Laboratory crushing of rock aggregates

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Abstract: Testing and quality assessment of aggregates should be carried out from products that are crushed with industrial crushing plants. However, aggregate raw materials and larger aggregates, like armourstones, need to be crushed with laboratory crushers prior to testing. Laboratory crushing is not a standardised procedure and this can cause an error in results of mechanical tests of aggregates, which can also lead to false expectations of the quality of rock aggregates. Therefore, it is crucial to know how laboratory crushing affects the mechanical and shape properties of aggregates.

In the present study laboratory crushing was carried out on four rock types in one Swedish and four Finnish laboratories. Flakiness index, grain size distribution, and mechanical properties (resistance to abrasion) of the aggregates were analysed. Run characteristics and crusher settings were monitored from crushers.

The results of this study indicate that standardisation of laboratory crushing is needed in order to minimise uncertainties of mechanical test results, and furthermore, to be able to assess the quality of aggregate resources. The reason for this is that different laboratory crushers produce aggregates with varying shape properties and micro-crack densities. This has a critical impact on the mechanical-physical characteristics of the laboratory-crushed products.

Résumé: Les essais et l'estimation de la qualité des granulats doivent être effectués sur des produits qui ont été concassés dans des installations de concassage industriel. Le matériau brut de granulat et les grands granulats, tels que les pierres d'armure, doivent être toutefois concassés à l'aide de concasseurs de laboratoire avant les essais. Le concassage en laboratoire n'est pas une procédure normalisée et cela peut produire une erreur dans les résultats des essais mécaniques sur des granulats, ce qui peut également conduire à de fausses attentes concernant la qualité des granulats de pierre. C'est pourquoi il est primordial de connaître l'effet du concassage en laboratoire sur les propriétés mécaniques et de forme des granulats.

Dans cette étude, le concassage en laboratoire a été effectué sur quatre types de pierre dans un laboratoire suédois et quatre laboratoires finlandais. L'indice d'aplatissement, la distribution de la taille des graines et les propriétés mécaniques (résistance à l'abrasion) des granulats ont été analysés. Les caractéristiques de marche et les réglages de concassage des concasseurs ont été surveillés.

Les résultats de cette étude montrent que la normalisation des concasseurs de laboratoire est nécessaire pour réduire au minimum les incertitudes des résultats de l'essai mécanique et pour pouvoir estimer de plus la qualité des ressources en granulat. La raison en est que les différents concasseurs de laboratoire produisent des granulats ayant des propriétés de forme et des densités de micro-fissures différentes. Cela joue un effet considérable sur les caractéristiques mécano-physiques des produits concassés en laboratoire.

Keywords: Igneous rock, mechanical properties, metamorphic rock, rock description, strength, testing.

INTRODUCTION

The importance of standardised testing and quality criteria for aggregates has increased. European standards have been implemented by CEN (Comité Européen de Normalisation, European Committee for Standardization). The standards have been developed for production control and products, such as aggregates. The purpose is to set convergent quality criteria for construction materials in order to ensure that construction materials that are tested according to the harmonised standards can be transported and used in all EU countries. However, in order to be able to carry out quality and potential end-use application assessment of aggregate raw materials and larger aggregates, like armourstones (CEN 2002b), aggregates need to be crushed with laboratory crushers prior to testing, even though the EN test standards are intended for testing products. However, laboratory crushers are not standardised, and there are no official or uniform instructions for laboratory crushing. According to new production standards (e.g. CEN 2002a), the aggregate producer needs to assess the nature of the raw material. For evaluation of conformity of aggregate products, the producer shall undertake initial type testing and factory production control. The first step in this is detailed geological mapping of quarries followed by laboratory crushing of rock samples and mechanical testing as part of the initial type testing and quality estimation.

The correlation between mechanical and petrographical properties from various rock types has been studied in numerous investigations using various methods (e.g. Irfan & Dearman 1978; Brattli 1992; Shea & Kronenberg 1993; Tugrul & Zarif 1999; Åkesson et al. 2003; Räisänen 2004a). Because petrographical properties vary significantly, and various properties can have opposite effects on mechanical properties, additional studies are needed. Mechanical tests are the key method when the quality of aggregates is defined. However, petrographical information assists in understanding the mechanical test results and in quality estimation of aggregates. This is essential when bedrock quarrying and crushing are being planned and performed (Räisänen 2004b). This holds true even for laboratory crushing. Heikkilä (1991) states that each rock aggregate has a certain attainable mechanical strength level (e.g. abrasion or fragmentation resistance), but the obtained strength is greatly dependent on the shape properties of aggregate particles.

