Aggregates in Norway—Properties defining the quality of sand, gravel and hard rock for use as aggregate for building purposes

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Geological knowledge of aggregate deposits is fundamental in order to achieve optimum exploitation of the resources. Two site examples, Gardermoen superficial deposit and Såt hard-rock deposit, are used to demonstrate the importance of geological knowledge. Based on information from the Database for sand, gravel and hard-rock aggregates, established at the Geological Survey of Norway (NGU), general trends for the quality, as defined by several mechanical properties, are documented for different rock types. Combined with geological information, the results show that particularly the grain size of the rock has a significant influence on the product quality.

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Introduction

The Norwegian production of aggregates in 2007 was 66 million tonnes, of which about 13.4 million tonnes, mostly hard-rock aggregates, were exported (Neeb 2008). The domestic consumption has remained more or less stable, while the export has increased by 95% over the last 10 years. The aggregate industry in Norway has received increased attention as an important supplier to countries in northern Europe.

Norway's geology offers a broad variation in the quality of aggregates available for use in the building and construction industry. The quality of the aggregates is determined by different mechanical and physical test methods. The term 'quality' is not precise, but depends on the use of the aggregate. In this text, the terms 'good', 'high' or 'best quality', is used for aggregate suitable for purposes where the requirements are high, for instance in wearing course for roads with high traffic density. Aggregate with poor or low quality can still be used, for instance as filling compound. The demand for high-quality aggregates is principally for use in concrete and for road purposes as pavement. Besides cement, natural sand and gravel are the principal constituents of concrete, while hard-rock aggregates and to a certain extent crushed gravel is used mainly for pavement. For instance, asphalt pavements consist of 90–95% aggregates, whereas the rest is bitumen and filler.

The mechanical and physical properties of the aggregates determine how the material can be utilised. Different mechanical and physical test methods express different properties such as resistance against impact, crushing, wearing or polishing, and geometrical properties such as grading, shape, angularity or flakiness. The experimental mechanical test methods model the breakdown of the material, which occur in practical use. Both the mechanical and physical properties depend on geological parameters such as grain size, grain-size distribution, grain shape, texture, mineralogy and deformation (Brattli 1992, Lundqvist and Göransson 2001).

Geological knowledge

Geological knowledge of the resource is fundamental for all forms of extraction of natural raw material. The Database for sand, gravel and hard-rock aggregates at NGU gives an overview of available resources. The data are useful for both regional and local planning, but detailed geological information is only occasionally available. Two site examples will illustrate the essential need for detailed information obtained by resource mapping of the geology.

Sand and gravel—Gardermoen

One of the largest Quaternary deposits of sand and gravel in Norway, which also is a huge groundwater resource, is located near Gardermoen, north of Oslo (Figure 1).

In 1998, a new main airport for Oslo was opened at Gardermoen. The airport and its infrastructure occupy large areas of land. Consequently, available areas for industry and trade, as well as areas designated for sand and gravel exploitation, have become scarce. However, future development of this area requires access

