Degradation of railway ballast through large scale triaxial and full scale rail track model tests - Comparison with mechanical laboratory tests.

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ABSTRACT: The aim of the research was to assess if the standard tests provided a reliable ranking of nine ballast aggregate materials with respect to mechanical strength. Standard tests were compared with the results from large scale triaxial and full scale model tests employed to simulate in-service stress and environment. Four different mechanical strength tests were conducted on nine crushed rock railway ballast types with fixed grading (22.4 - 63 mm) to investigate degradation with respect to breakage and production of fines. The equipment used are the standard tests: Los Angeles Abrasion (31.5-50 mm/10-14 mm) and micro-Deval (31.5-50 mm), large scale repeated load triaxial, and a full scale railway track model test for cyclic loading, all performed in the laboratory environment. The test procedure also included simulation of the impact loading from tamping. Aggregate petrographic tests were used to reveal whether there was any possible rating weakness associated with the mechanical strength. The rock samples were three igneous rocks, four metamorphic rocks and two consolidated/ metamorphosed sedimentary rocks, all fine and medium grained. The results of the study indicate that the three types of mechanical tests rank the ballast samples in three different ways.

KEY WORDS: Railway ballast degradation, triaxial test, Los Angeles Abrasion test, full scale railway track model test, micro-Deval test.

1 INTRODUCTION

In railway track, repeated wheel loads transferred from sleepers to the ballast layer cause abrasion and degradation of ballast aggregates over time which contributes to the fouled content in the ballast layer and alter the gradation (Boler et al. 2012). These changes weaken the bearing capacity of the ballast layer and eventually cause track geometry problems. To maintain the optimal track alignment, tamping is commonly applied. Tamping, on the other hand, contributes to degradation of aggregates in ballast layer. Tamping loosens ballast, rearranges particles and produces new particle contact points which fracture under contact stress. When this degradation is added to degradation caused by traffic loading, fouling content of ballast layer can increase to a level that prevents free drainage of water after some years in service.

Both Selig and Waters (1994) and Lim (2004) showed that tamping speeds up the fouling of ballast when they used ballast box tests to investigate the effect of particle rearrangement on particle breakage. This finding was recently confirmed by Nålsund (2010) from triaxial tests.

Lims (2004) investigation of four granitic rocks simulating the effects of both train loading and ballast tamping provided only a slight correlation between Los Angeles Abrasion (LAA) test and ballast degradation, but this conclusion was quite uncertain mostly due to few results in the commercial area (LAA less than 20%) of the diagram. The main crushing process realized in both LAA test and in the field under the sleepers is that rock particles lose weight due to loss of fracturing and chipping off the sharp corners and therefore, the angularity decreases (Boler et al. 2012). This fragmentation depends on the rock's tensile strength which in turn depends on, to some extend, the frequency of micro-cracks (Johansson et al. 2011). Ugur (2010) and Kahraman and Gunaydin (2007) have revealed that LAA results corresponded well with Point Load Index, which indirectly expressed rock core tensile strength properties of 14 different rock types. Hence, the magnitude of breakage under train loads might be predicted by the LAA value.

In a considerable study by Raymond and Diyaljee (1979) ballast aggregate breakdown on eight different rock types tested under repeated triaxial loading were related to mechanical tests and showed high correlation with Mill Abrasion tests. This result suggested a grinding mechanism and the importance of mineral hardness. The Mill Abrasion test used requires an aggregate charge of 3 kg with 20 - 30 mm particles together with 3 liter of water and no steel balls. Lower correlation was obtained with LAA suggesting toughness as a secondary factor for breakdown. The ballast materials were subjected to a repeated deviator stress of 210 kPa and a confining stress of 35 kPa.

It is of great interest that the selection of ballast material for construction purposes is based on sufficient resistance to load associated degradation. The most common way of predicting ballast degradation under train loads is through the use of LAA test which celebrated its 100 year anniversary in utilization in 2016 (Woolf and Crandell 1936). It is a quick and easy test that mainly measures coarse aggregate resistance to crushing. Many rock properties contribute to the mechanical strength, e.g. the average mineral grain size, grain size distribution (uniformly graded or well graded), shape (perimeter) and spatial orientation (foliation) of mineral grains. In addition, other petrological properties like mineral hardness, modulus (E), grain boundary relations (suturing), amount of micro-cracks, mineral deformation and degree of alteration (sericite in feldspar) make the situation quite complicated. Hence, it is quite difficult to predict a rock´s mechanical strength and corresponding functional properties. It can be suggested that it is too good to be true that such a simple test can separate in all aspects good performing ballast materials from the poor performance ones in a reliable way.

The purpose of the current study described in this paper has been to assess if the standard tests for mechanical strength provide a reliable ranking of the ballast materials in comparison with results from the triaxial and the full scale model tests. The two latter are employed to simulate in-service loading and environmental aspects in laboratory condition and to improve our understanding of ballast behaviour through petrographic characteristics. In addition, evaluating to what extent the parameters average grain size, amount of micro-cracks and mineral composition govern the mechanical strength has also been an essential task.

