Laboratory study on two-dimensional image analysis as a tool to evaluate degradation of granular fill materials

E. Bergliv. Corresponding / primary author
Luleå University of Technology, Sweden, elin.bergliv@ltu.se

T. Edeskär. Co-Author
Luleå University of Technology, Sweden

ABSTRACT
The shape of granular materials is known to affect strength and stiffness properties of soil and fills. Settlements in coarse fills are often explained by rearrangement within the soil skeleton induced by crushing and rounding of the individual aggregates in the intergranular contact points. These processes are not well investigated since it is difficult to measure changes at an aggregate level.

Currently few attempts have been made to effectively measure and classify shape of granular soil and fill materials. One of the more promising methodologies is digital image analysis. Even if there are some studies on both two and three dimensional analyses on shape of aggregates, no study has focused on identifying shape changes as function of degradation effects of the fill materials.

In this study degradation of ballast material has been studied in standardized micro Deval and Los Angeles tests and analysed by two dimensional image analysis and statistical methods. The results showed it was possible to statistically separate the shape and size of the materials before and after the degradation tests. To identify this difference it is essential to use more than one variable each for size and shape.

The conclusion of the study is that two-dimensional image analysis can be used as a tool to measure and quantify shape changes on an aggregate level in order to measure degradation. If further developed, the technique can be useful to study deformation processes, e.g. crushing and rounding of aggregates, in coarse fill materials.

Keywords: Digital image analysis, granular material, degradation, factor analysis.

1 INTRODUCTION

Physical weathering and degradation affects the size and shape of soil and ballast materials. In this study weathering is defined as natural geological processes and degradation the effect of induced loads by use in e.g. roads and railway constructions.

Effects of degradation of the material come with deformations and lower strength, possibly failure. The degradation changes mechanical properties (friction angle, stiffness, strength, and so on) and causes deformations due to wearing, rearranging/sliding, or fragmentation of the individual grains (Alshibli & Alsaleh, 2004; Cho et al, 2006; Cox & Budhu, 2010; Guo & Su, 2007; Hansson & Svensson, 2001; Zeghal, 2009; among others). Currently the standardized methods of measuring (resistance to) degradation are by material quality testing with Los Angeles or micro Deval tests. These tests measure the generated amount of degraded material (smaller than 1.6 mm) after milling. For roads and railways the results from the tests are used as material quality requirements (Trafikverket, 2011; Banverket, 2004).

Image analysis of grains is a new concept to investigate degradation of large grains on particle level, due to the shape and size change that occurs during degradation. If properties of a granular material can be connected to the grain shape, it will be easier to understand how degradation, which causes changed grain shape, affects a material. Granular materials can be evaluated for their performance depending on their grains' shape.

The shape of grains has an effect on properties of granular material (Alshibli & Alsaleh, 2004; Cho et al, 2006; Cox & Budhu, 2010; Guo & Su, 2007; Hansson & Svensson, 2001; Zeghal, 2009; among others). One generally accepted shape division is crushed and natural material; natural material is rounded and smooth and crushed material is angular, rough and has sharp edges. In construction crushed material is often preferred due to interlocking effects of the angular shape and high friction due to the surface friction. In this division between natural and crushed material the shape of the grains are quite different and the materials can be distinguished by ocular inspection.

Another way in which grain shape is taken into consideration for construction purposes is by limiting the amount of flat or elongated grains. Flat and/or elongated grains can bend and therefore give higher deformations (Lambe & Whitman, 1969). This shape factor is measured in two standardized ways; LT-index and flakiness index.

According to Mitchell & Soga (2005) grain shape is described in three different scales, see Figure 1. Morphology is the largest and describes the overall shape of a grain taking the different dimensions into consideration. Examples of descriptive terms are elongated, round, elliptical, cubic, or flat. The intermediate scale is called roundness and takes the level of unevenness and edges into consideration. The edges are described as round or angular. The smallest scale is called roughness, and takes the small edges and the structure into consideration. A grain's roughness is described as smooth/even or rough. There is no distinct line between what characteristics are classified as roundness and roughness, other than that roughness describes shape on a smaller scale than roundness.