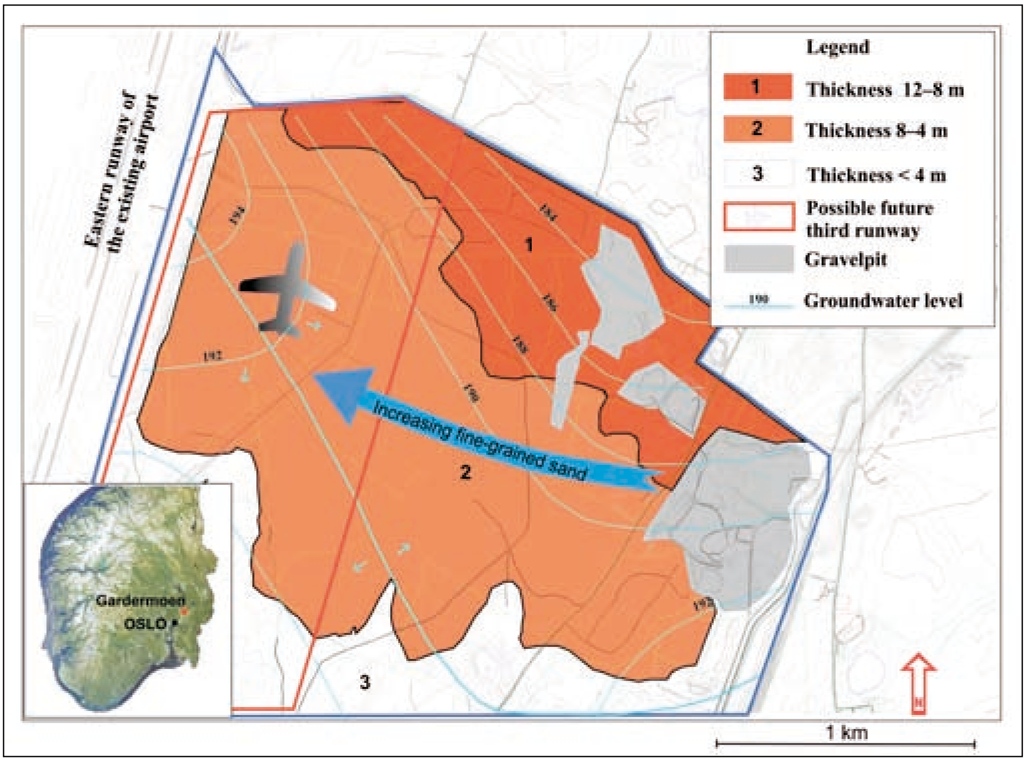

Figure 1. Variation in thickness in the investigated part of the Gardermoen sand and gravel deposit.

to such resources. Hence, there has been and will continue to be a need to optimise land-use planning in the area.

NGU has been involved in planning the future extraction of the most important part of the deposit before, during and after the construction of the airport (Wolden 2002). Fundamental tools in this work have been the existing geological map of the Quaternary deposits of the area (Longva 1987, Østmo and Olsen 1978) and comprehension of the land-forming geological processes in this area. Glaciofluvial processes have transported the sand and gravel in this deposit from its origin in Gudbrandsdalen (Østmo 1977). The deposit consists of 50% Precambrian rocks with the rest being Eocambrian sandstone and quartzite. Usually, these are regarded as strong rocks, which will meet the mechanical standards for use as aggregate in both concrete and asphalt. This assumption has been confirmed by mechanical tests. Investigation of the grain size, rock types and mineral content of the sand and gravel has also been important for identifying potential confines in the use of the material as aggregate.

In addition to quantity, knowledge about the thickness of the deposit is also important to ensure optimum utilisation of the resource. During extraction, it is vital that there is enough material remaining above the groundwater level to maintain filter effects and avoid contamination of the groundwater. Seismic investigations and georadar surveys have been used in order to obtain information about the deposit thickness and the depth to groundwater. These methods provide important information about layers and structures as well as confirming the exact depth to groundwater. They can also be used to estimate the expected average grain size in the layers. Drilling, shaft digging and sampling have supported the interpretation of the geophysical methods. In addition, a grab-dredger for depth penetration has been used to gain visual estimates of both volume and quality of the deposit. The sound picture during drilling, velocity, flush pressure, and knocks are important for the interpretation of the georadar profiles.

The data were collected in small areas and were then extrapolated to estimate the thickness together with the groundwater level of the deposit (Figure 1). Subsequently, this will be utilised in the municipal development plans to ensure that the right quality aggregate is produced for use in the correct areas. For instance, one alternative for a planned third runway is located in an area with fine-grained sand, which is normally only used for filling compound (Figure 1). The thickest part and the best quality of the material are available at the northeastern part of the investigated area of the deposit. This area has therefore been earmarked for future aggregate production.