2 TEST MATERIALS AND ROCK CHARACTERISTICS

The selection of rock samples was based on representing a wide variation in the mechanical properties, i.e. LAA and micro-Deval (MD) values. All samples are taken from quarries, and most of them are supplying The Norwegian National Railway Administration with railway ballast (nominal 31.5-63 mm). All samples were required to have passed two crushing stages, first, with a jaw crusher and secondly with a cone crusher. The ballast samples represented both igneous rocks, metamorphic rocks and consolidated /metamorphosed sedimentary rocks.

Tables 1 and 2 list all investigated aggregates from 9 deposits (quarries) where the rock types have been classified according to their geological names, and the following features have been taken into account: Mineralogy, mineral grain size, mineral grain size interval (from D_{min} to D_{max}), specific density, grain shape, and mechanical properties such as LAA and MD values. Note that several of the quarries produced aggregates naturally "blended" with different rock types (heterogeneous).

Table 1: Aggregate deposits with geologic names and mineralogical compositions . Minerals: Q(quartz), F (plagioclase), K (k-feldspar), B (biotite), M (muscovite), A (amphibole), E (epidote), Chl (chlorite), Car (carbonate).

Deposit no. 08115-	Quarry	Geological name	Minerals									Grain size mm interval
			Q	F	K	B	M	A	E	Chl	Car	
1	Steinkjer	Meta sandstone, meta greywacke, quartzite	48	18	15		18					0.1-1.5
2	Meraftåsen	Greenstone	5	32	5		6	8	9	29	6	0.01-0.2
3	Lauvåsen	Meta greywacke-argillite	14	23	3		26			25	9	0.05-0.5
4	Vassfjell	Meta gabbro, cataclasite	1	18	6			41	12	18	4	0.1-5
6	Aplitt	Cataclasite, crush breccia, granite	54	15	29					2		0.05-2.5
11	Lørenskog	Mylonite, gneiss, gabbro	28	48	6	4		14				0.05-1
12	Freste	Monzonite	7	59	23			7		2	1	7-10
23	Rombak	Mica gneiss	46	21	2	10	17			3	1	0.01-0.4
26	Sefrivatn	Gneiss granitic	24	42	27	2		2		2	1	0.1-0.5

The mineralogy has been estimated by means of both microscopic examination of thin sections (measurement grid, 363 points) and semi-quantitative X-ray diffraction (XRD) analyses.

Table 2: Aggregate deposits with mechanical strength, shape, rock density and roughness.

Deposit nr	Quarry name	LAA_{dry}	LAA_{wet}	Micro Deval	SI20	Specific density	Surface Texture Index	$LAA_{10\text{-}14mm}$	Mineral grain size D_{50} mm
1	Steinkjer	16.9	14.1	4.8	18.2	2.71	2.00	20.9	0.138
2	Meraftåsen	12.4	18.3	11.2	7.1	2.95	0.88	17.5	0.088
3	Lauvåsen	25.7	26.7	15.7	13.5	2.77	0.90	19.2	0.119
4	Vassfjell	13.3	23.4	8.7	7.3	3.08	1.33	14.4	0.333
6	Aplitt	21.4	20.7	3.4	13.4	2.67	1.89	21.3	0.487
11	Lørenskog	12.8	16.3	6.0	14.7	2.91	1.56	20.3	0.203
12	Freste	21.8	21.9	6.6	13.9	2.73	1.10	22.5	3.815
23	Rombak	13.7	20.2	9.5	11.7	2.78	1.40	18.1	0.180
26	Sefrivatn	24.4	19.3	4.6	11.2	2.67	2.27	24.9	0.263

The rock characterisation is performed on fraction 31.5-50 mm.

In addition, a quantitative aggregate surface texture (ST) index was also investigated to reveal a possible impact on crushing and abrasion resistance. To calculate the ST, an image analysis technique, known as “erosion and dilation” integrated in the University of Illinois Aggregate Image Analyzer system for analysing coarse aggregate particles, was used (see Figure 1). Determination of ST is further described in Rao et al. (2003).

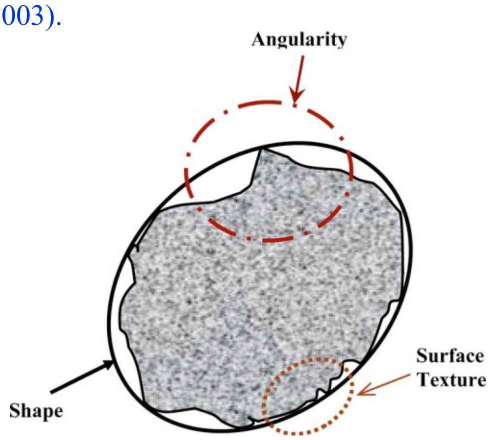

Figure 1: Key morphological properties of an aggregate particle (Pan and Tutumluer 2005).

3 TEST METHODS

It is assumed that the standard ballast testing methods consistently provide results reflecting the performances of different ballast materials in situ in the railway trackbed. In this research, extensive laboratory tests were conducted to investigate the correlation regarding degradation between two standard simple ballast index tests (i.e. Los Angeles abrasion and micro-Deval), a large scale cyclic loading triaxial test with constant confining pressure and a full scale rail track model test with pulsating jack simulating field conditions. A total of nine different ballast materials were investigated. The first two tests mentioned above were conducted in accordance with EN-NS1097-1, EN-NS1097-2 and EN-NS13450. The sample fractions used were 31.5 to 50.0 mm in sizes, partly 10-14 mm. The last two tests were non-standard. The large triaxial equipment was described in detail by Skoglund (2002) and Skoglund et al. (2002) and the sample fraction used was 22.4 to 63.0 mm in accordance with Norwegian requirements for railway ballast. The grading curves used for both the triaxial and the full scale model tests were identical (Table 3), and the weight of the samples for the triaxial testing varied between 67 to 72 kg to achieve a sample height of approximately 600 mm and allow for differences in specific densities. The corresponding sample weight for the full scale model test was 240kg.

