotteranalyse und ihre Anwendung auf die Glattalschotter, Promotionsarbeit, ETH Zürich.

Appendix

Data is available in the electronic appendix on the application CD-ROM.