Determining abrasivity with the LCPC Test

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ABSTRACT: A new approach to rock and soil abrasivity testing is presented focusing on the needs of underground excavation. The abrasivity assessment is based on the LCPC Abrasivity Test which was developed by the Laboratoire Central des Ponts et Chaussées in the 1980ies. The LCPC Abrasivity Coefficient (A_{BR} or LAC) can be used as a measure for both the abrasivity of the material and the influence of the grain size. A calibration chart has been established using different artificial and natural soil materials, containing both rounded and angular grains, different rock materials and especially highly abrasive material such as quartz and non abrasive material such as limestone. This chart allows the classification of different materials using the background of tool wear and drillability problems. Applied in the correct framework of geological and geotechnical investigations, the LCPC test allows a reliable, quick and hence, cost effective assessment of the abrasivity of rock and granular materials.

1 SCOPE

Numerous methods exist for determining abrasivity of hard rock, however very few are established in the field of coarse granular materials of sand and gravel size. This is due to the fact that there is a long tradition of predicting e.g. TBM performance rates and tool wear (Thuro 2002, Plinninger 2002, Thuro & Plinninger 2003). As it is generally agreed, that abrasivity plays a key role in hard rock tunnel boring since it directly influences both the cost and schedules of the project (Büchi et al. 1995). Although this might not apply to the same extent for coarse granular material, such as gravel and sand, soil abrasivity can have a significant impact on the performance of shielded TBMs or large diameter drillholes in soft ground. Also in soft ground, a reliable prognosis of the abrasiveness of the soil material would be of great value for the designer as well as the client and the contractor in order to calculate the tool costs and to minimize underground risk. This paper contributes to the actual discussion of TBM wear prediction in soft ground.

Using the experience in abrasivity testing of rock, the CERCHAR abrasivity test, developed by the Centre d´Études et des Recherches des Charbonages de France (1986) and the LCPC abrasivity test introduced by the Laboratoire Central des Ponts et Chaussées (Normalisation Française P18-579, 1990) were evaluated for rock and soil abrasivity testing. Basic results of a comparison between the both testing procedures are already given in Büchi et al. (1995). Although the-state-of-the-art CERCHAR abrasivity test can be used for testing individual components e.g. of a gravel sample, the procedure is not feasable for small grains or mixed soil samples. Only the LCPC abrasivity test allows the testing of mixtures containing different grain sizes and therefore large and representative soil samples.

The abrasivity testing of rock is controlled by well known parameters (Thuro 2002, Plinninger 2002, Thuro & Plinninger 2003), whereas in soils many factors are influencing the abrasivity such as in-situ soil conditions (inhomogeneity, density, porosity), sedimentary petrology (mineral composition, roundness) and technical properties (uniaxial compressive strength and abrasivity of the individual grains).

To date, there is no ISRM Suggested Method nor national or international standard for rock and soil abrasivity testing. The necessity for a new application-oriented approach has recently been made clear by Nilsen et al. (2006 a, b). Currently the NTNU Trondheim is developing an own method (Nilsen et al. 2006 c) based on the classic NTNU testing suite (Bruland 1998). Up to now, in the NTNU test only the soil fraction of less than 1 mm (in the future possibly 2 mm) can be tested, which reduces its application to sand.

2 THE LCPC TEST

2.1 *General introduction*

The LCPC abrasivity testing device is described in the French Standard P18-579 (1990) (Fig. 1). The “abrasimeter” is built of a 750 W strong motor holding a metal impeller rotating in a cylindrical vessel containing the granular sample. The rectangular impeller is a metal plate of the size 50 × 25 × 5 mm and is made of standardized steel with a Rockwell hardness of B 60-75. The steel impeller has to be exchanged after each test.

After the French standard (Normalisation Française P18-579, 1990) 500 g ±2 g of the air-dried sample of the fraction 4–6,3 mm is poured into the cylindrical container through the funnel tube. The rectangular metal impeller rotates for 5 minutes at a speed of 4,500 rpm in the cylindrical container with the sample material. For abrasivity determination the impeller is weighed both before and after the LCPC Test (Fig. 2, No. 1 against No. 2 – 5). The mass loss of the metal impeller is a measure of the sample abrasivity and therefore a material property. Through this procedure it is clear, that the impeller cannot be used again. Together with the mass loss, the metal impeller is deformed depending on the strength of the grains due to the rotation in the container. The more abrasive the sample, the larger is the deformation and the material loss (Fig. 2).

By comparing the grain distribution curves of the sample before and after the LCPC Test and by determining the fraction below 1.6 mm, conclusions on the breakability or brittleness of the sample material can be drawn.