Table 3: Similar grading curve used for both triaxial and full scale model tests.

Fraction	22.4-31.5 mm	31.5-40.0 mm	40.0-50.0 mm	50.0-63.0 mm
Per-cent by weight	10	30	35	25

The two large-scale tests were both performed in such a manner that the test specimens were subjected to the same stress level as expected in railway tracks in service. The stress level is equivalent to 25 tonnes axle load. Hence, the degradation results from the two types of tests are comparable. The axle load limit on most railway lines in Norway is 22.5 tonnes.

3.1 Triaxial test procedure

The quarried ballast material was washed, sieved, air dried and blended into one fixed predetermined grading curve (Table 3). The specimens were built with five equal layers in a cylindrical steel mould. Each layer was compacted in a dry state for 30 seconds using vibration. Each specimen had to be at a height of approximately 600 mm in the beginning of the loading. After compaction, the specimen was dressed with two rubber membranes. After preparation, the specimen was placed in the triaxial rig and instrumented with four LVDTs for axial and radial deformation measurements. Then, the specimen was moistened by adding water through the drainage system from the bottom pedestal and then drained immediately.

The single-graded railway ballast specimens as described above were subjected to long term cyclic loading to simulate railway traffic. All triaxial tests were performed with a maximum dynamic axial stress of 250 kPa corresponding to about 250 kN axle load given a stiff foundation, and a cyclic loading rate of 5 Hz. The static confining (air) pressure was 60 kPa for all samples.

3.2 Tamping simulation

Each test is conducted in four steps. To simulate the tamping operation the load application (step 1) was stopped after 1 million cycles. The test specimen got dismantled, re-compacted with the same material used in step 1 and subjected for another 1 million load applications (step 2). This loading procedure was followed by two additional similar steps (3 and 4) until a total of 4 million dynamic loads or approximately 100 million gross tons. After each dismantling and before rebuilding, the tested ballast was sieved to remove breakage material with grain size less than the original grading (22.4-63 mm). This material was accumulated and weighed at the end of the test to show the total amount of breakage after 4 million load applications (inclusive tamping). The removed crushed material was not compensated with fresh material and a lower sample height (and lower sample weight as well as lower bulk density) was accepted.

3.3 Water influence

Another four triaxial tests (4x1million loadings) were accomplished to investigate water influence (also an attempt to simulate wet climate). In this case the material was soaked in water for 7 days before testing, drained during compaction, and subsequently soaked during the cyclic loading.

3.4 Full scale rail track model test procedure

The general test setup is shown in Figure 2. A railway track section was built with ballast, sub-ballast and subgrade of crushed rock and confined within a rigid test box 3m long by 1.5m wide, all resting on a concrete floor. The support layers under the upper layer of ballast were neither changed nor removed during the complete test.

Figure 2: Full scale rail track model test setup for cyclic loading.

A standard concrete sleeper 2400 mm long, 260 mm wide and 200 mm deep (at rail seat) was placed in the middle directly on the ballast floor with another sleeper on each side with 500 mm spacing to simulate typical track structure but without any ballast in the cradle in an attempt to run a less time consuming test. Limited with a steel frame with inside dimensions of 400 mm width and 1000 mm length, a test sample weighing 240 kg was placed within the ballast layer under each end of the middle sleeper (see Figure 3). The ballast degradation for each tested rock (9 in total) was calculated as average of the two test samples. No under-sleeper-pads were used.

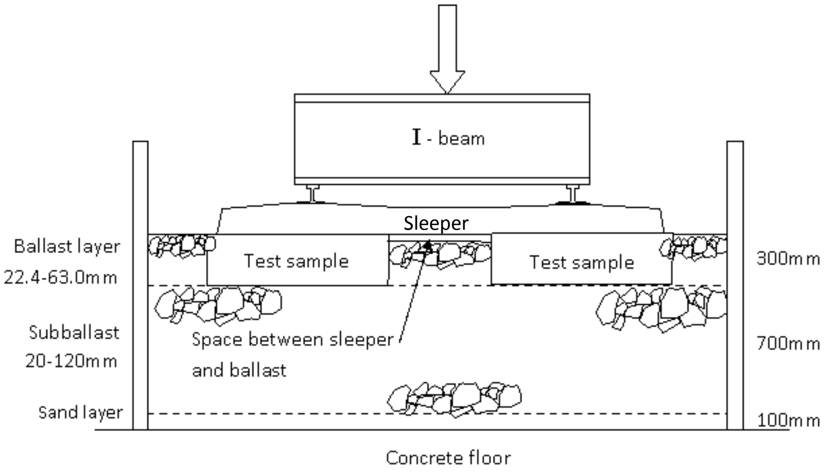

Figure 3: Cross-section of the full scale rail track model test setup.