This paper is about laboratory rock crushing and testing of aggregate raw materials. It is an extension study to Räisänen & Mertamo (2004), in which the tests were done with one rock type in three laboratories. In the present study, we have so far tested six laboratory crushers in five laboratories with four rock types. The study is not completed yet, as we still lack the results from two additional crushers. The aim of these studies is to show the importance of the procedure of non-standardised laboratory crushing in testing raw materials, because EN standards are applied to test products, not raw materials.

MATERIALS AND METHODS

Geological properties are decisive in rock comminution (e.g. Lizotte & Scoble 1994; Briggs & Bearman 1996). Besides crusher and crushing properties, petrographical properties of rock pay an important role what grading and shape properties aggregates gain in crushing procedure. Furthermore, un-representative sampling and poor sample preparation can cause variation and uncertainty in the results of mechanical tests.

Laboratories and crushing

Close-side setting (minimum distance between the crushing plates), length of stroke (distance between the maximum and minimum distances of the crushing surfaces), geometry of crushing camber, and speed are the most important characteristics of compressive crushers (Heikkilä 1991). If the setting is close to the required size of test material, shape properties will improve and micro-cracks are effectively eliminated from the crushed aggregates.

Six jaw crushers were used to crush fragments of rock in order to obtain a 11.2-16 mm fraction for the Nordic abrasion test (A_N-test). The aim was to compare the mechanical and shape properties of aggregates produced with different laboratory crushers. Table 1 shows the characteristics of tested laboratory crushers. The capacity estimation is only a rough estimation, which describes that the crushers are different in size. Capacity is dependant also on mechanical-physical properties of crushed materials, setting, and running condition of crusher.

During the crushing, the particle size of the material is reduced due to compression and shear forces as the material flows through the crushing plates. Crushing was carried out in two or three stages; the last stages were completed by choke feeding the crusher. 0-8 mm aggregates were sieved off before the last crushing stage.

At VTT laboratory (Technical Research Centre of Finland) crushing was performed in three stages (pre, 2nd and 3rd). In primary crushing the close-side setting of crusher was 35 mm wide, and it was adjusted to 15 mm in 2nd and 3rd stages. The surface pattern of jaws is smooth, but the jaws are badly worn. At LEM laboratory the setting was reduced from 15 to 13 mm between stages 1 and 2. At TTY laboratory, the close-side setting was 15-30 mm in first stage and 0-15 mm in the second stage. The jaws are badly worn, especially from middle, which explains 15 mm range (e.g. 15-30 mm) of single setting. At TIEL laboratory, the crushing stages 2 and 3 were performed with separate laboratory crusher than first crushing stage. Crushing jaws are sigmoid in both TIEL crushers, but the jaws are worn. It is notable that the crusher of TTY has the largest length of stroke of final stage crushers. At SKAN laboratory (Skanska Sweden) crushing is performed in three stages, because setting of crusher is clearly wider (25 mm) compared to needed fraction size of Nordic abrasion value (11.2-16).

Table 1. Characteristics of laboratory crushers, primary-crushing with a separate crusher (pre), first crushing stage of two stages (1st), (second crushing stage (2nd), third crushing stage (3rd).

Laboratory	Crusher	Fragment size (cm)	Jaw type	Close-side setting/ length of stroke (mm)	Capasity estimation
VTT	Scanmachine LM 20	15*10*10	Smooth	35/2 (pre) 15/2 (2nd, 3rd)	500 kg/h
LEM	Fritsch Pulverisette 1	0.95	Smooth	15/2 (1st) 13/2 (2nd)	200 kg/h
TTY	KHD Humboldt Wedag MN 931/11	12*12*12	Sigmoid (V-shape)	15-30/10 (1st) 0-15/10 (2nd)	1 000 kg/h
TIEL	KHD Industrieanlagen AG, N.o 9	20*10*10	Sigmoid (V-shape)	35/12 (pre)	1 000 kg/h
TIEL	Retsch BB3	15*10*10	Sigmoid (V-shape)	15/2 (2nd, 3rd)	500 kg/h
SKAN	Svedala Arbrå R2513	20*10*10	Smooth	25/2 (1st, 2nd, 3rd)	900-1200 kg/h

Source of test materials and quality requirements

The Finnish bedrock is composed nearly entirely of Precambrian igneous and metamorphic rocks, which are overlain by Quaternary glacial sediments. Both bedrock and sediments are used as raw materials for aggregates. In northern latitudes, some aggregates have special quality demands due to the climate. Cars use studded tyres during winter to obtain more traction on the icy road surfaces. Therefore, asphalt aggregates need to have good resistance to abrasive wear.