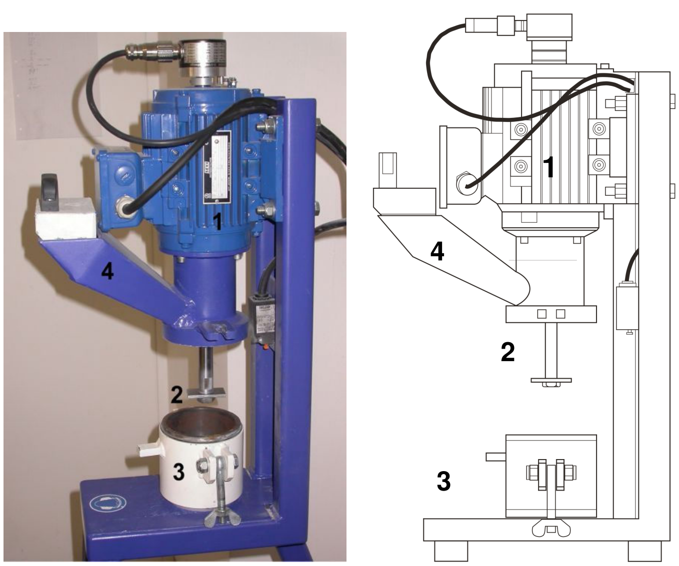

Figure 1. LCPC abrasivity testing device (“abrasimeter”) after (Cerchar, 1986). 1 – motor, 2 – metal impeller, 3 – sample container (∅ 93 mm × 100 mm), 4 – funnel tube.

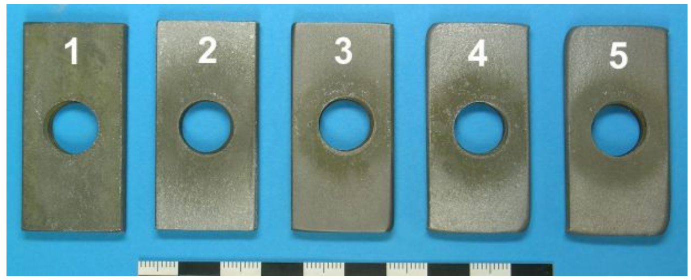

Figure 2. Impeller before and after the LCPC test. 1 – new impeller, 2 – limestone (not abrasive), 3 – quartzitic sandstone (abrasive/very abrasive), 4 – diorite (very abrasive), 5 – vein quartz (extremely abrasive).

2.2 *Sample preparation*

The LCPC testing device is designed for granular materials with a size of 4 – 6.3 mm. Coarser material has to be crushed in advance and the desired fraction has to be obtained by sieving. This is due to the diameter of the sample container and the dimension of the steel impeller. Although consideration has been given to construction of larger containers, the technical complexity would be too high. The vessel diameter for e.g. gravel (63 mm) would be about 1 m and the dimensions of the impeller, which has to be exchanged after each test, rises from 50 × 25 × 5 mm to 50 × 25 × 5 cm. Therefore the test would no longer be cost effective.

The testing of rock material implicates, that the rock specimen has to be broken to a granulate material in a crusher. Subsequently the sample has to be sieved to gain the desired fraction between 4 and 6.3 mm. The fines < 4 mm are excluded from the sample and the fraction 4/6.3 can directly be used for testing. When testing soil or other granular material, some considerations have to be made in order to agree with the technical recommendations and to get the desired abrasivity for tool wear, So far, two procedures have been performed:

– Testing the entire soil sample leads to a representative value for the mixture of all grain sizes.
– Testing of fractions of the soil sample, e.g. 4/8, 8/16, 16/32, 32/64, > 64 mm. Abrasivity values for each fraction can be obtained. The summation of the values according to the grain size distribution lead to an abrasivity value for the entire soil sample.

In the first case, different sub procedures are possible:

– Testing the grain sizes between 4 and 6.3 mm of the soil sample as originally intended by LCPC. The fraction has to be obtained by sieving. The fraction below 4 mm and higher than 6.3 mm is discarded. This leads to low abrasivity values, which do not represent the real abrasivity of the entire soil sample. (Note: NTNU (Bruland 1998) in comparison is only using the fraction below 1 mm.)

– Testing the grain sizes less than 6.3 mm of the sample accordingly. This also leads to low abrasivity values, which do not represent the real abrasivity of the entire soil sample. Note, that originally the LCPC test was not intended to contain fine-grained material less than 4 mm.
– Testing the entire soil sample and crushing the grains larger than 6.3 mm in a crusher. The sample has to be sieved to gain the desired fraction < 6.3 mm. Depending on the scope of the abrasivity determination, the fines < 4mm have to be used for the test or excluded.

No matter which procedure is selected, a grain size distribution analysis has to be carried out before separation and crushing of the sample. If this is not done a geotechnical interpretation of the obtained abrasivity values is not possible. The grain size distribution analysis after the test is needed for the interpretation of the breakability of the material. Changes in grain size distribution can then be clearly visualized. Figure 4 shows a gravel sample before and after processing as well as after the LCPC test.