To differ test sample from surrounding ballast and avoid loss of degraded fines, a geotextile was used which also enabled lifting by crane. Having backfilled the surrounding ballast material and removed the steel frame, the area was leveled by hand and compacted with a vibrating device “LOPPE” with ten passages for each sample. Under the middle of the sleeper, some ballast was removed to avoid riding during the test due to experience from Raymond (1977). The area of interface between sleeper and ballast at each end of the sleeper was 260 mm by 950 mm.

3.5 Tamping simulation

The wheel load was assumed to be distributed equally with 50% to the main sleeper and 25% to each of the neighboring sleepers according to Selig and Waters (1994). A computer-controlled closed-loop electrohydraulic actuator applied a 5 kN to 125 kN repeated load to the I-beam and distributed 62.5 kN load to each rail seat for a duration of totally 4 million load repetitions interrupted after each 1 million to perform a “tamping operation.” After having temporarily moved the hydraulic jack, the I-bar and the middle sleeper, the samples were penetrated with a crowbar “in situ” on ten different points to loosen the ballast with the intention to re-orientate each rock particle to get new contact points. Then, the next step that followed was a new compaction and a new sequence with 1 million loadings until 4 million was reached. The degraded material was recovered after test completion as distinct from the triaxial test. The test samples were finally sieved (finer than 22.4 mm) and the material breakdown was assessed as an average of the two test samples.

4 TEST RESULTS AND ANALYSES

4.1 Ballast breakage under triaxial testing

The results of the cyclic triaxial tests on dry and wet ballast are displayed in Figures 4 and 5.

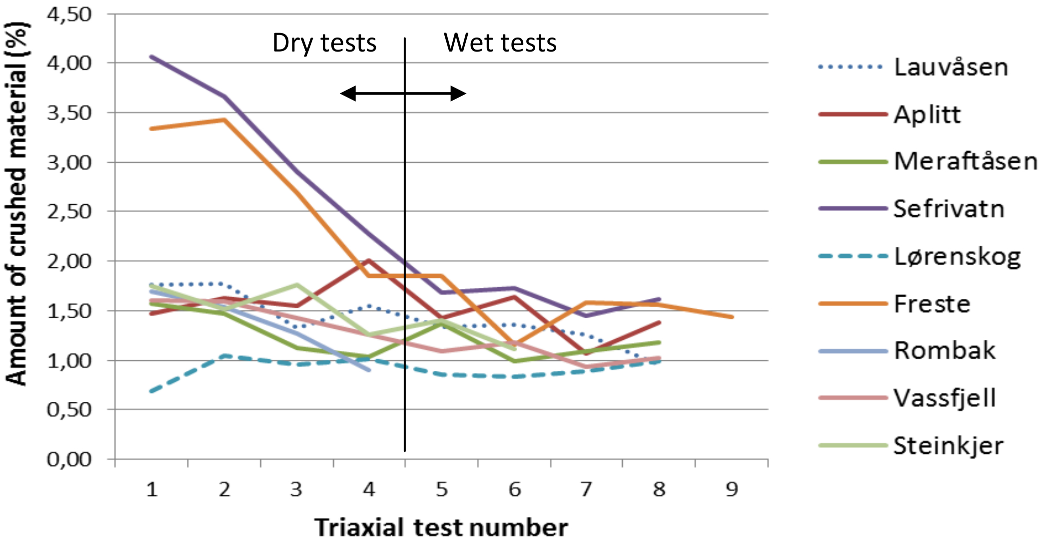

Figure 4: Amount of crushed material 0-22.4 mm after each triaxial test. The test fraction at the beginning of each test was 22.4- 63.0 mm. Number 1 to 4 represent dry state, and 5 to 8 represent wet state. Mica gneiss from Rombak was tested only in dry state.

There are several methods to characterize breakage (Anderson and Fair 2008, p 323. Indraratna 2011), but the reason why the fraction 0-22.4 mm is being used in this study, is that it corresponds with one of the recommendations in European Rail Research Institute's report (ERRI 1994) on ballast durability and fouling characterization.

Overall, the resistance to crushing does not seem to change significantly during eight test repetitions conducted on seven out of the total of nine ballast materials (Figure 4). The last two (Sefrivatn and Freste) however show an increase in strength during the first part of the test series. This is previously documented by Heikkila (1991) for medium to coarse grained rocks in Finland by using full scale crushing tests in quarries, which suggested that mineral grain size can influence rock's ability to recover mechanical strength when there is repeated crushing. As opposed to Heikkila's rock materials, Sefrivatn is fine grained and should behave in accordance with the other seven tested ballasts with no strength improvements, since they are fine to very fine grained with D_{50} within range 90 to 490 µm (D_{50} = 90 means that half the area of the thin section consists of mineral grains with diameter greater than 90 µm). Freste (monzonite) is the only one that is coarser than fine grained with D_{50} equal to 3815 µm (medium grained).

It has been known for a long time that moisture has in general a negative influence on rock strength (Kessler et al. 1940). Among the nine test materials in this project, four specimens (Lauvåsen, Rombak, Meraftåsen and Vassfjell) have a pronounced drop in mechanical strength when measured by wet $LAA_{31.5\text{-}50mm}$ test with an increase in LAA value from 27% to 75%. This phenomenon is not observed from the triaxial tests as shown in Figure 4. Surprisingly, there is no increase in ballast breakage in tests 5 to 8 (wet state) compared with the dry state tests.