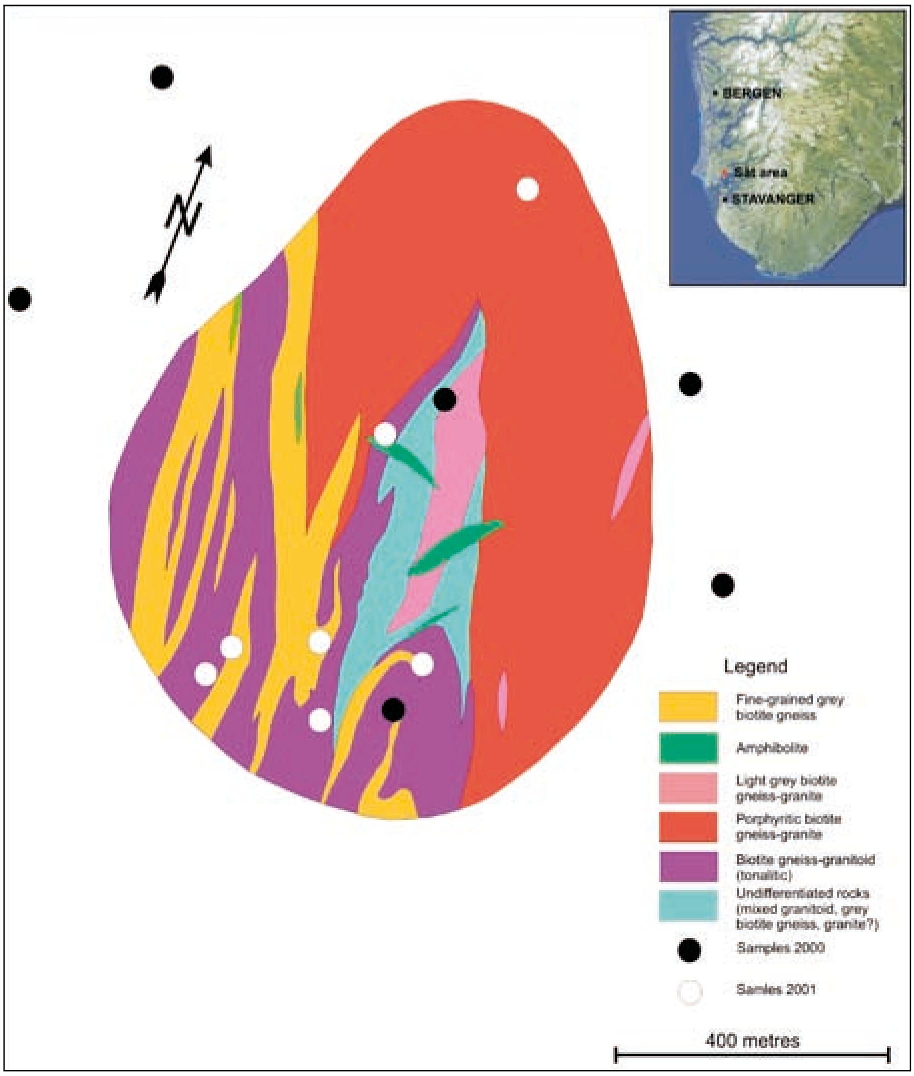

Figure 2. Geological map covering the potential extraction area of Såt (Marker and Erichsen 2002).

Hard-rock aggregate—Såt

The Såt site is located in Tysvær municipality, Rogaland county, in southwest Norway (Figure 2). The operator of a nearby existing quarry, where most of the production is exported, wanted to increase the reserves by establishing a new extraction area for hard-rock aggregates. The area was preliminary examined by sampling of material for mechanical testing in 2000 (Holm 2000). The samples were collected without any detailed references to the bedrock geology other than a regional geological map in 1:250,000 scale. Among various mechanical test methods indicating rock properties, the Los Angeles value was considered to be most relevant for potential export of the aggregates. Many samples showed Los Angeles values greater than 20 (Figure 3), which the operator believed was too high for exporting high-quality material to the European market.

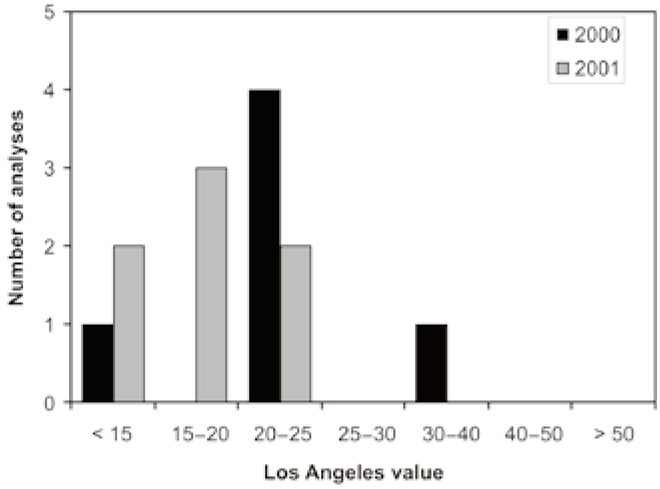

Figure 3. Variation in the Los Angeles value for samples collected in 2000 and 2001 from the potential extraction area of Såt (Marker and Erichsen 2002).

Despite the negative results, the operator still considered the area to be of interest and wanted to map the area geologically in detail before any final decision was made. The mapping (Marker and Erichsen 2002) showed that the Såt area is much more complex than previously imagined (Figure 2). Formerly, porphyritic biotite gneiss-granite was known to form the north-eastern half of the prospect. In addition to this, the new investigation indicated that the southwestern half consists of veined, fine-grained grey gneisses, which are intruded by porphyritic to even-grained, grey biotite granitoid gneisses. The two rock types occur in roughly even proportions. The different types of biotite gneiss-granites and gneiss-granitoids are generally well foliated to mylonitic, which give a textural variation in addition to a compositional variation. Based on the new geological information, further mechanical sampling was carried out in 2001, however, this time with more promising results (Figure 3).