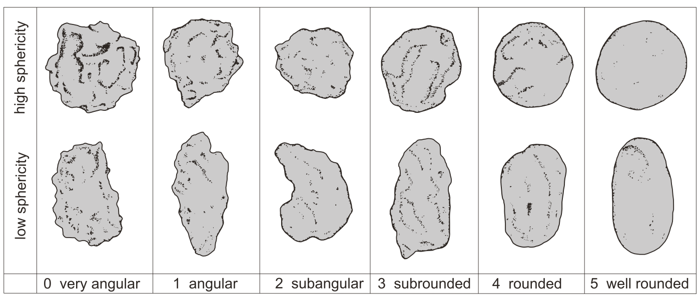

Figure 3: Classification of grain roundness (Pettijohn et al. 1973, Tucker 1981).

Figure 4: Crystalline-rich, sandy gravel before preparation (left picture), before (middle picture) and after (right picture) LCPC test. Scale: 1 black bar equals 1 cm (1 pitch line equals 1 mm).

In addition to the grain size distribution, a mineralogical and petrologic analysis of the components should be performed. The fines below 2 mm can be analyzed by X-ray diffractometer, whereas the larger components can be determined manually and optically. For the fine gravel a microscope has proven to be useful. Also it is necessary to obtain the roundness of the grains before the sieving, crushing and testing (Fig. 3).

It should be mentioned that it is crucial for the interpretation of the obtained data to use a representative sample of the ground containing all grain sizes and rock types. Otherwise the abrasivity values lead to misunderstanding of the processes with respect to tool wear.

2.3 *Testing the entire sample*

Testing the grain fraction below 6.3 mm or the grain fraction between 4 and 6.3 mm means excluding the components above 6.3 mm from the test. In our experience, components larger than 6.3 mm dominate the wear process of cutting tools. Especially the large components as pebbles, blocks and boulders may damage cutter tools or bits shortly after contact. Using the coarse material in the LCPC test has a severe impact on the obtained abrasivity value.

The use of a larger sample container and impeller has been considered. In addition to the already mentioned “oversize” (container ∅ 1 m) for testing gravel up to 63 mm or even larger, no data background and experiences would be available for the interpretation of the results. Each test would be so expensive that from a practical point of view the test would never be applied in a framework of a preliminary investigation program.

In our experience a grain fraction below 4 mm reduces the overall abrasivity of a gravel sample significantly. Therefore the wear process on site is crucial in any decision to discard the fines or not. For example the fine fraction of the soil, especially sand and fine gravel, may have a great impact on tool wear e.g. of a TBM shield. In such cases the grain fraction below 4 mm is very important. Other considerations may lead into the original LCPC procedure, where the fines are rejected to get a maximum or worst-case value for the abrasivity.

When using the entire soil sample, the following procedure has proven to be useful: After sieving the entire sample, the grain fraction above 6.3 mm is crushed by a jaw crusher. The crushing process is repeated for the grains above 6.3 mm until the whole sample has a grain size below that size. After this process the crushed material is mixed with the remaining fraction < 6.3 mm. Now the roundness of the crushed grains represents more or less the former grain size distribution: the larger the former grains, the more angular are the processed grains and the higher is the abrasivity of the processed soil sample. This is, of course, a basic change of the natural soil composition. Finally the test results have to prove if the obtained abrasivity represents the original grain size distribution and therefore come close to the abrasivity of the natural sample.

2.4 *Testing separate grain size fractions*

If the abrasivity of different grain size fractions is to be determined, the time and effort for sample separation and preparation rises significantly. After grain size distribution and petrologic analysis, the sample has to be separated into the desired grain size fractions. A possible way to deal with large gravel samples is to separate into the fractions of 4/16 mm, 16/32 mm, 32/64 mm and > 64 mm. These four samples have to be treated as described above to obtain a grain size below 6.3 mm. In this case, in total four LCPC tests have to be performed.

In the end about 2 – 2.5 kg of soil sample are needed to get 500 g of crushed sample material in the desired 4/6.3 fraction for the LCPC test. In our experience, about 20 kg sample material is necessary to run four to five LCPC tests on different grain size fractions of a gravel material, provided each desired fraction contains enough material (> 2.5 kg).

3 DERIVED PROPERTIES AND THEIR CLASSIFICATION

3.1 *The LCPC Abrasivity Coefficent (LAC)*

The LCPC Abrasivity Coefficent LAC is calculated as the mass loss of the impeller divided by the sample mass (500 g).

$$LAC = (m_0 - m) / M \qquad (1)$$

where: LAC = LCPC Abrasivity Coefficient (g/t); m_0 = mass of the steel impeller before LCPC test (g); m = mass of the steel impeller after LCPC test (g); M = mass of the sample material (= 0.0005 t).

The naming of this coefficient follows international rules, referring the institution (LCPC), the property (abrasivity) and the type of the property (coefficient). The abbreviation LAC stands for <u>L</u>CPC <u>A</u>brasivity <u>C</u>oefficent and is exactly the same value as "A_{BR}" in Büchi et al. (1995) and Normalisation Française P18-579 (1990). E.g. the name of the CERCHAR Abrasivity Index CAI followed the same standard.