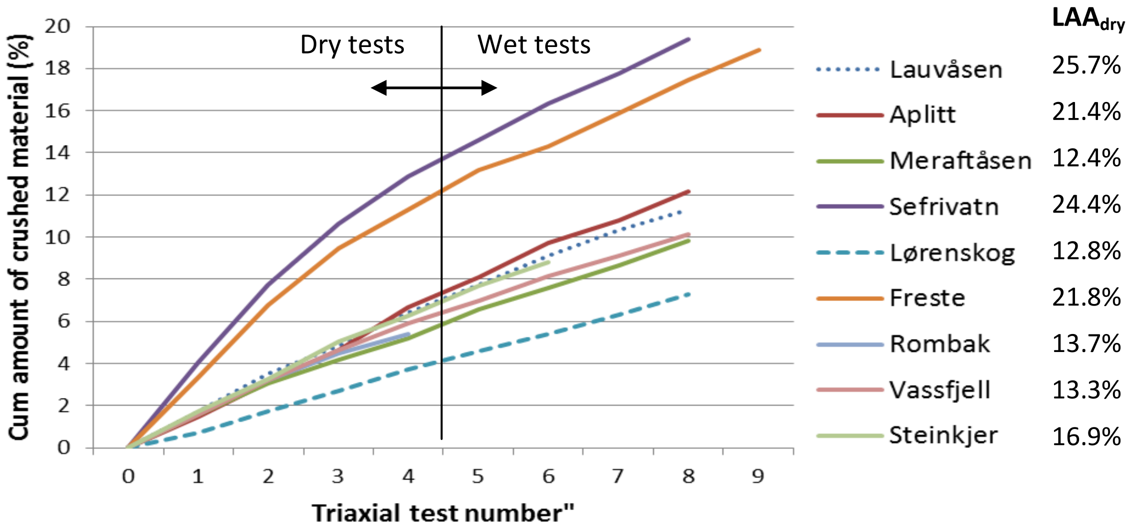

Figure 5: Cumulative amounts of crushed material 0-22.4 mm after 8 triaxial tests. Freste was tested 9 times. Test number 1 to 4 represents dry state, and number 5 to 8 represent wet state. Mica gneiss from Rombak was tested only under dry conditions. All rocks are fine to very fine grained except Freste.

The total amounts of material breakdown from all the test series are shown in Figure 5, and indicate a ranking of the ballast's durability under simulated field conditions with train loading, tamping (sample compaction between each test) and climate (wet state). The diagram shows a fair correlation between crushing and the results from LAA tests (fraction 31.5-50 mm). However, there are three interesting deviations that attract attention. Sefrivatn (granitic gneiss) should perform better than shown in the diagram due to this rock's average mineral grain size. But presence of a great amount of inter and intra granular micro-cracks may have a negative effect on the strength. Aplitt (cataclasite) and Lauvåsen (meta-greywacke) had slightly more breakage than Vassfjell and Meraftåsen despite its almost twice as high LAA value. An explanation is hard to find, but Lauvåsen consists of nearly 60% soft minerals, which should be a drawback in this context. Thus, it is regarded as an outlier in this study. According to LAA results, Lørenskog was equally durable with Vassfjell and Meraftåsen but performed 20% better than the other two. A possible explanation is that Lørenskog is almost without micro-cracks and appears somewhat solid which can contribute to high strength. Micro-Deval values do not correlate at all with the amount of breakage material after triaxial testing, neither plotted against fraction 0-22.4 mm nor 0-0.125 mm. Hence, in this study, abrasion seems to be less important for ballast degradation compared with resistance to crushing when the rocks are fine grained.

The rate of strength improvement for ballasts Sefrivatn and Freste shown in Figure 4 levels out after four triaxial tests performed in the dry state. The rest of the test samples do not have any change in mechanical strength, which makes it difficult to create reliable correlations between mechanical strength and other parameters. Most of the fine grained rock materials had strengths unaffected (resistance to crushing) through all eight triaxial tests. This implies that the breakage results from wet stage (step 5 to 8) are representative for the long term performance. A plot of LAA results against cumulative wet triaxial test breakage is shown in Figure 6. The correlation is fair but there is some scattering. The triaxial test performs mainly a dynamic impact (only crushing) while the LAA method uses shock (strokes) and abrasive impact (Erichsen et al. 2011). Hence, their rates of degradation are different for the different rocks as shown in Figure 6.