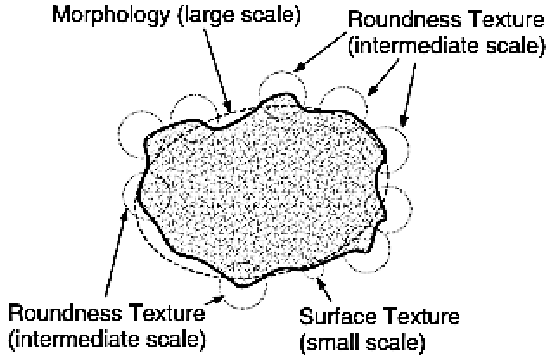

Figure 1. Scale descriptors of a grain (Mitchell & Soga, 2005).

Grain shape can be measured in two or three dimensions. Different measurement methods are hand measurement, photography with image analysis and laser scanning, all with different required equipment, variability and data output (Rodriguez et al, 2013).

Image analysis is a way of performing grain shape measurement. More complex measurements can be taken and more data can be collected faster than by hand. Both 2D and 3D image analysis is possible, where 2D image analysis uses one photograph to identify and analyse grain shape based on one projection. 3D image analysis requires two or more photographs, often orthogonally oriented, to find the shape of a grain. There are different methods of photographing for 3D image analysis, either each grain is mounted in a holder, where one or two cameras capture the shape from two different directions, or an orthogonal camera set up is used to capture the shape of falling grains. Photography for 2D image analysis is faster than for 3D image analysis, but at the cost that only two dimensions are captured.

To be able to use 2D image analysis to investigate degradation it has to be verified that the method can identify shape changes and investigated if, at all, degradation can be identified. In this paper the hypothesis is that 2D image analysis can be used to identify degradation by using shape and size related parameters. This is studied by evaluation of ballast material in standardized micro Deval and Los Angeles tests.

2 MATERIAL & METHODS

The experimental part of the study was conducted according to the schema in Figure 2. The samples for the laboratory testing were prepared to correct size (10-14 mm) by sieving, followed by image acquisition of either the whole sample (mDe) or a representative part of the sample, performing the degradation test and final image acquisition of the sample according to the earlier principle.

The images were analysed with the software ImageJ with respect to the size and shape variables; *area*, *Feret's diameter*, *Feret's minimum diameter*, *aspect ratio*, *circularity*, *roundness*, and *solidity*. The data from the image analysis (seven variables) was processed in MATLAB to find the best matching statistical distribution. These distribution values were plotted and further analysed in Microsoft Excel.

Data from the image analysis (ten variables) was processed in MATLAB by factor analysis. Three size variables were added into the data compared to the distribution analysis; *circumference*, *major* and *minor*.

Two different kinds of degradation tests on ballast materials were performed; standardized Los Angeles (LA) and micro Deval (mDe) tests. The tests were performed by an accredited laboratory and the results from the tests were anonymised.

Los Angeles tests were performed according to Swedish standard SS-EN 1097-2:2010, the micro Deval tests were done according to SS-EN 1097-1:2011. Both the two tests were performed by rotation of granular material and steel balls in a drum, where the steel balls degrade the grains. The milling effect on the ballast materials is different. For Los Angeles tests the degradation mode was fragmentation and for micro Deval it was wearing. The same sized material was used for both tests, 10-14 mm, but more material was used for Los Angeles tests, 5 kg, compared to two subsamples of 500 g each for micro Deval tests. Before the tests started, photographs were taken for the image analysis.