The LAC varies between 0 and 2000 g/t for natural rock and soil samples. This range can be divided in five classes. Since there is a close linear correlation between LAC and CAI (Fig. 5), the abrasivity classification of the well-known CERCHAR Abrasivity Index CAI can be used. The coherence between both abrasivity spectrums is crucial for all practical problems. Also, there is a lot of data available where the CERCHAR Abrasivity is connected with tool wear problems. Hence it is highly recommended to use the newly introduced LAC classification given in Table 1, instead of the original LCPC classification given in Büchi et al. (1995). The authors state the linear correlation of LAC and CAI, but unfortunately do not connect the abrasivity scales.

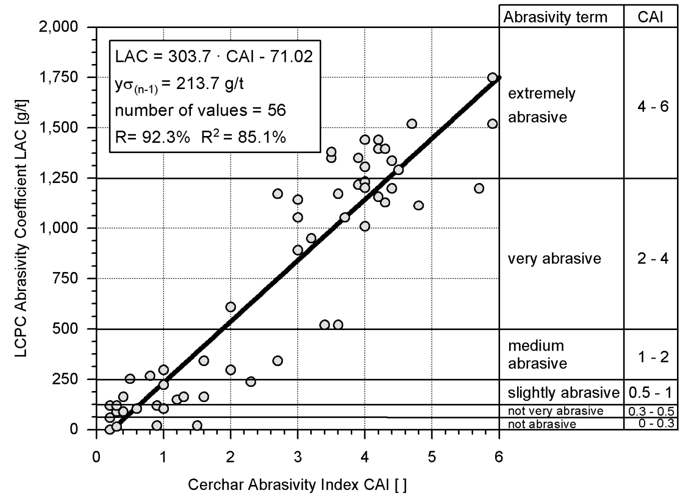

Figure 5: Correlation between CAI and LCPC abrasivity testing results using data in Büchi et al. (1995) and results from this study.

Table 1. Classification of the LCPC abrasivity Coefficient LAC in connection with the CERCHAR Abrasivity Index CAI.

LAC [g/t]	CAI [0.1]	Abrasivity classification	Examples
0-50	0.0-0.3	not abrasive	organic material,
50-100	0.3-0.5	not very abrasive	mudstone, marl
100-250	0.5-1.0	slightly abrasive	slate, limestone
250-500	1.0-2.0	(medium) abrasive	schist, sandstone
500-1250	2.0-4.0	very abrasive	basalt, quartzitic sdst.
1250-2000	4.0-6.0	extremely abrasive	amphibolite, quartzite

3.2 *The LCPC Breakability Coefficient (LBC)*

With the aid of the LCPC abrasivity test, the breakability or brittleness of the sample material can be quantified. The LCPC Breakability Coefficient LBC is defined as the fraction below 1.6 mm of the sample material in the grain size distribution curve (see Figs 9, 11, 12):

$$LBC = 100 \times M_{1,6} / M \qquad (2)$$

where: $M_{1,6}$ = mass fraction < 1.6 mm after LCPC test (g); M = mass of sample material (= 0.0005 t).

As before, the naming of this coefficient follows international rules, referring the institution (LCPC), the property (breakability) and the type of the property (coefficient). The abbreviation LBC stands for <u>L</u>CPC <u>B</u>reakability <u>C</u>oefficent and is exactly the same value as "B_R" in Büchi et al. (1995) and Normalisation Française P18-579 (1990).

The LBC for natural rock and soil samples normally varies between 0 and 100%. This range can be divided in five classes including one above 100% (Tab. 2). Up to now, there is no reason to diverge from the original LCPC classification given in Büchi et al. (1995). The higher the value of the LBC, the easier it is to break the material and the higher is the brittleness.

The breakability or brittleness of a sample material depends mainly on the mineralogical composition of the grains components when testing rock or coarse soil (gravels). This does not apply for fine grained soils such as sands. Since the grain size distribution of the entire soil sample is decisive for the LBC, the grain size distribution curves before the sample preparation (crushing) and after the LCPC test have to be determined and compared. In addition this provides a good basis for discussion of abrasivity and its origin. Evidence for this statement are given later.

Table 2. Classification of the LCPC Breakability Coefficient LBC according to Büchi et al. (1995).

LBC [%]	Breakability classification
0-25	very low
25-50	low
50-75	medium
75-100	high
> 100	very high

4 RESULTS

4.1 *Abrasivity*

In Figures 6, 7 a synopsis of typical testing results is given. The diagrams show the LCPC Abrasivity Coefficient plotted against the medium grain diameter of the original sample at 50% (D_{50}) and 70% mass fraction (D_{70}) resepectively for different soil materials. For this classification diagram, "artificial" single grain sizes of different materials were tested to provide a background for interpretation of the abrasivity of "natural" soil samples. Rounded grains of limestone range quite low in abrasivity (*not abrasive* to *slightly abrasive*). Angular grains of limestone have an increased abrasivity in comparison with rounded grains (up to *medium abrasive*). The abrasivity of rounded quartz grains range up to *very abrasive*, whereas angular quartz gives the highest values in the field of *extremely abrasive*. In summary, there is a close correlation with the former or "original" grain diameter of the artificial samples as well as the natural soil samples, although the processed and hence crushed sample only contains grains up to 6.3 mm! The coherence of these reference samples can be used in the interpretation of the natural grain mixtures or soil samples.