A first criterion for material selection to this study was adequate homogeneity of test materials (compositional and size of rocks). Kytäjä, Pernaja, and Piikkiö aggregates were crushed from railway ballast (32/64). At Taivassalo quarry were selected rocks, which sizes were between 40 and 70 mm. The last selection criterion of rock types was based in their mineralogical, textural, and mechanical properties. The aim was to test laboratory crushers with following material characteristics:

- Aggregate with high resistance to abrasion and fragmentation (Kytäjä volcanic rock)
- Aggregate with high resistance to abrasion and good resistance to fragmentation (Pernaja granite)
- Aggregate with strong preferred orientation and high percentage of mica minerals (Piikkiö migmatiszed mica gneiss)
- Aggregate with poor resistance to abrasion and fragmentation (Taivassalo rapakivi granite)

Table 2 gives mechanical properties of tested aggregates. These measurements were not carried out from same samples as in this study, but they are test results from mechanical tests series of production plants of quarries Kytäjä, Pernaja, Piikkiö, and Taivassalo. Los Angeles value (CEN 1998a) of aggregates from Taivassalo quarry was defined from laboratory-crushed aggregates. Nordic abrasion value of Taivassalo rapakivi granite (19.0) is clearly higher (poorer quality) compared to results of this study (13.3-16.4). This can be explained in that crushing of dimension stone left-over stones is usually done with minimum costs (large crushing ratio with minimum crushing stages). Due to this densities of micro-fractures of produced aggregates are high and shape properties are poor.

Table 2. Mechanical properties of aggregates from aggregates that were crushed with industrial crushing plants. Nordic abrasion resistance value (A_N), Fragmentation resistance (LA=Los Angeles value).

Site	A_N	LA
Kytäjä	5.7-7.2	12
Pernaja	5.5-7.0	15
Piikkiö	13.0-15.4	18
Taivassalo	19.0	32

The Kytäjä intermediary volcanic rock (KYvr)

The Kytäjä quarry is located in southern Finland ca. 50 km north of Helsinki. The bedrock at the quarry belongs to the palaeoproterozoic Svecofennian schist belt. Kytäjä rocks are originally pyroclastic ashes and crystal tuffs. The fine-grained rock is a macroscopically homogenous and it has a faint preferred orientation. The average grain size of the rock is < 0.2 mm, and minerals have complex grain boundaries. Good mechanical properties of Kytäjä volcanic rock are due to the evenly distributed dark minerals, the fine grain size, appropriate modal composition, and lack of micro-cracks.

The Pernaja granite (PEgr)

The Pernaja granite quarry is located in southern Finland in the contact zone of the ca.1900 Ma palaeoproterozoic Svecofennian schist belt and 1650-1540 Ma aged Wyborg rapakivi granite batholith (Vaasjoki 1996). The fine- and even-grained Pernaja granite is Svecofennian, and it has a faint preferred orientation. The average grain size is 0.2-0.5 mm, and grain boundaries are curved. Feldspars are clearly altered to sericite and saussurite. There are only a few intragranular microcracks. Biotite is often altered to chlorite, and these crystals are evenly distributed. The amount of mica minerals is < 5 %.

The Piikkiö mica gneiss migmatite (PImgm)

The Piikkiö quarry is located in southwestern Finland, and it belongs to The Svecofennian schist belt. Rock is medium-grained migmatitized garnet-cordieritte mica gneiss, and it has a strong preferred orientation. The composition of this gneiss in granitic, and the average grain size is 1-2 mm. The grain boundaries are curved to straight. The amount of biotite is ca. 30 %. Analysed samples were homogeneous, and they contained only minor amount of felsic migmatitised veins.

The Taivassalo rapakivi granite (TSrgr)

The Taivassalo dimension stone quarry is located in southwestern Finland, and it belongs to Vehmaa rapakivi granite batholith. The age of Taivassalo rapakivi granite is 1582 ±4 Ma (Lindberg & Bergman 1993). Taivassalo rapakivi granite is coarse-grained, and it has a porphyritic texture. K-feldspar phenocrysts are ≤ 2 cm in length, and the main minerals are K-feldspar, quartz, plagioclase, and biotite. Mineral grain boundaries are straight, and the rock contains micro fractures. Therefore the rock has high average hardness, but it is brittle due to its textural properties. Samples of this study are crushed from left-over stones of dimension stones.