The Los Angeles values for the porphyritic biotite gneiss-granite are on average similar to those for the Espevik gneiss-

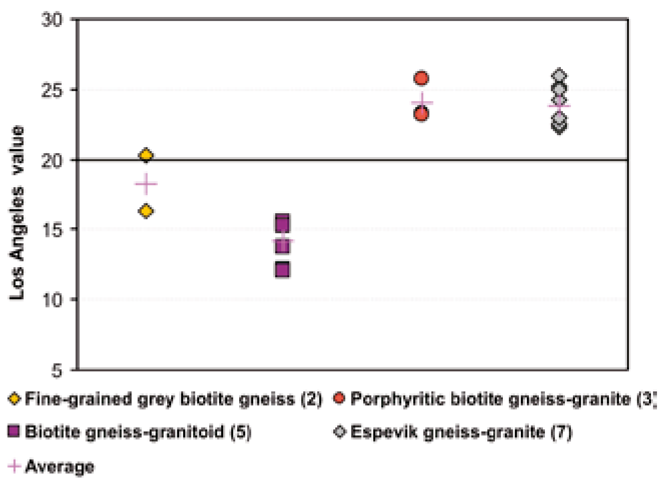

Figure 4. Variation in the Los Angeles value for different rock types (Marker and Erichsen 2002).

granite (Figure 4), where the existing quarry is located. The rock types within the southwestern half of the prospect, mainly fine-grained grey gneisses and grey biotite gneiss-granitoids, show much better results for the Los Angeles test. The conclusion from the new sampling and mechanical testing based on the geological map was that the rocks in the Såt prospect are a significant resource, which satisfied the requirements for the producer.

Mechanical properties

Various test methods are used to determine the mechanical quality of aggregate in Norway. The Norwegian impact test (Statens vegvesen 1997a, kapittel 14.451), the Los Angeles test (Norwegian Standard, NS–EN 1097–2) and the Nordic abrasion test (Norwegian Standard, NS–EN 1097–9), measure how much fines are produced, the Norwegian abrasion test (Statens vegvesen 1997b, kapittel 14.454) measures the resistance against wearing, while the polishing test (Norwegian Standard, NS–EN 1097–8) measures the polishing. Except for the polishing test, the quality improves when the value of the test result decreases.

Hard-rock aggregates and sand/gravel are used separately or in a mixture depending on their different properties, especially due to mechanical homogeneity and shape, which can be favourable for specific applications. Different aspects for the two types of raw material define the quality of the material where the geological genetic history and other geological parameters play an important role. They are therefore discussed separately.

Sand and gravel

The quality of sand and gravel varies both within and between deposits. The distinguishable difference that separates sand and gravel from hard rock is mainly the heterogeneity of the material. Especially gravel may contain several types of rock, both weak and strong. The sand and gravel deposits commonly mirror the bedrock. Areas containing weak rocks usually result in deposits that have weak material strength.

In the middle part of Norway, weak Cambro–Silurian rocks like phyllite, schist, greywacke and greenstone are abundant. In the western part of Norway, the bedrock typically consists of stronger Precambrian gneisses of variable composition. Analyses from the Database for sand, gravel and hard-rock aggregates at NGU show that the average value for the Norwegian impact test, the Nordic abrasion test and Los Angeles test is better (lower number) in the western part of Norway than in the middle part (Table 1).

The transport distance and how much the material is processed by water will also influence the material quality. In general, alluvial deposits (Table 2) have better mechanical and abrasive properties than glaciofluvial deposits (Table 1) and tills. Water has washed and worn weaker particles of alluvial deposits, and the grains obtain a rounder shape.

Table 1. Analyses of glaciofluvial deposits. Average values.

Glaciofluvial deposits	Norwegian impact value (n)	Nordic abrasion value (n)	Los Angeles value (n)
Mid-Norway	50.5 (77)	19.0 (29)	28.8 (12)
Western Norway	46.2 (123)	13.5 (27)	26.0 (22)

n = number of analyses

Table 2. Analyses of alluvial deposits. Average values.

Alluvial deposits	Norwegian impact value (n)	Nordic abrasion value (n)	Los Angeles value (n)
Mid-Norway	46.9 (8)	15.1 (3)	24.3 (2)
Western Norway	45.4 (10)	– (0)	30.3 (2)

n = number of analyses

Glaciofluvial deposits may have very short transport distances so angular and flaky grains normally will dominate the material. Then, if the source material is weak, there is a large possibility that the resulting superficial deposits may not exhibit good quality.