The two different diagrams allow distinction between finer and coarser soil samples. The commonly used medium grain diameter at minus 50% mesh (D_{50}) is used in the diagram of Figure 6. The fine and medium sized gravels are displayed best in this layout. For the coarser natural gravels as well as the fine clays, silts and sands the D_{70} diagram in Figure 7 is most suitable since there is no overlap between sand/fine gravel and coarse gravels (and even larger grains). Future experience and testing will lead to an improved design of this classification diagram. Using the largest grain on the x-axis of the classification diagram did not prove appropriate.

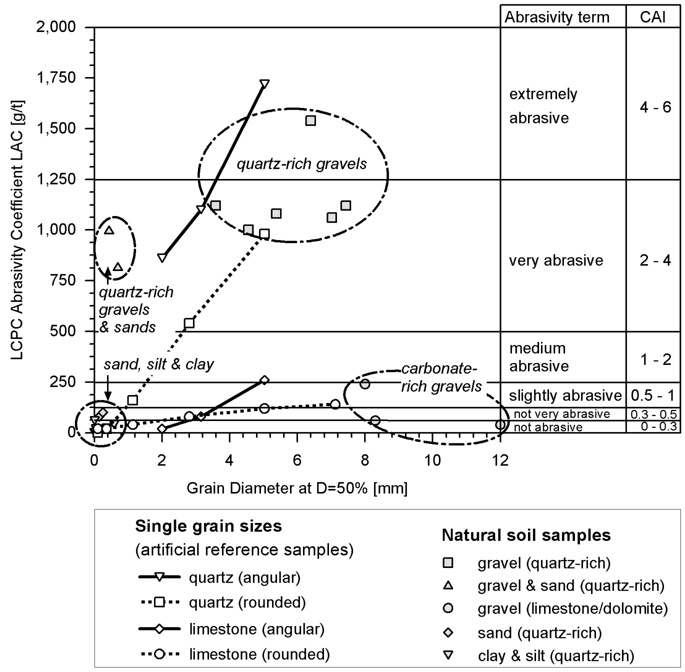

Figure 6. LCPC abrasivity coefficient plotted against the medium grain diameter at 50% mass fraction (D_{50}) for different soil materials.

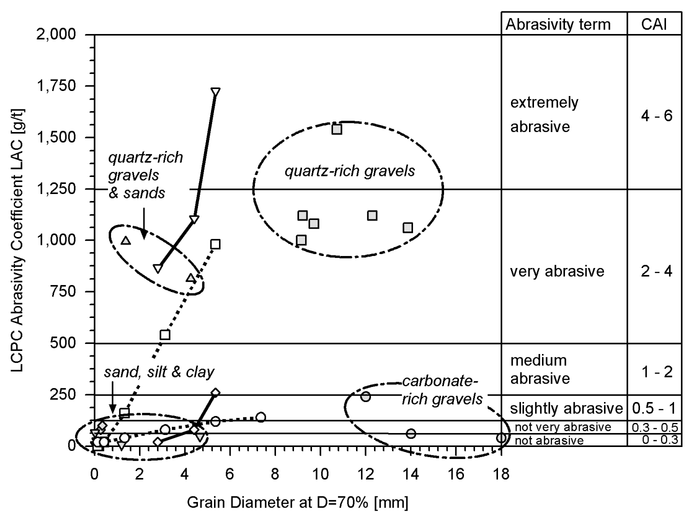

Figure 7. LCPC abrasivity coefficient plotted against the medium grain diameter at 70% mass fraction (D_{70}) for different soil materials.

The following trends can be derived from both diagrams (Figs 6, 7):

– The abrasivity of natural samples consisting of sand, silt and clay altogether is low (classification *not abrasive* to *not very abrasive*) although they might still be quartz-rich. In pure quartz sand abrasivity increases slightly (classification *slightly abrasive*).

- The reference samples of limestone (angular and rounded) range predominantly between *not abrasive* to *slightly abrasive.* There is a significant correlation with grain size.
- The natural river gravels containing limestone and dolomite predominantly range between *not abrasive* to *slightly abrasive.* With increasing crystalline content (containing high amounts of highly abrasive minerals such as quartz, amphibole, garnet, epidot) abrasivity might increase significantly. Figure 8 shows the LCPC Abrasivity Coefficient of a series of river gravels plotted against the content of crystalline or abrasive components (data from (Festl 2006)). The correlation is very good, although the number of tested samples may still not be deemed sufficient and the "crystalline" content, although well known, is not specified here.
- The natural river gravels containing quartz and other abrasive crystalline components, range between *very abrasive* to *extremely abrasive.* There is only a vague correlation with grain size, possibly related to the fact that no differentiation of mineral content is made here. Generally the function in Figure 8 is valid.
- The main correlation with grain size can be seen in the reference samples (plotted single grain sizes). Note that the abrasivity of angular quartz grains is much higher than the abrasivity of rounded quartz grains of the same size.
- The abrasivity of the natural quartz-rich gravels and sands lie between that of pure gravels and pure sands but are still higher than the abrasivity of limestone/dolomite gravels. Abrasivity seems to be related to the small amount of large pebbles in the samples, which are not represented in both diagrams.