Resistance to wear by abrasion from studded tyres, Nordic abrasion test (CEN 1998b)

The resistance to wear from studded tyres tests, e.g. the Micro Deval test (CEN 1996), measures the ability of aggregate to tolerate abrasive wear. According to Vuorinen (1999), the correlation between these two test methods is 0.87-0.99, depending on the rock type. The mass of test specimen is $(1000*\rho_s)/2.66 \pm 5$ g, where ρ_s = particle density. The test specimen (65 % 11.2/14 mm and 35 % 14/16 mm fractions) is placed in a steel mill with 2 litres of water and 7000 ± 10 g 15 mm steel balls and the mill rotated for 5400 (90 ± 3 rpm) revolutions. The small sample size emphasises the importance of representative sampling. The result of the test is the Nordic abrasion value (A_N); an average of two runs calculated from the equation:

$$A_N = 100(m_i - m_2)/m_i$$

where m_i is the original mass of the test specimen, m_2 is the mass after the test (> 2 mm fraction). Repeatability $(r)=0.13*A_N - 0.17$ and Reproducibility $(R) = 0.14*A_N + 0.27$.

TTY and SKAN laboratories carried out A_N-tests in their laboratories. Other samples were analysed at laboratory of LEM.

Sieving, sample reduction and flakiness index (CEN 1997b)

Samples were reduced according to CEN (1999), and sieved according to CEN (1997a). The flakiness index (FI) is the transmission % of flaky particles in weight % (the shape which particles are broken into during the crushing process). The particle is either flaky or not. Hence, the degree of flakiness is not described. When a bulk sample is reduced into laboratory samples and test specimens, there is a risk that flat shaped particles are segregated. If these particles are separated on the bottom of the sample dish, the FI of the sample might not be representative, and thus, give rise to errors in the mechanical test results. This unreliability was minimised by measuring the flakiness index before sample reduction and from actual laboratory samples or test specimens for the Nordic abrasion test.

The FI was also used as a quality control method for sample preparation. Representativeness and comparability of test specimens was defined by measuring the FI directly after the crushing and by measuring the FI from the A_N-test specimen. One sieve size is 10 mm (CEN 1997b), so the FI from the A_N-test specimen (minimum particle size 11.2 mm) is somewhat lower than if measured after crushing.

RESULTS

Figure 1 shows that A_N-values vary a great deal between various rock types, because each rock has a specific mineralogical, textural, and mechanic-physical combination. Each group of four columns (four rocks) has similar appearance, but their dimensions vary. This reflects the fact that rocks are homogeneous and A_N-tests results are reliable. Furthermore, it suggests that the differences are caused in sample preparation. In this case the sample preparation means laboratory crushing. Flakiness index values are marked in Figure 1B. Samples with highest flakiness index values give usually highest A_N-valued due, because flaky aggregate particles have more surface area compared to more cubical particles to be abraded and flaky particles break also easily to smaller sized particles.