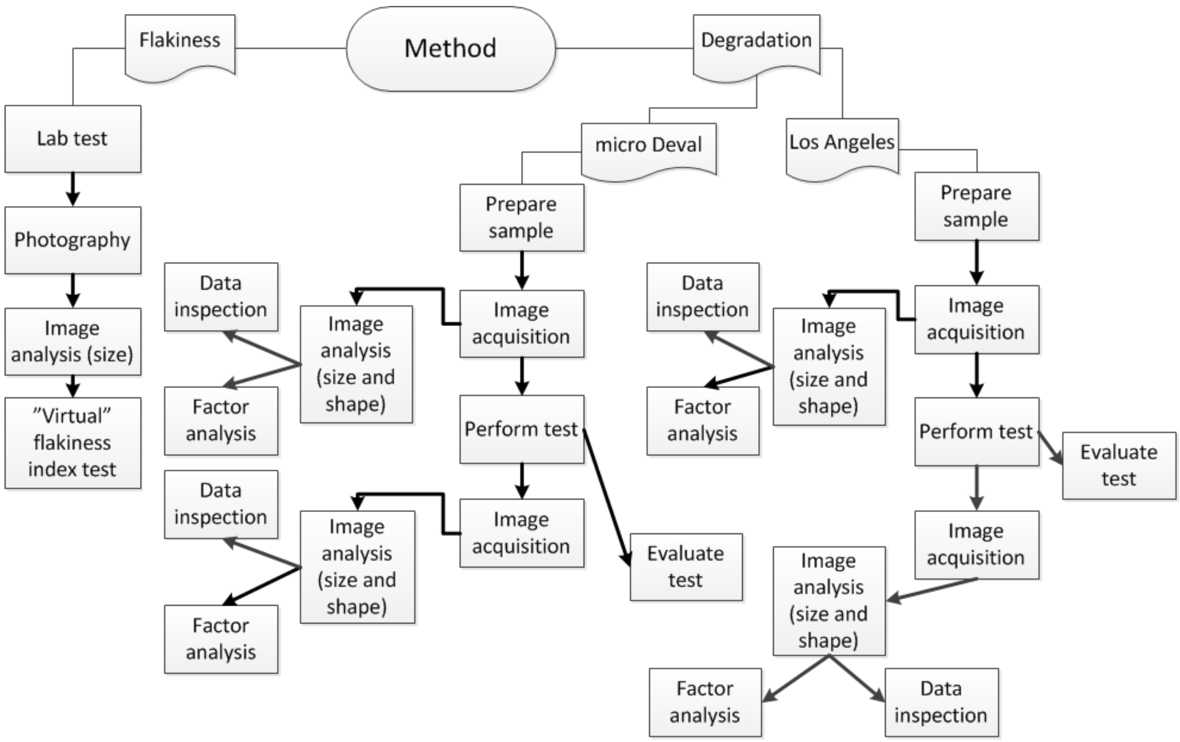

Figure 2. The method description.

The testing procedure and equipment also differs; for Los Angeles tests the drum was bigger and there were fewer but bigger steel balls. The micro Deval testing procedure used many small steel balls and the tests were done in wet condition. The Los Angeles testing is done for 500 revolutions in 31-33 rpm, while 12 000 revolutions were used for micro Deval at around 100 rpm.

After testing the sample was separated from the steel balls and the sample was sieved (the micro Deval samples were dried before sieving). The weight of the material retained on the sieves larger than 1.6 mm is called *m*. The LA and M_{DE} values were calculated with equations 1 and 2.

$$LA = \frac{5000-m}{50} \quad (1)$$

$$M_{DE} = \frac{500-m}{50} \quad (2)$$

For the micro Deval samples the mean value of the two subsamples is used as a representative mean value for the whole sample. The grains that were 4 mm or greater were used for photography, since smaller grains cause dusting and requires higher resolution images to analyse.

The photographs were taken with the camera Nikon D5200 with resolution 24 megapixels. The lens was an AF-S Nikor 18-550 mm f/3.5-5.6G VRII. The camera with lens was mounted on a tripod and angled to take photos from above. Below the camera setup there was a light table, of the size of an A3 paper, covered by 4 mm thick glass. The whole setup can be seen in Figure 3. Two 100 mm scales on a paper below the glass aided in setting up the camera perpendicular to the light table and to identify the size of grains in the image analysis.

The aggregates were randomly dropped to get an arbitrary orientation of the grains and, if it was needed, spread to make sure the whole edge was visible. The grains were also moved from the edge of the light table to cover the entire edge of the grain. Two photos were taken of each grain spread, one that was used for image analysis and one with a note of the unique serial number used for identification and pairing with laboratory results.

Figure 3. Photography setup.

For the Los Angeles tests there was too much material to be able to efficiently photograph all of it. One photograph could contain about 250-300 g of material in the size range 10-14 mm, leading to about 15-20 photographs to document the entire sample (and another 15-20 for identification purposes). To document an entire Los Angeles sample would have been time consuming both in the photography work and in the analysis work. Instead a test was done to see how much material gave a representative sample. The conclusion was that two photographs each containing about 300 g of material gave a representative sample. The whole Los Angeles sample was divided using sample divider three times, leaving about one eighth of the sample (625 g) to be photographed in two photographs. The micro Deval subsamples were of 500 g and using two photographs all the material of the subsample was photographed.