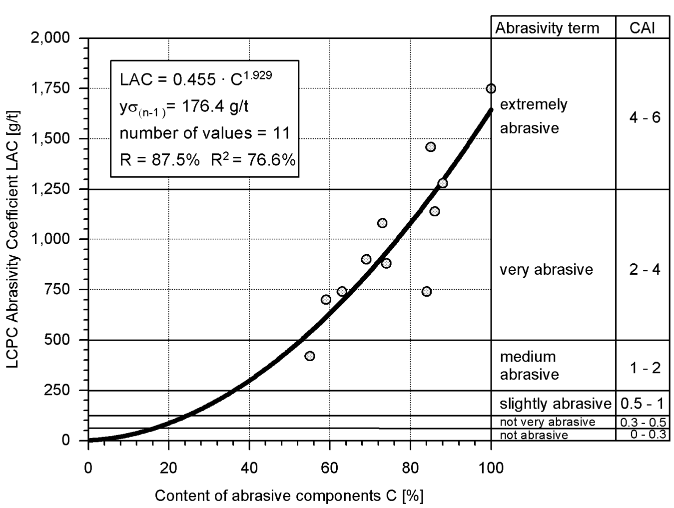

Figure 8. LCPC abrasivity coefficient plotted against the content of abrasive (crystalline) components in the gravel.

4.2 *Breakability*

Figure 9 shows the classical application of the LCPC Breakability Coefficient. Limestone and quartz components were crushed and tested and the grain distribution curves before and after the test plotted in the diagrams. The "higher" the left curve, the more fines are produced by the LCPC testing device and the higher is the breakability or brittleness of the material. This process is also illustrated in Figure 10 where the samples before and after the LCPC test are displayed. The breaking or grinding process is evident by the amount of fines produced, which is higher in the quartz sample.

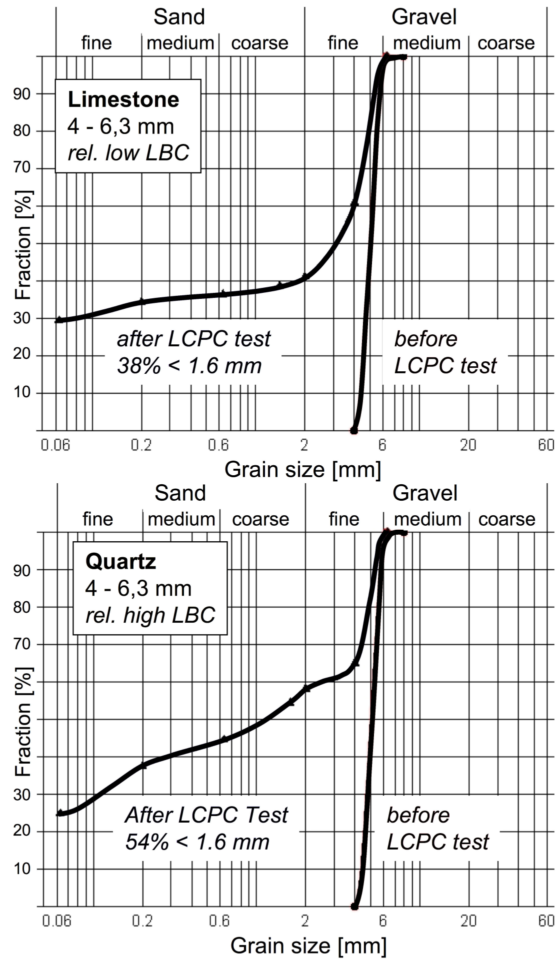

Figure 9. Grain size distribution curve before and after the LCPC test for crushed limestone and quartz components. A distinct difference in the LCPC Breakability Coefficient is visible.

In Figures 11, 12 the breakability or brittleness of two samples are visualized with their grain distribution curve, composition of rock components and their LCPC Abrasivity and Breakability Coefficient LAC/LBC. Both the gravel and the sand have been processed using the entire sample and crushing the grains > 6.3 mm as described above. For the test, the entire material between 0 and 6.3 mm has been used. The line on the right shows the grain size distribution of the original sample whereas the line on the left displays the material after the LCPC test.