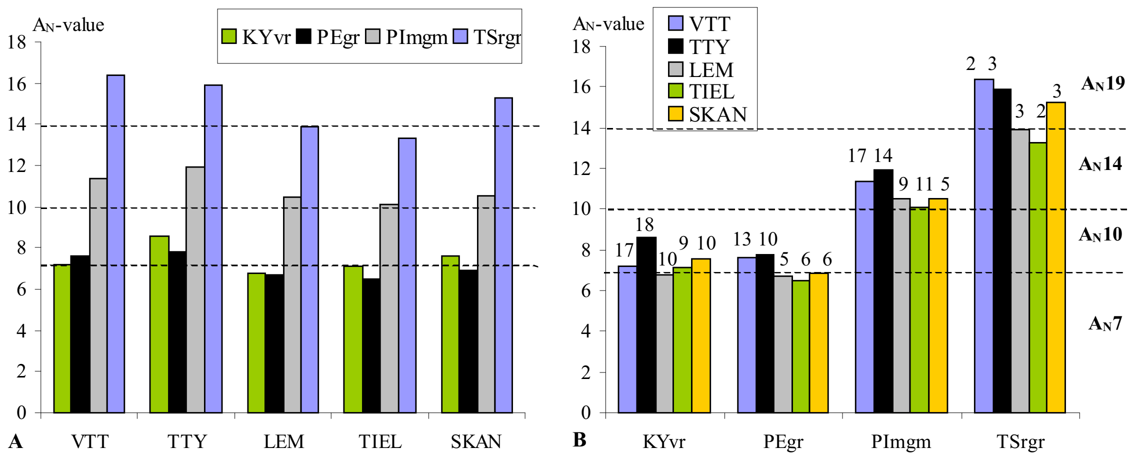

Figure 1A. Abrasion resistance (A_N-value = Nordic abrasion value) measurements of five laboratories. A_N-value categories are marked with dash line (A_N7, A_N10, A_N14 and A_N19). KYvr (Kytäjä volcanic rock), PEgr (Pernaja granite), PImgm (Piikkiö mica gneiss migmatite), TSrgr (Taivassalo rapakivi granite), Laboratories: Technical Research Centre of Finland (VTT), Tampere University of Technology (TTY), Lemminkäinen Ltd. (LEM), Finnish Road Enterprise (TIEL), Skanska Sweden (SKAN). **1B.** Abrasion resistance variations of four rock types. Flakiness index values of tested materials (11.2/16 mm) are given above columns.

Due to the aggregate classifying systems, which is based on classes with specific limits, too high or low quality expectations of aggregates may arise during mapping and testing aggregate raw materials. This may give rise to optimistic expectations of the quality of the aggregates or can lead to abandoning a proposed quarry area. Relative difference percentages between minimum and maximum values were 12.9-26.5 (Table 3). These differences are very high, and show the importance of trustworthy laboratory work and crushing procedure.

Table 3. Statistics of Nordic abrasion values (A_N).

	Min A_N	Max A_N	Relative difference % 100*(Max-Min)/Min	Ave A_N	Std A_N
KYvr	6.8	8.6	26.5	7.5	0.7
PEgr	6.5	7.8	20.0	7.1	0.6
PImgm	10.1	11.4	12.9	10.9.0	0.7
TSrgr	13.3	16.4	23.3	15.0	1.3

The fragment size of the feed has an effect on the reduction ratio. LEM and TTY laboratories carry out crushing in two stages. Therefore, their reduction ratios are higher compared VVT, TIEL, and SKAN laboratories, where crushing is carried out in three stages. Because of this, FI of once-crushed aggregates is generally higher in TTY and LEM laboratories (Figure 2). Aggregates from final stage (labelled with FI2 in figure 2) show that crushers in LEM, TIEL, and SKAN laboratories produce aggregates with lowest FI-values (best shape properties).

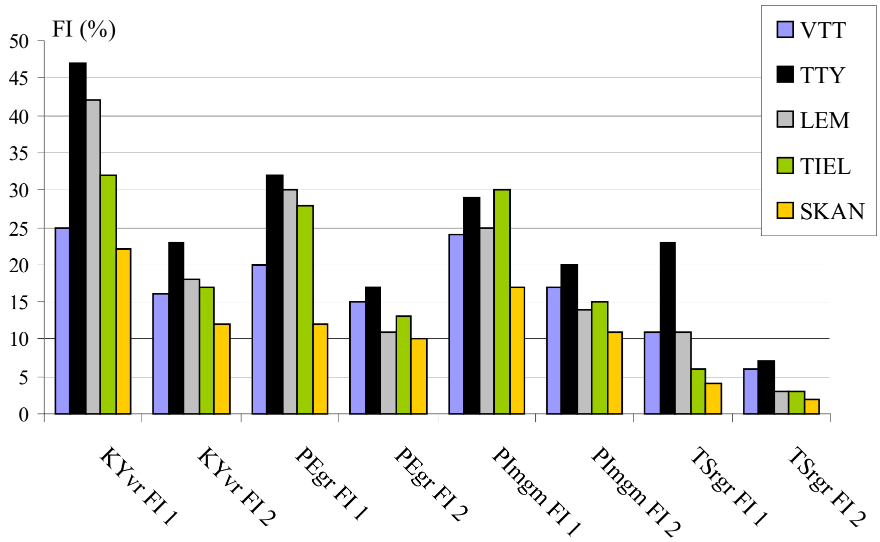

Figure 2. Flakiness indexes (FI) of once (1) and twice (2) crushed aggregates. Note that in VTT, TIEL, and SKAN laboratories rocks are crushed in three stages, and therefore, results of VTT, TIEL, and SKAN are from two-three times crushed aggregates. Symbols are same as in Figure 1.