The image analysis was done with the program ImageJ v1.47. After opening an image with the program, the image was inspected for overlapping grains and other faults. Sometimes it was possible to separate the grains (in an image handling program, PaintNet), other times the only option was to delete the overlapping aggregates. When deciding between separating and deleting, the option that would lead to the minimum error was chosen. When the faults have been dealt with the image analysis could begin. The image was turned into a binary mode (only black and white) and the setting were set to exclude grains on the edge of the light table and to only include grains larger than 20 mm^2 to avoid analysing possible dust (mostly in effect in the post test images). The grain shape parameters used in the image analysis is presented in equations 3-6.

$$Aspect\ ratio = \frac{major}{minor} \quad (3)$$

$$Circularity = \frac{4\pi A}{C^2} \quad (4)$$

$$Solidity = \frac{A}{A_{convex}} \quad (5)$$

$$Roundness = \frac{4A}{\pi \cdot major^2} \quad (6)$$

Where *major* and *minor* (mm) is the greatest and the smallest dimension of the 2D ellipse projection of the grain respectively, A is the area (mm^2), C is the circumference (mm) and A_{convex} is the area of the grain if all the irregularities would be jointed (mm^2). Despite the name of the last variable, *roundness*, the variables does not measure the intermediate scale (also called roundness) but rather the overall shape of the grain (largest scale).

The output from the analysis was presented in a numbered table containing each grain's data and an outline image with numbered grains. The data was exported to Microsoft Excel where the image analysis result from the scales were identified and removed. Other possible deviant results could also be identified in Excel by sorting from smallest to largest and finding more faults. If faults were discovered, the results were removed or the faults were corrected and the image analysis redone. The data from the two different pictures for each sample were added to the same Excel file.

From Excel the data was imported into MATLAB, where the best statistical distribution for each variable was identified, using the *Distribution fitting tool* and ocular inspection. The best distribution matches of all variables of all samples were documented and the most common distribution for each variable was chosen as the overall best. Using the same distribution for the same variables both before and after and for both kinds of degradation test makes it possible to fully compare the results. The distribution values are imported into Excel where the results are visualized and compared.

To see variations between different shape parameters and how they vary with degradation multivariate data analysis was used. The analysis method factor analysis was used to find fewer independent factors than there are shape and size variables in the image analysis.

The factor analysis was done in MATLAB. There are a number of steps to performing a factor analysis, not covered here, instead a reference handbook in the subject can be used, for example Hair et al, 2010. The most important parts are choosing the number of factors in the analysis and the rotation of the loadings matrix Λ. For this analysis the number of factors and the rotation had to be the same for all samples to be able to compare the results.

3 RESULTS

3.1 Lab test

In total twelve micro Deval tests were done, with most values between 10 and 13, but also two values at five and seven each. Seven Los Angeles tests were done with more varied results, from 16 to 32. In Figure 4 and Figure 5 the laboratory results are presented, even though the main purpose of the figures show size parameters from the image analysis.

3.2 Image analysis

The distributions for all variables were found by ocular comparison in MATLAB’s *Distribution fitting tool*. For two variables the best distribution was extreme value distribution; *circularity* and *solidity*, for all other variables the best distribution was generalized extreme value distribution.

In the following figures the distribution value (location parameter) for each of the different variables are presented. In Figure 4 the size parameters before and after micro

Deval test are presented. All the parameters show decrease after test. In Figure 5 the same trend can be seen for Los Angeles test, decreasing size after test. The higher the LA value or M_{DE} value, the more the grains are affected by the degradation. Despite this there cannot be found any trend that shows larger size decrease after testing for higher test values.

One can note that before testing *Feret's diameter* is in the range of 15-21 mm, and *Feret's minimum diameter* is in the range of 11-14 mm. Since the samples are sieved to 10-14 mm this result shows that the image analysis does not measure the same dimension as determined by the sieving.

The shape parameters *circularity* and *solidity* from the image analysis is presented in boxplots in Figure 6. The variable *circularity* clearly shows increase after testing for both Los Angeles and micro Deval. This means that the grains become more circular. For Los Angeles tests the *solidity* shows no clear change after testing, but for the micro Deval test the *solidity* show increase, indicating more even grains after testing.

The *aspect ratio* boxplots are seen in Figure 7. For Los Angeles testing the variation decreases after testing and the *aspect ratio* becomes lower after testing, indicating that the grains become more circular. For micro Deval the variation of the *aspect ratio* increases after testing, but the means is approximately the same. This means no clear trend can be seen.

The *roundness* boxplots are seen in Figure 8. The Los Angeles testing results in increased *roundness*, giving more circular grains. The micro Deval *roundness* shows increase variation, but no clear trend caused by testing.