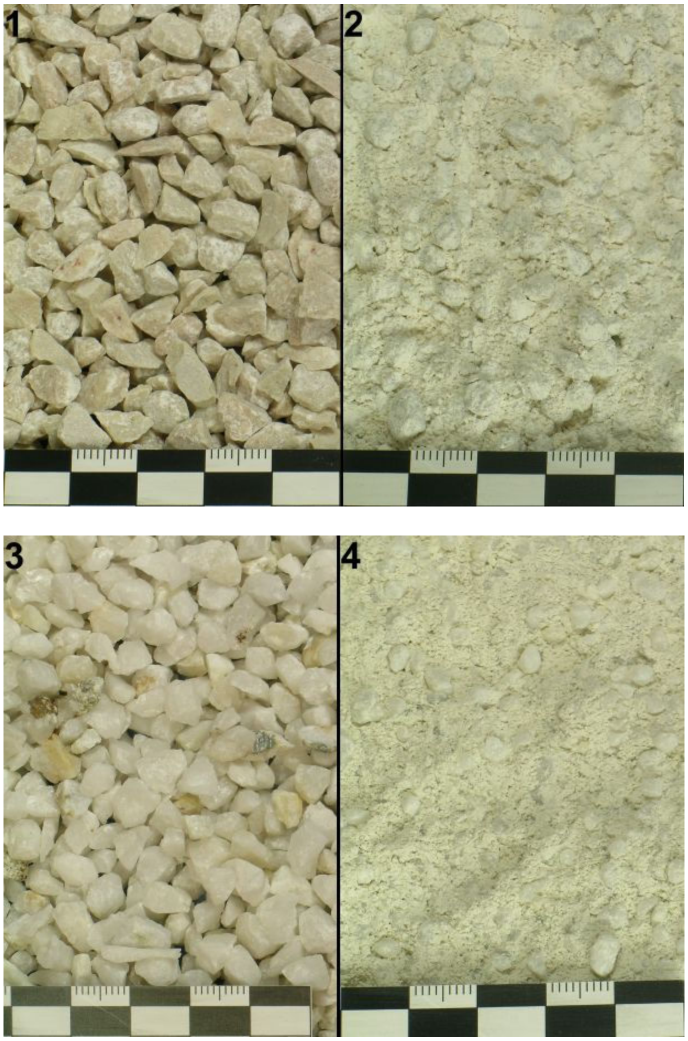

Figure 10. Limestone (1, 2) and Quartz samples (3, 4) before and after the LCPC test illustrating differences in breakability. (1 black bar equals 1 cm).

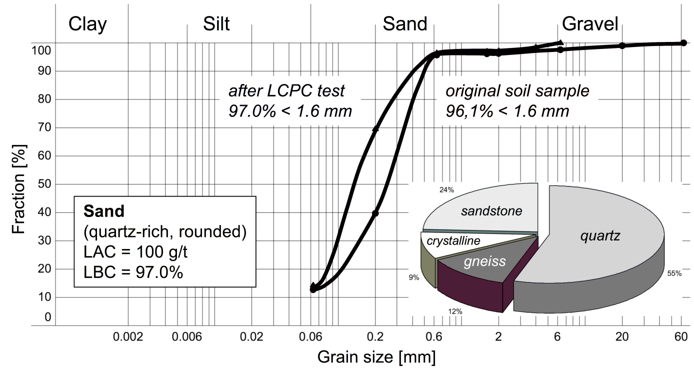

Figure 11. Grain size distribution curve before and after the LCPC test for sand with mainly well rounded quartz and other crystalline grains. The LAC = 100 g/t is classified between *not very abrasive* and *slightly abrasive*.

In Figure 12 the entire graph is shifted more or less to the left resulting in a LBC of 65.3% (classification *medium*).

Due to the lower medium grain size of the original sand sample in Figure 12 this shift is much lower although the LBC of 97% seems to be still *high*. This shows, that in soil samples, the LBC is only meaningful in coarse material such as gravels. Therefore the recording of the grain size distribution curves is extremely important, much more than the value of the LBC itself.

5 CONCLUSIONS

In the preceding paragraphs a procedure for abrasivity assessment using the LCPC testing device has been introduced. For rock material and soil or granular material different procedures have been suggested. Rock specimen simply have to be crushed to a granulate material between 4 and 6.3 mm to be directly tested in the LCPC abrasimeter. A grain size