According to laboratory crushing studies of Erichsen (1992) and Ulvik (1994), best mechanical test results and shape properties are gained from those aggregate fractions, which amounts are most produced in the crushing procedure. Therefore it is vital to adjust the setting of laboratory crushers according to needed test fractions. Nordic abrasion value is determined from 11.2-16 mm fractions. Figures 3 and 4 presents percentages of 10-16 mm fractions for laboratories and rock types. Figure 3 shows that highest amounts of 10-16 mm fractions were gained at TIEL and LEM laboratories, which also had lowest (higher quality) A_N-values. Figures 1 and 2 show that aggregates from LEM and TIEL laboratories had best shape properties (FI). Figure 4 also shows how geological and mechanical-physical properties of crushed aggregates cause variations in percentages of gained 10-16 mm aggregates.

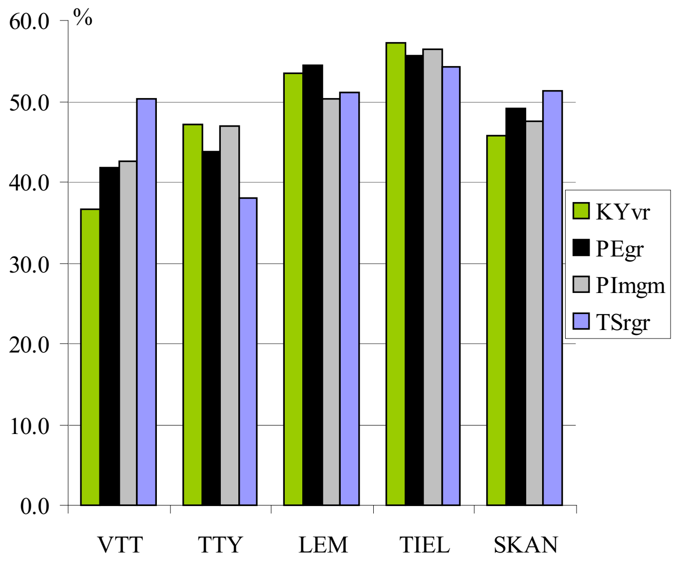

Figure 3. Percentages of 10/16 mm fractions after last crushing stage from five laboratories (measured from sieving results of flakiness index analysis). Symbols are same as in Figure 1.

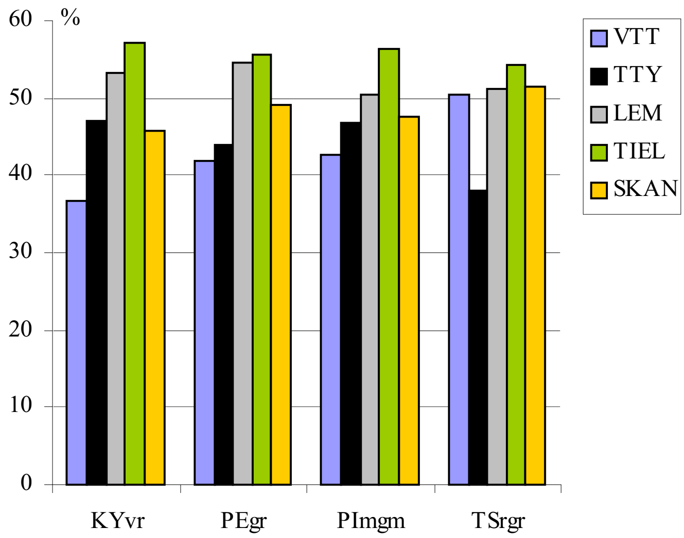

Figure 4. Percentages of 10/16 mm fractions after last crushing stage for each rock type in tested laboratories (measured from sieving results of flakiness index analysis). Symbols are same as in Figure 1.

Grain size distribution histograms show how studied aggregates are broken into smaller sized aggregates (Figure 5). Aggregates that are crushed in VTT and SKAN laboratories contain generally the largest portion of coarser (> 16 mm) aggregates. This may explain partly, why laboratory-crushed aggregates from VTT had poorer mechanical and shape properties compared to the results from LEM and TIEL laboratories. Results from SKAN laboratory are in-between of tested laboratories. Coarser grain size distribution of aggregates crushed at VTT and SKAN laboratories reflects the fact that due to setting/running condition of used crusher aggregate particles are not broken efficiently. This may also explain why SKAN results are slightly higher compared to LEM and TIEL results; even FI of SKAN aggregates were the lowest.