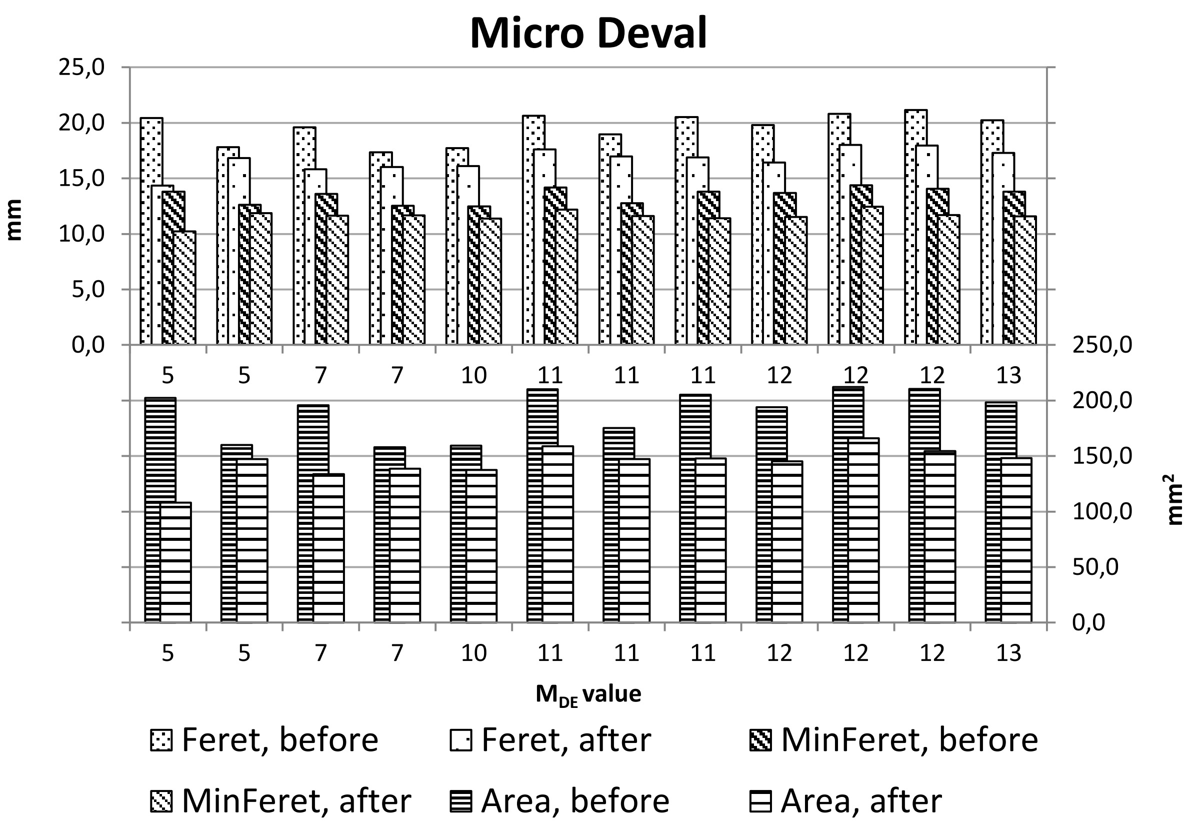

Figure 4. Size parameters for micro Deval samples.