Hard-rock aggregates

NGU's Database for hard-rock aggregates contains information from nearly 1500 sites in Norway and cover a wide spectrum of rock types that are assumed to be suitable as aggregate for building proposes. Most of them have been sampled and analysed for mechanical and physical properties (Table 3). Lithological identification is based on a simplified thin-section analysis (Norwegian Standard, NS–EN 932–3). The information from the database is used to evaluate the quality properties for the rocks given by different mechanical test methods. The standard methods for testing mechanical properties used in Norway concerning requirements today are the Los Angeles test, the Nordic abrasion test and the polishing test. Earlier, there were requirements also to the Norwegian impact test and the Norwegian abrasion test. For the existing standard test methods, analyses from the database show a wide variation both within and between the different rock types (Figures 5a–c).

Strength tests

The strength of the aggregate can be measured by different test methods. Until recently, the Norwegian impact test was the standard test for measuring brittleness. This method is replaced by the Los Angeles test, which is the new European Standard test method for determination of resistance to fragmentation. NGU's data verify a satisfying correlation between the two methods (Figure 6a). The Norwegian impact value is defined as the amount of fines (< 8 mm) produced, while the Los Angeles value is measured with a 1.6 mm sieve. By instead using a 2 mm sieve for the Norwegian impact test (Norwegian impact value < 2 mm), the correlation coefficient increases from 0.90 to 0.96 (Figure 6b).

The different types of rock classified in Table 3 show a wide range in mechanical quality for both of the two mechanical strength tests (Figures 7a, b). The variation is large and overlapping between the main types of rock. On average, extrusive/hypabyssal rocks show the lowest values, i.e., best quality, followed by sedimentary, plutonic and metamorphic rocks. So far, it can be documented that grain size is the factor that has the largest influence on the strength of the rocks. Both the extrusive/hypabyssal and the sedimentary rocks are characterised by fine to medium grain size compared to the two other types (Figure 8). For the plutonic rocks, the effect of grain size on mechanical strength is obvious (Figures 9a, b), increasing grain size leading to increasing Norwegian impact value and Los

Table 3. Rock types analysed for mechanical and physical properties. For each type the number of samples is given in parentheses. Data from NGU's Database for hard-rock aggregates. Nomenclature according to Norwegian Standard, NS–EN 932–3.

Igneous		Sedimentary		Metamorphic
Plutonic	*Extrusive/Hypabyssal*	*Clastic*	*Chemical and biogenic*	Amphibolite (43)
Anorthosite (55)	Basalt (35)	Arkose (22)	Dolomite (1)	Banded gneiss (12)
Charnockite (3)	Greenstone (56)	Breccia (2)	Limestone (18)	Eclogite (30)
Diorite (21)	Rhyolite (50)	Greywacke (33)		Mica-gneiss (27)
Gabbro (282)	Tuff (1)	Conglomerate (9)		Gneiss (255)
Granite (140)	Diabase (11)	Sandstone (55)		Granitic gneiss (174)
Granodiorite (46)	Porphyry (19)			Hornfels (43)
Hyperite (7)	Rhomb porphyry (32)			Quartzite (48)
Larvikite (16)				Marble (9)
Mangerite (9)				Mylonite (64)
Monzonite (13)				Augen gneiss (29)
Norite (19)				
Pyroxenite (3)				
Syenite (24)				
Trondhjemite (76)				