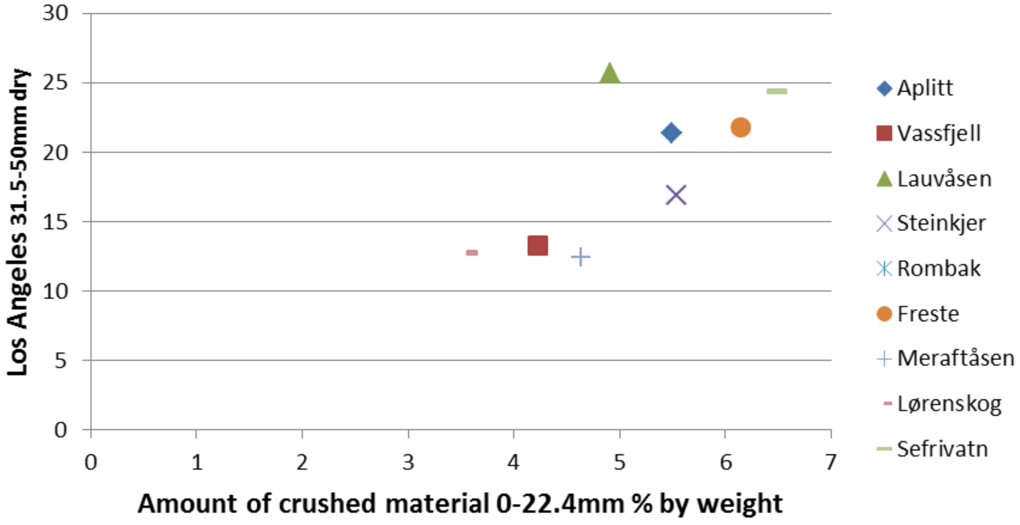

Figure 6: Correlation of LAA (dry) against cumulative wet triaxial test breakage (four repetitions and totally 4 million loadings). Ballast test fraction 22.4-63 mm. R^2 without Lauvåsen is 0.83.

However, if we replace $LAA_{31.5-50}$ with $LAA_{10-14mm}$ which causes a more uniform crushing impact on the test material (Erichsen et al. 2011), a better correlation can be obtained, as will appear from Figure 7. This suggests that $LAA_{10-14mm}$ can be a more suitable test for assessing durability of ballast materials when compared to $LAA_{31.5-50mm.}$

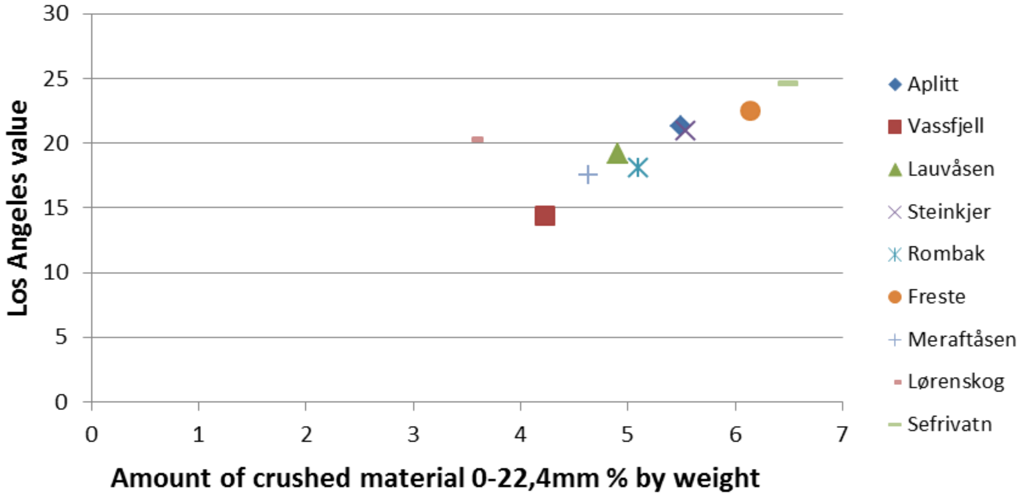

Figure 7: LAA values (10-14 mm) plotted against breakage from triaxial tests performed in wet state (4 million loadings). R^2 without Lørenskog is 0.97.

4.2 Permanent deformation

As mentioned above, abrasion seems to be less important for ballast degradation in this study. But on the other hand, micro-Deval values correlate well with the ballast's permanent settlement under cyclic triaxial loading as shown in Figure 8. This was first discovered by Raymond and Diyaljee (1979). This correlation depends in turn on the material's surface texture (test results displayed in Table 2). The lower the micro-Deval value is, the higher is the surface texture index, which means that the surface friction decreases when the micro-Deval value increases. The ballast settlement during cyclic triaxial loadings is therefore probably mainly caused by rotation of aggregate grains causing a higher density of the ballast. Some crushing may occur during the cyclic loading, but the recorded correlation between settlements and LAA values is poor in this study. The major part of the aggregate's crushing takes place during compaction under sample preparation.