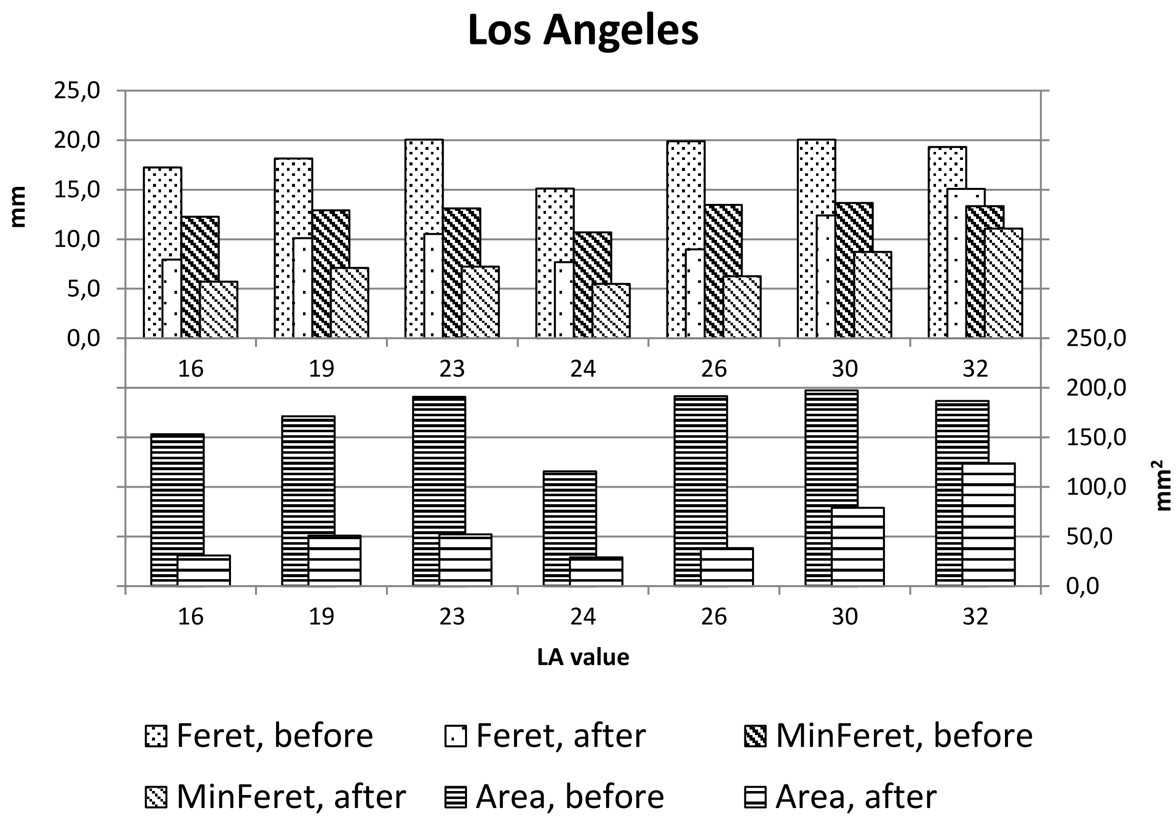

Figure 5. Size parameters before and after Los Angeles test.

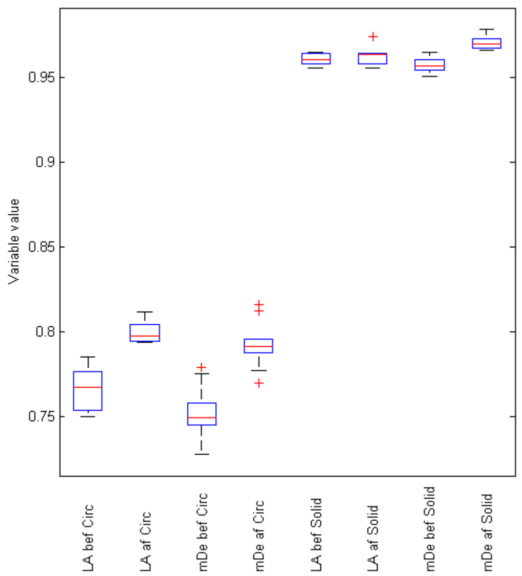

Figure 6. Shape parameters circularity and solidity.

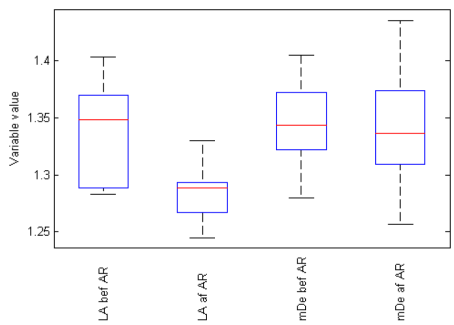

Figure 7. Boxplots for aspect ratio.

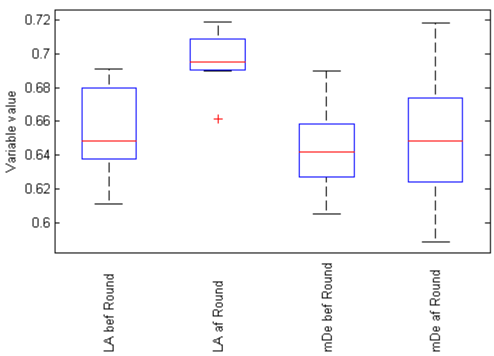

Figure 8. Boxplots for roundness.