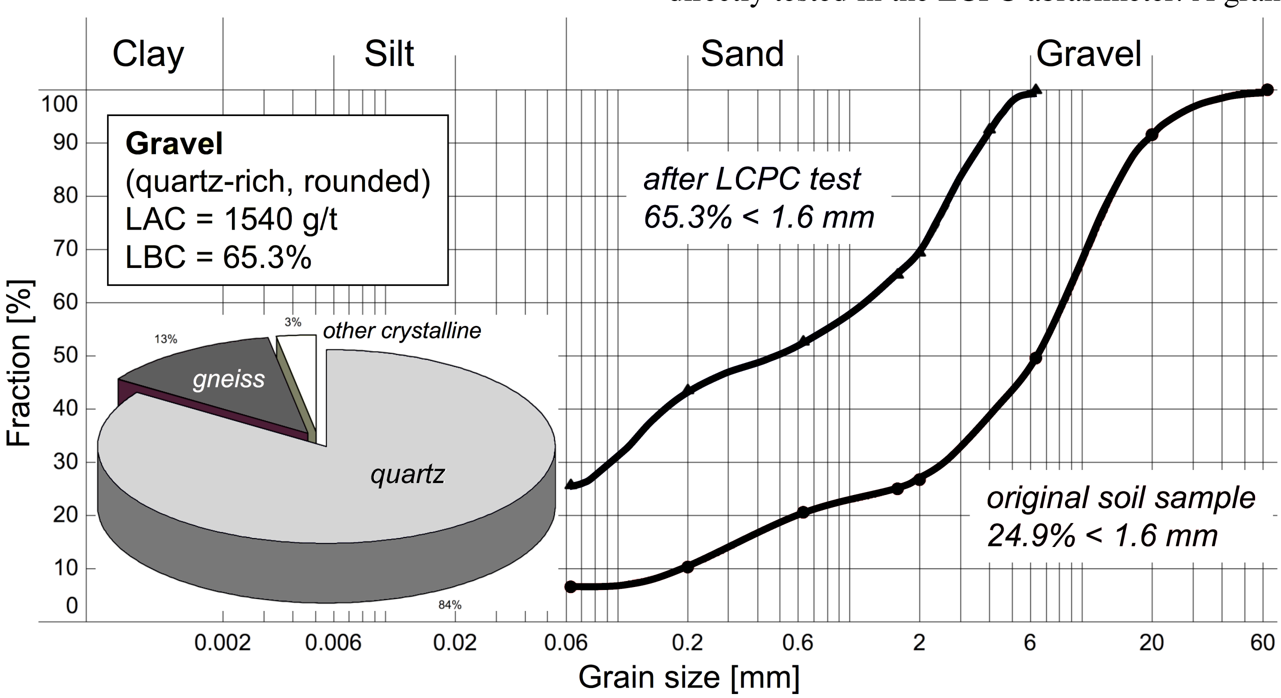

Figure 12. Grain size distribution curve before and after the LCPC test for gravel with mainly well rounded quartz components. The LAC = 1540 g/t is classified as *extremely abrasive*.

distribution analysis after the LCPC test as well as a mineralogical and petrologic analysis of the material should be performed subsequently.

The processing of a soil or granular sample is much more complicated and should be accompanied by a grain size distribution analysis before crushing and after the LCPC test as well as a mineralogical and petrologic analysis of the material. Both background data of artificial samples and a classification system lead to an understanding of the key parameters *petrologic composition* and *grain size*:

– Material composition: quartz-rich and crystalline rock with high amounts of highly abrasive minerals feature high abrasivity, limestone and dolomite low abrasivity.
– Grain size distribution: Abrasivity increases significantly with grain size. Especially large pebbles, blocks and boulders which behave like “hard rock” in combination with cutting tools and are therefore essential for abrasivity.
– Grain roundness: Abrasivity increases with higher angularity. Angular or crushed grains are much more abrasive than well rounded grains.

Nevertheless some geological factors that cannot be determined in the laboratory play a key role in the abrasivity of soils and should be recorded in on site:

– Packing density: Abrasivity increases with density of a sediment or soil.
– Cemented layers: Abrasivity increases significantly in cemented layers. The extent of the effect is dependent on the type of binder mineral for example calcitic cementation (medium, e.g. Quarternary gravels or breccias), silicic cementation (high, e.g. Tertiary sands = quartzites). Tool wear may increase excessively in such lithified soil layers due to their high compressive strength.
– General factors like inhomogeneity (soft versus hard layers or components, matrix versus components), water level and water content or porosity may also play important roles in abrasivity effects.

Summarizing the investigations that have been carried out, the discussed soils can be characterized as follows:

– Quartz- and crystalline-rich gravels show a very high to extremely high abrasivity.
– The content of highly abrasive rock components like quartzitic sandstone, granite, diorite, basalt, gneiss, amphibolite, eclogite, quartz-rich schists etc. is important especially when deposited as large pebbles, blocks or boulders.
– Silt and clay only play an inferior role in considerations concerning abrasivity. Actually they may act as a moderator when present in a matrix embedding larger grains, i.e. the abrasivity of a mixture of clay, silt, sand and gravel has a lower abrasivity than the gravel alone.
– The abrasivity of sand has yet to definitively assessed. Clean sand does not seem to be of high abrasivity even if composed mainly of quartz, especially in contrast to quartz-rich gravels. But when combined with a slight gravel content abrasivity appears to rise significantly.

On the basis of these observations it is clear, that neither laboratory testing nor geological field work and testing alone will allow, abrasivity to be clearly defined using formulae. The entire system of contributing geological parameters and geotechnical properties, its interaction with the ground or in-situ soil and the cutting or dredging tool process must be understood before significant advances in quantifying tool wear problems in soil size materials ca be achieved..

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