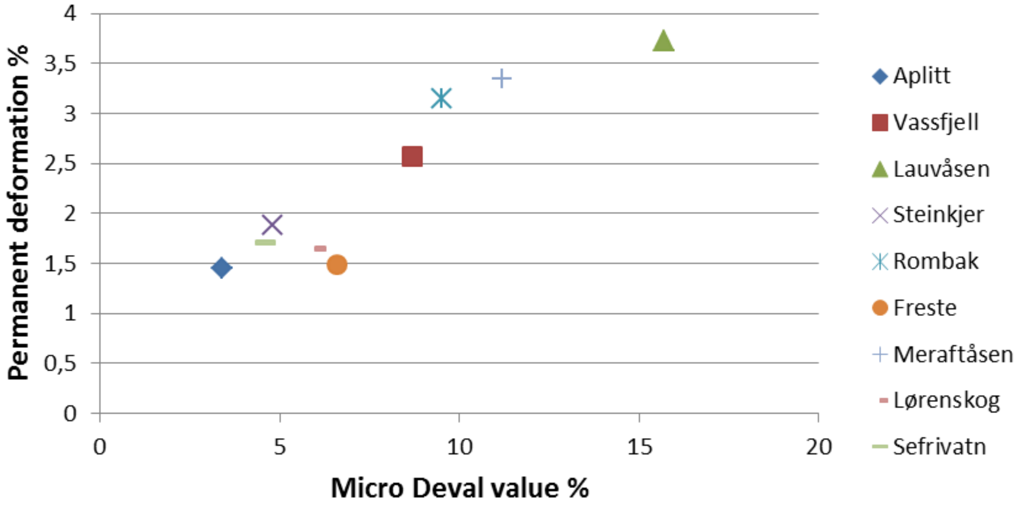

Figure 8: Ballast permanent deformation from dry triaxial tests (4x1mill loadings) plotted against micro-Deval values (31.5-50 mm). R^2 is 0.86 with Lauvåsen included.

4.3 Ballast breakage under full scale model testing.

Full scale model tests were conducted on all nine materials tested. It was supposed that the full scale model test would simulate field condition very well and therefore provide more reliable results. Figure 9 shows the relationship between LAA loss and ballast degradation from the full scale model test (totally 4 mill loadings with ballast loosening after each million). The correlation is far from as good as in Figure 6 (LAA vs. triaxial cyclic impact). If we replace $LAA_{31.5\text{-}50mm}$ with $LAA_{10\text{-}14mm}$, no correlation occurs in contrast to what was expected with reference to Figure 7. A possible explanation can be that the LAA test does not simulate the materials' field performance in a reliable manner, and the triaxial test also is a bit away from the reality in situ.

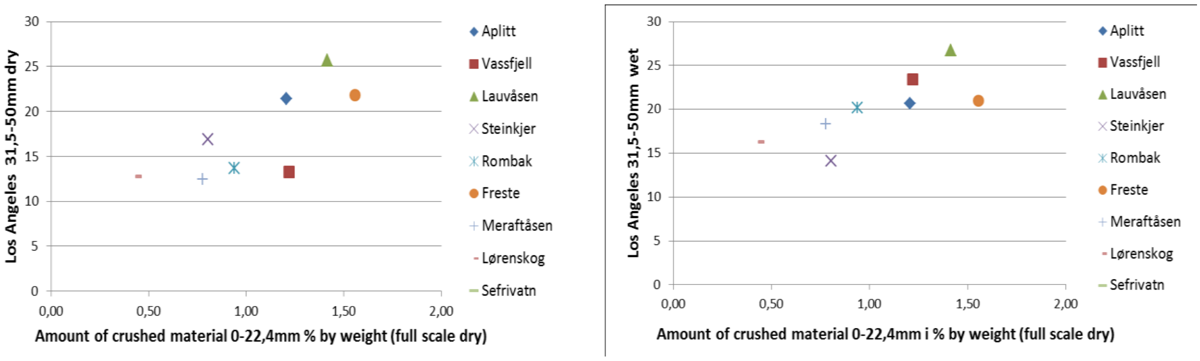

Figure 9: Total amount of crushed material from full scale model test (4x1 million loadings /only dry state) plotted against $LAA_{31.5\text{-}50mm}$. Left: dry state with $R^2 = 0.56$. Right: wet state with $R^2 = 0.58$, but increase to 0.73 when Freste (medium grained) is removed.

Neither crushed material from the triaxial test nor from the full scale model test shows any correlation with micro-Deval values (not shown). Hence, it is likely to believe that abrasion does not occur or is of secondary importance for ballast degradation in this study. According to Figure 9 (left), the LAA method dry state does not rank the aggregate materials in a proper way compared to the full scale model test. The judgment of the four samples all with LAA loss around 13% (Lørenskog, Meraftåsen, Rombak and Vassfjell), says that they are equal in mechanical strength. But the full scale model test (supposed to be the most reliable test) separates the four samples clearly based on ballast breakage. Lørenskog is more than twice as good as Vassfjell. A replacement with data from $\mathrm{LAA}_{10\text{-}14\mathrm{mm}}$ did not improve the correlation.

If we compare the breakage material 0-22.4 mm with $\mathrm{LAA}_{31.5\text{-}50\mathrm{mm}}$ wet state (see Figure 9 right), the regression coefficient increases from 0.58 to 0.73 if sample Freste leaves out. This can be done due to the fact that the nine test samples consists of two groups, one that recover improved mechanical strength during repeated crushing, and one that does not recover any change in mechanical strength (see Figure 4). The four test samples mentioned above, Lørenskog, Meraftåsen, Rombak and Vassfjell, are not equal any longer according to $\mathrm{LAA}_{31.5\text{-}50\mathrm{mm}}$ wet state. The ranking now comply with the results from the full scale model test. But it looks strange that the strongest correlation is obtained when comparing a dry test with a wet test.

5 DISCUSSION

5.1 Improved ranking of ballast materials

This study suggests that ballast breakage in situ is mainly governed by the resistance to crushing, and that the process of abrasion contributes in a minor degree, provided that the rock is fine grained, crystalline and is composed of mainly hard minerals. An interesting phenomenon appears when the crushed material from the full scale model test was sieved on 0.125 mm grain diameter as illustrated in Table 4.