3.3 Factor analysis

The factor analysis aims at describing size and shape of the samples with a few factors instead of many variables. Here three factors are used and to have a valuable result the three factors must contain the same variables for different samples, otherwise the factors will not describe the same thing. The rotation that was best in most cases was promax with power 4, and this rotation was used for all samples when comparing the factor analysis results.

Since the samples have different origin the factors do not contain the same variables in the before samples, for neither the micro Deval nor Los Angeles samples. In the Los Angeles after samples factors do contain the same variables, one factor contains *circularity* and *solidity*, and another contains *roundness* and *aspect ratio*. The rest of the variables are grouped in a residue factor describing size, see Figure 9. For the micro Deval after samples there is no clear grouping of the same variables for many samples.

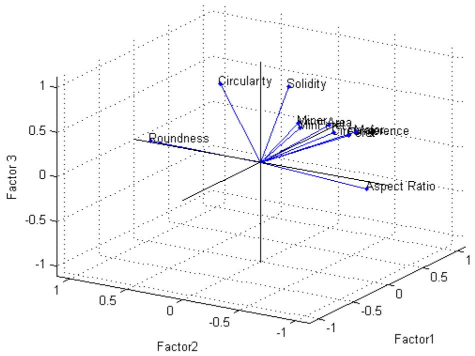

Figure 9. Factor analysis result after Los Angeles test.

4 DISCUSSION

The pre-test samples show a variation in size and shape, indicating that the samples are not homogenous, most likely caused by the different origin. Due to the anonymisation the origin cannot be controlled for the samples.

For both micro Deval and Los Angeles test the grains decrease in size after testing, as expected after a degradation test. The Los Angeles samples decreased in 34-80% in the projected *area* and 17-55% in *diameter*, while the micro Deval samples decreased 8-47% in the projected *area* and 6-30% in *diameter*, showing that the Los Angeles samples decrease more in size than micro Deval samples.

The micro Deval image analysis results show that the grains become more even and more circular (increasing *solidity* and *circularity*) after testing. The Los Angeles results indicate that the grains become more circular (increasing *circularity* and *roundness* and decreasing *aspect ratio*).

In both size and shape parameters there is difference between before and after sample, clearly indicating that degradation can be identified with 2D image analysis, supporting the hypothesis.

The different degradation modes for the tests are fragmentation for Los Angeles test and wearing for micro Deval test. A fragmented material is expected to have smaller grains than a material exposed to wearing. Grains exposed to wearing are also expected to be more even than fragmented grains. The overall shape is predicted to become more circular for the grains after degradation, but it is unclear if anything can be said about which type of degradation give the most circular grains. It is possible to expect more circular grains for wearing than fragmentation since non-circular grains are created when a grain is split (more or less) down the middle. The opposite is also possible, more circular grains can be expected for fragmentation than wearing since this degradation mode affects the grains in greater extent.

The results show that the Los Angeles grains are smaller than the micro Deval grains after testing, supporting that fragmentation occurs for Los Angeles testing. The micro Deval grains become more even after testing, indicating that these grains have been exposed to wearing. These results support that micro Deval tests induce wearing in grains and Los Angeles tests performs fragmentation of grains.

Los Angeles testing shows more circular grains afterwards for all parameters measuring overall shape. The micro Deval grains show more circular grains for one parameter measuring overall shape (*circularity*) and no clear trends for the other two overall shape parameters (*aspect ratio* and *roundness*).

It is possible to judge if the ballast material has been degraded by micro Deval or Los Angeles test. More studies are needed in order to verify how wearing and fragmentation affect the different geometric measures in the image analysis.

The factor analysis shows the same variables in each factor after Los Angeles test, despite differences in the factors before testing. Having a factor with *roundness* and *aspect ratio* is not strange, since they are the inverse of each other. Another factor uses *solidity* and *circularity* to describe the shape. The "residue" factor, with the remaining variables, describes size. For the micro Deval samples no unified factors could be found, either before or after testing.

Many authors have found relations between shape or roughness parameters of grains and soil properties. Hansson & Svensson (2001) used a shape determining method based on abrasion number from studded tyre tests (surface roughness) and harp sieving (flakiness). In stability testing in a ring chamber, the horizontal stresses were found to be higher for flaky materials than for cubic materials. Alshibli & Alsaleh (2004) measured surface roughness with interferometry. Biaxial tests were performed and the friction and dilatancy angle was found to increase with increasing surface roughness.