If grain size distribution histograms contain a larger amount of finer sized materials (< 8 mm) this may be partly caused by problems in choke feeding of crushers. According to Briggs and Evertsson (1998), choke feeding causes a multi-point loading stress field on aggregate particles, which results in cracks that are located within the edges of the original particles. As a consequence, the size reduction ratio is not too high and the shape improves. If choke feeding fails partly, aggregates particles are broken between jaws. As a consequence of this double-point loading, the shape of aggregate particles does not improve, and the size distribution of gained aggregates is weighted to smaller sized particles.

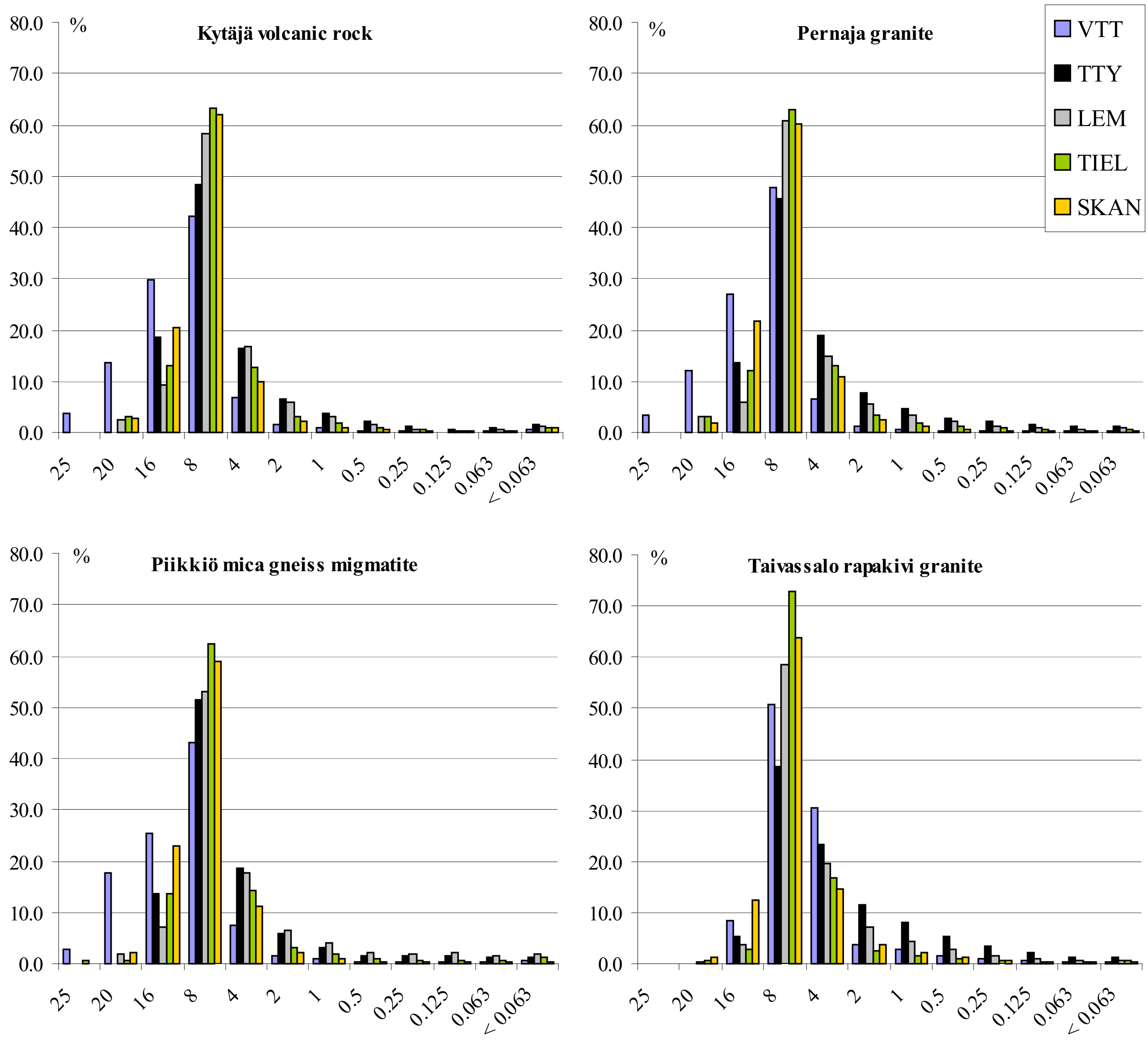

Figure 5. Grain size distribution histograms of four rock types after last crushing stage. Symbols are same as in Figure 1.