Table 4: Amount of fines (0-0.125 mm) in the crushed material after the full scale test compared with respective values from fraction 0-22.4 mm (ref. Figure 9). Per cent refers to sample's total weight.

Quarry	Aplitt	Vass-fjell	Lauv-åsen	Stein-kjer	Rom-bak	Freste	Meraft-åsen	Løren-skog	Sefri-vatn
0-22.4 mm (%) after sieving	1.21	1.22	1.41	0.80	0.94	1.56	0.|78	0.44	1.59
0-0.125 mm (%) after sieving	0,13	0,12	0,37	0,09	0,14	0,11	0,12	0,07	0.17
0-0.040 mm (%) after Coulter test	0.075	0.087	0.263	0.059	0.079	0.067	0.088	0.039	n.d.

Graywacke from Lauvåsen is an outlier within the present rock suite, since it consists of about 60% soft minerals (mica, chlorite and carbonate) but performs apparently as an ordinary hard rock. An extraordinary production of fines (three times more than expected) was revealed when sieved on 0.125 mm sieve after strained in the full scale model test. This was also confirmed by Coulter test (Table 4). The poor quality (Lauvåsen) was not detected neither by LAA, micro-Deval, triaxial test nor full scale model test when sieved on 22.4 mm sieve. In general, rocks with equal mechanical strength do not produce the same amount of fines (less than 0.125 mm) when they get crushed (West et al. (1970). West analysed the amount of fines after LAA tests. This is an important property because the content of fines in the fouling material is the main reason for the loss of performance of the ballast bed (Han and Selig (1997), This can be developed to a simple technique to discriminate rocks in a more reliable manner based on LAA method, but more investigations are necessary to document the correlation between laboratory work and in situ performance.

5.2 Improving the triaxial test procedure

The amount of crushed material (0-22.4 mm) from the triaxial test run on one sample, compared with the corresponding amount of crushed material from the full scale model test (after four parallel tests and four million load applications) is quite different. Due to the selected procedure for the triaxial test in this study, it produced up to 8 times more breakage material than the full scale model test on the same type of material. The difference in impact of stress under the two test methods can cause a difference in response from the materials which may give two different ballast durability rankings. Less crushing under compaction of the triaxial test samples can be an improved approach to simulating field stress conditions. The triaxial test samples were compacted in 30 seconds in the steel mould. Duration of 10-15 seconds could probably have been a more proper practice.

6 CONCLUSIONS AND RECOMMENDATIONS

It is difficult to obtain good correlations between mechanical tests and rock parameters particularly when many different rock types are involved. Hence, this introduces many variables which can influence the mechanical strength in different magnitudes. Specific conclusions are as follows.

On the basis of triaxial testing:

1. With reference to the triaxial test, seven out of totally nine rock samples did not change their resistance to fragmentation during impact from repeated compaction, both in dry and wet state.
2. Two rock samples improved their crushing resistance during impact from repeated compaction.
3. It is not clear why some rocks developed higher mechanical strength as a consequence of repeated crushing while others did not. A possible explanation may consider linkages to average mineral grain size and amount of micro-cracks.
4. Contrary to the literature review findings, a change from dry to wet triaxial testing procedure did not reduce the mechanical strength of ballast materials.
5. Micro-Deval values did not correlate well with the amount of material breakdown after triaxial testing without regard to use of fraction 0-22.4 mm or 0-0.125 mm. Hence, in this study, abrasion seemed to be less important or had no effect on ballast degradation regarding resistance to crushing for fine grained rocks.
6. Dry Los Angeles Abrasion$_{31.5\text{-}50mm}$ (LAA) results correlated fairly well with cumulative wet triaxial test breakage (0-22.4 mm). An increase in regression coefficient from 0.83 to 0.97 was obtained when LAA$_{31.5\text{-}50}$ was replaced with LAA$_{10\text{-}14mm}$. This suggests that LAA$_{10\text{-}14mm}$ can be a more suitable test for assessing ballast durability than LAA$_{31.5\text{-}50mm.}$
7. Micro-Deval values correlated well with the ballast's permanent settlement under cyclic triaxial loading. Decreasing micro-Deval values gave reduced permanent settlements. This correlation is probably caused by the rocks' surface roughness (Surface texture Index). No good correlation could be established between permanent deformation and LAA results.

On the basis of full scale model test:

8. The correlation between the full scale model test and LAA$_{31.5\text{-}50mm}$ dry state was poor. Consequently, the LAA test did not predict ballast degradation in a reliable way, assuming that the full scale model test simulated the field condition taking properly into account applied rail track stresses. Replacing LAA$_{31.5\text{-}50mm}$ with LAA$_{10\text{-}14mm}$ had no improving effect.
9. A fair correlation war obtained between the full scale model test and LAA$_{31.5\text{-}50mm}$ wet state.

Comparison of results from the triaxial testing and the full scale testing:

10. The amount of crushed material (0-22.4 mm) from the triaxial test was four to eight times more compared with the corresponding amount of crushed material from the full scale model test.
11. Less compaction in the triaxial test conditioning phase can be an improved approach. Reduced vibration from 30 seconds to 10-15 seconds could probably have been a more proper practice to avoid initial crushing.

ACKNOWLEDGEMENTS

The authors are very grateful for the financial support from the Norwegian National Railway Administration.

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