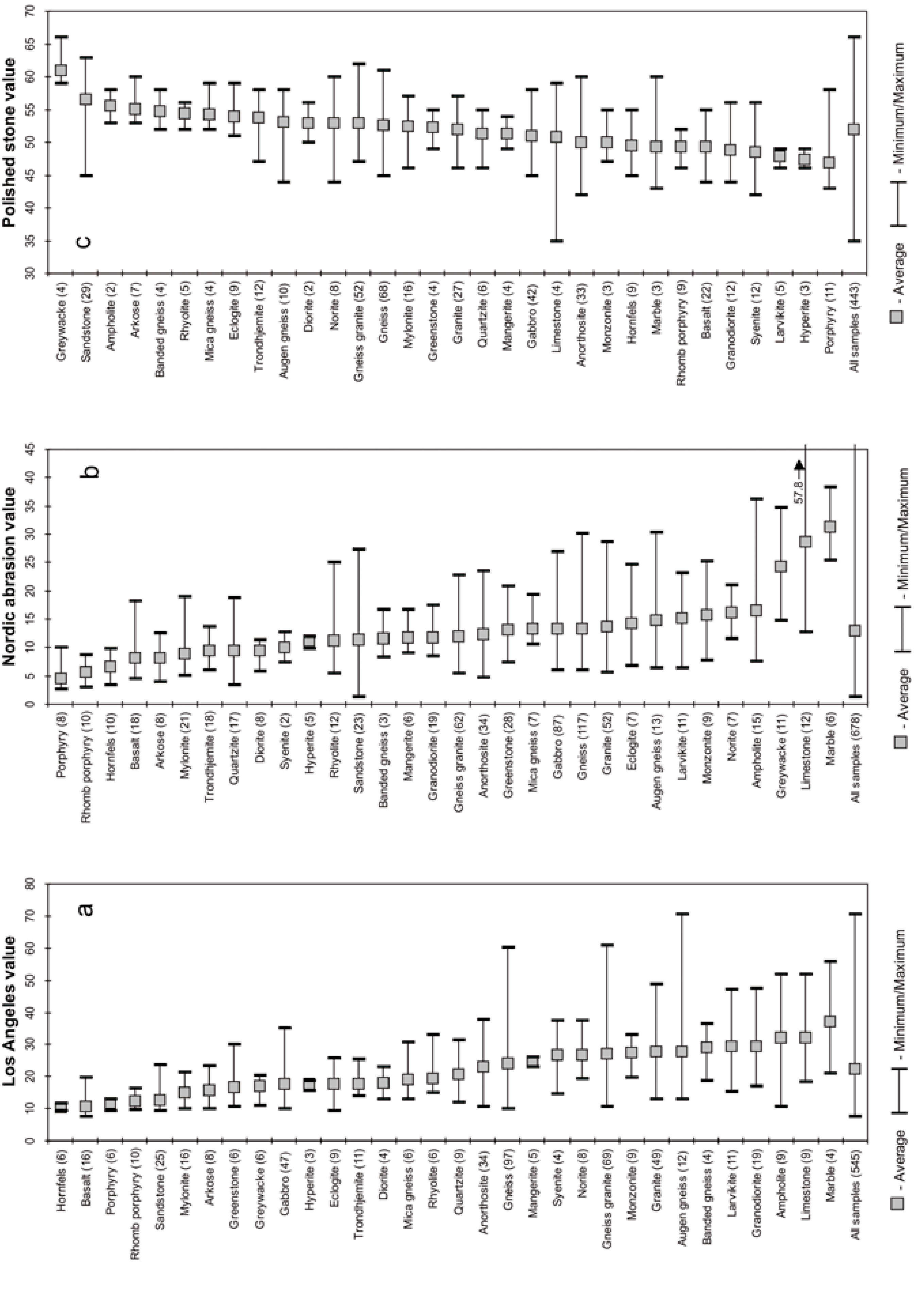

Figure 5. Variation in (a) the Los Angeles value, (b) the Nordic abrasion value, and (c) the polished stone value for different rocks. Number of analyses in parentheses.

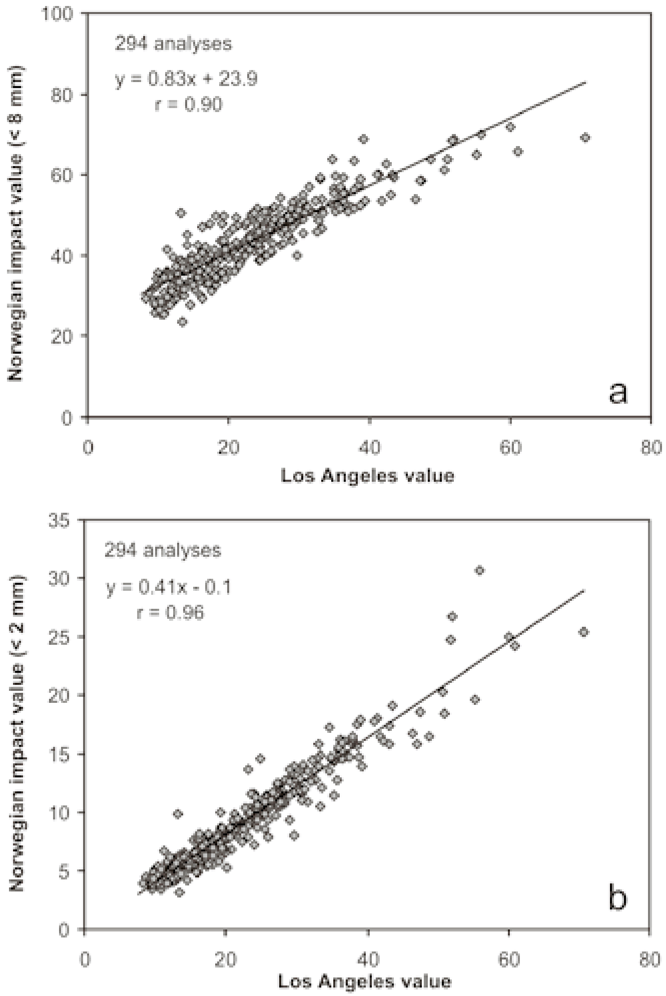

Figure 6. Los Angeles values versus Norwegian impact value (a) < 8 mm, (b) < 2 mm. Analyses from NGU's Database for hard-rock aggregates.