Geological properties

Petrographical properties are decisive in comminution of rock aggregates. Fine- and microcrystalline rocks that are composed of hard minerals tend to break into flaky or blade-shaped particles especially, when rocks have a preferred orientation. This is the reason why Kytäjä fine-grained (< 0.2 mm) intermediary volcanic rock gained worse FI-values in this study. However, there are distinctive differences between crushers as well.

Pernaja granite is slightly coarser-grained compared to Kytäjä rock, but its texture is also more massive. Mineral grains of Pernaja granite are more or less cubical, and this explains why Pernaja rock gains better FI-values with all crushers. Migmatized Piikkiö mica gneiss contains > 30 % of flaky biotite, which forms planes of weaknesses trough which Piikkiö gneiss breaks easily creating flat-shaped aggregates. However, laboratory crushers seem to cope quite well with this challenging mica gneiss. In practise, production crushers gain aggregates from Piikkiö quarry that have higher A_N-values, and this is probably caused by poorer FI-values and larger densities of micro fractures that are located in biotite-rich zones.

Medium-gained Taivassalo rapakivi granite contains hard cubically shaped minerals (especially K-feldspar) that have straight grain boundaries. In addition, rock contains micro fractures that usually promote rock to break to particles with even dimensions. Due to these features Taivassalo granite forms cubical particles already after first crushing stage. Rocks tend to break easily through mineral surfaces. Taivassalo granite has low resistance to fragmentation, and therefore, when this granite is crushed, it forms more finer-sized particles that are close to its average (0.5-4 mm) grain size (Figure 5).

DISCUSSION AND CONCLUSIONS

The purpose of laboratory crusher studies is to point out the importance of the procedure of non-standardised laboratory crushing. They show how grading, shape, and mechanical properties of aggregates can vary significantly depending on the laboratory crushing, and especially on geological/mechanical properties of feed material. Therefore, it is essential to make as accurate quality assessments of aggregate raw materials as possible in order to promote usage of aggregates according to principles of sustainable development. Furthermore, results from this study do not define which test results are correct or closest to real production crushers, because these matters depend on material, crusher, and crushing properties. Different types of laboratory crushers have different types of crushing parts, and they are in various running conditions and settings. This study emphasises that the understanding of petrographical properties of rocks helps to understand the behaviour of various materials in crushing and in mechanical tests. This is essential in initial testing and quality assessment of aggregate raw materials. Overall, when the quality of aggregate raw materials is evaluated using tests that are designated only for products, the shape properties of aggregates have to be considered. It is vital that the setting of laboratory crushers is adjustable, and it should be adjusted close to or above of the required particle size of a particular mechanical test.

Future studies and recommendations

In the next stage of this study, more data from other laboratories shall be attached to the current data. Furthermore, correlation analysis between flakiness index and grading is performed. We aim also to study the running state of crushing parts and crushers in more detail by carrying out a separate study with one or two laboratory crushers.

This study is finished during 2006, and after this we suggest that laboratory crusher studies are continued with more rock types, crushers and other test methods. The authors agree with Erichsen (1992) and Ulvik (1994) that it is important to standardize working methods of laboratory crushing. Therefore, we call for standardisation of laboratory crushing in order to minimise uncertainties of mechanical tests of aggregates. However, more studies are still needed before standardization is possible.

When our studies are finished, we shall give some recommendations for standardized laboratory crushing procedure. Its important to discuss research topics and problems before next laboratory crushing studies are started. For example, the following subjects are considered as very important in laboratory crushing:

- Type of crusher, crushing parts and crushing method
- Maintenance of crushers
- Size of feed material and reduction ratio
- Setting of possible pre-crushers
- Length of stroke
- Number of crushing stages
- Setting of final crushing stages depending on the required fractions of certain tests (e.g. geometrical average)
- Running state and geometry of crushing parts and crushing chamber
- Bar sieving samples
- Sieving finer-sized aggregates (e.g. < 4 mm or < 8 mm) off before last crushing stage
- Geological and mechanic-physical characteristics of materials

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