Cho et al (2006) determined sphericity and roundness by comparing grains to standard images in a chart by Krumbein & Sloss (1963). Void ratios e_{max} and e_{min} increase for decrease in sphericity and roundness. Guo & Su (2007) determined two different materials to be angular and rounded, respectively, using scanning electron microscope. Triaxial tests were done and higher angularity showed increased shear strength and affected dilatancy characteristics. Cox & Budhu (2010) used digital image analysis and created a weighted shape parameter consisting of data from six different shape parameters. They found that the weighted shape parameter influenced the dilatancy characteristics found in direct shear box testing.

These authors have found good results, but the measuring methods and shape parameters are different and it is difficult to assemble the data to be able to quantify the behaviour of granular materials. Standardized grain shape parameters and measuring methods are needed to be able to quantify the relations between grains shape and soil properties.

Another observation is that this study is unique in targeting degradation and the shape changes that occur for a degradation exposed material. It is now proved that degradation can be identified in the grains' size and shape when the degradation is performed by standardized degradation tests. Continued studies should focus on image analysis of field samples from roads or railways. It would be possible to compare the size and shape of these samples to the after samples from degradation tests.

5 CONCLUSION

The study was conducted to investigate if it is possible to use image analysis to measure degradation in standardized degradation tests.

The results show difference between the results pre and post degradation test, enough to say that degradation can be identified by image analysis. The findings also show difference between the different degradation tests in size and shape change. The Los Angeles grain becomes smaller than the micro Deval grains after testing, and micro Deval grains show more even grains after testing, indicating that Los Angeles tests exposes the grains to fragmentation and micro Deval tests induce wearing the grains.

6 ACKNOWLEDGEMENTS

The laboratory testing was performed at Väglaboratoriet i Norr, an accredited laboratory. Thanks to Jan Hellström, supervisor at Väglaboratoriet, for supporting the study and to Emil Lemon, of Väglaboratoriet, for performing the tests and taking the photographs.

7 REFERENCES

Alshibli, K., & Alsaleh, M. (2004). Characterizing surface roughness and shape of sands using digital microscopy. Journal of Computing in Civil Engineering, 18(1), 36-45. doi:10.1061/(ASCE)0887-3801(2004)18:1(36)

Banverket. (2004). Makadamballast för järnväg. (No. BVS 585.52). Borlänge: Banverket.

Cho, G., Dodds, J., & Santamarina, J. C. (2006). Particle shape effects on packing density, stiffness, and strength: Natural and crushed sands. Journal of Geotechnical and Geoenvironmental Engineering, 132(5), 591-602. doi:http://dx.doi.org/10.1061/(ASCE)1090-0241(2006)132:5(591

Cox, M., & Budhu, M. (2010). Grain shape quantifications and their relationship to dilatancy. (pp. 540-549) American Society of Civil Engineers. doi:10.1061/41095(365)51

Guo, P., & Su, X. (2007). Shear strength, interparticle locking, and dilatancy of granular materials. Canadian Geotechnical Journal, 44(5), 579-591.

Hair, J. F. (2010). Multivariate data analysis: A global perspective Pearson Education.

Hansson, J., & Svensson, P. (2001). Stress distribution in unbound aggregate of road structure: Influence of surface roughness and particle shape. Bulletin of Engineering Geology and the Environment, 60(3), 223-226. doi:10.1007/s100640100103

Krumbein, W. C., & Sloss, L. L. (1963). Stratigraphy and sedimentation (2nd ed.). San Francisco: W.Hh Freeman.

Lambe, T. W., & Whitman, R. V. (1969). Soil mechanics. New York: Wiley.

Mitchell, J. K., & Soga, K. (2005). Fundamentals of soil behavior (3rd ed.) John Wiley & Sons.

Rodriguez, J. M., Edeskär, T., & Knutsson, S. (2013). Particle shape quantities and measurement techniques - A review. Electronic Journal of Geotechnical Engineering, 18(A), 169-198.

Trafikverket. (2011). TRVKB 10 obundna lager. (No. TRV 2011:083). Borlänge: Trafikverket.

Zeghal, M. (2009). The impact of grain crushing on road performance. Geotechnical and Geological Engineering, 27(4), 549-558. doi:10.1007/s10706-009-9256-1