Angeles value. For Norwegian basic igneous rocks, the same effect has been documented earlier (Brattli 1992).

Wearing tests

The Norwegian abrasion test was replaced by a new Nordic abrasion test, in accordance with the European Standardisation program for test methods. The methods are supposed to model the wearing due to the use of studded tires. Because the variation in the test results increases with higher values for the two parameters, the correlation between the test methods is not so obvious (Figure 10). Compared to the strength tests (Figures 6a, b), the two different wearing tests can therefore not reflect the actual same mechanical property.

The overlap between the main rock types is obvious also for the wearing tests (Figures 7c, d). For the Nordic abrasion test, extrusive/hypabyssal rocks give the lowest average values, similar to both the strength tests. The dominantly fine to medium grain size of extrusive/hypabyssal rocks (Figure 8) may be one reason for this observation. Despite the dominantly fine to medium grain size for the sedimentary rocks, they show the opposite to extrusive/hypabyssal rocks, on average the highest values for both the tests, i.e., poorest quality (Figures 7c, d). Sedimentary rocks usually contain hard minerals like quartz and feldspar, but usually they also contain soft minerals like chlorite, mica and calcite. These minerals are known to be little resistant against wearing.

For plutonic rocks, the Nordic abrasion value gradually achieves lower values (i.e., better quality) with decreasing grain size (Figure 9c), similar to the strength tests (Figures 9a, b). Alteration effects, changing the mineral content of the rock, can also influence the abrasion value. Primary gabbro seems to have lower abrasion value than metagabbro (Figure 11). For the Norwegian abrasion value, some rocks (norite, diabase) show a strong positive trend with increasing pyroxene content, while for other rocks (eclogite) amphibole has a weak negative effect (Figure 12).

Polishing test

Sedimentary rocks have on average the highest polished stone value (PSV), i.e., best quality (Figure 7e), but the variation within each main rock type is large and overlapping between the different types. In connection to quality, the polishing effect seems to have an inverse correlation to the Nordic abrasion value. For sandstones, this relation is especially distinct (Figure 13). The same inverse relation has earlier been documented for arenaceous rocks (Hawkes and Hosking 1972). The polished stone value becomes higher for Devonian sandstones (Figure 14) when the amount of hard minerals (quartz, feldspar and epidote) decreases at the expense of increasing amount of soft minerals (chlorite, mica and calcite). Mohs' hardness scale is used to weight and calculate the amount of hard and soft minerals. For Devonian sandstones, it seems that the polishing test expresses the roughness of the surface of the test material. A good mixture between hard and soft minerals gives a rough surface, which reduces polishing.

Conclusions

Generally, it is difficult to obtain any precise accordance between mechanical properties and geological parameters. The rough estimate of the geological parameters, which has been used for NGU's data, can be one reason for this, but also great variation in the mechanical properties has influence. Often, the variation in mechanical properties is greater within a specific rock type than between different rock types. Due to this variation it is often just possible to gain rough trends and precise statistical conclusions cannot be drawn.

For sand and gravel deposits, both the bedrock source and the genetic history of the deposit critically influence the quality as aggregate. In general, alluvial deposits show better mechanical quality than glaciofluvial deposits.

Extrusive and hypabyssal rocks show best quality with regard to both strength and wearing. So far, grain size seems to be the most provable geological parameter influencing the quality of the aggregate. A rule of thumb is that the quality improves with decreasing grain size.

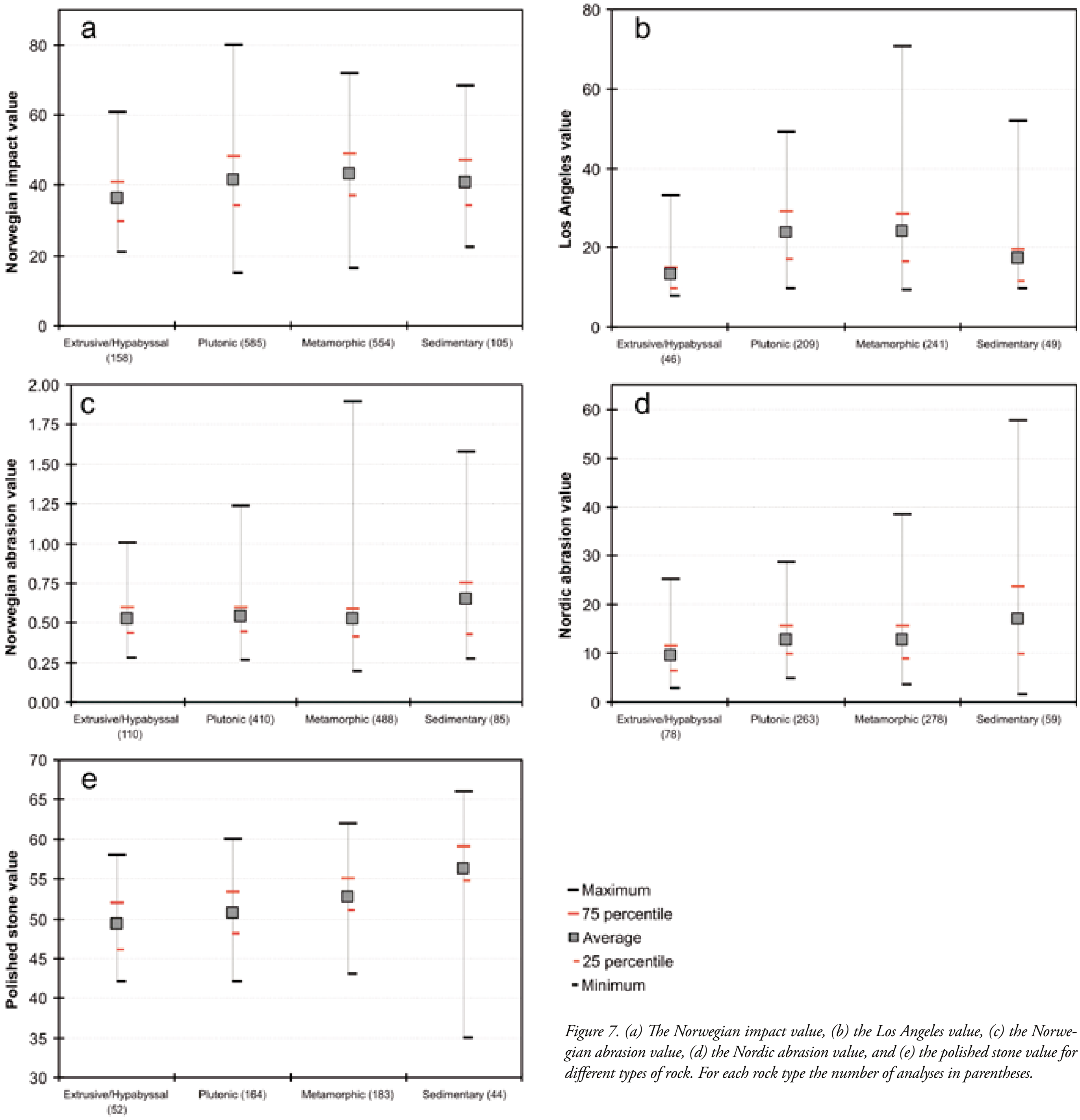

Figure 7. (a) The Norwegian impact value, (b) the Los Angeles value, (c) the Norwegian abrasion value, (d) the Nordic abrasion value, and (e) the polished stone value for different types of rock. For each rock type the number of analyses in parentheses.

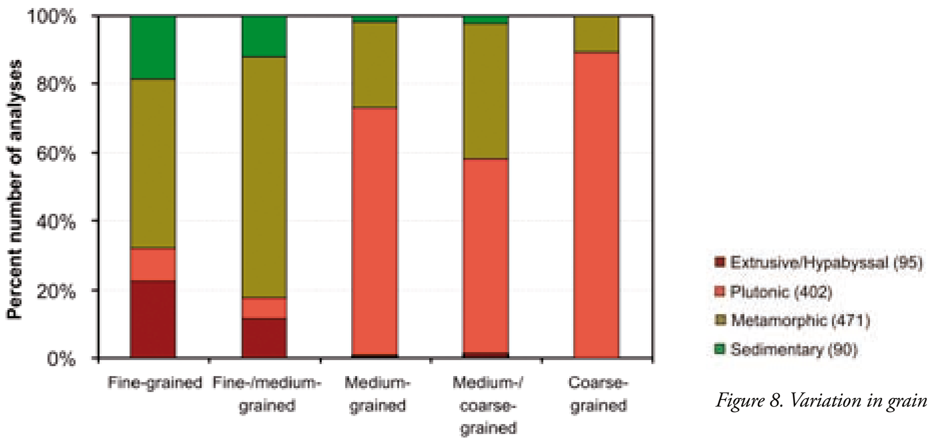

Figure 8. Variation in grain size for different types of rock.

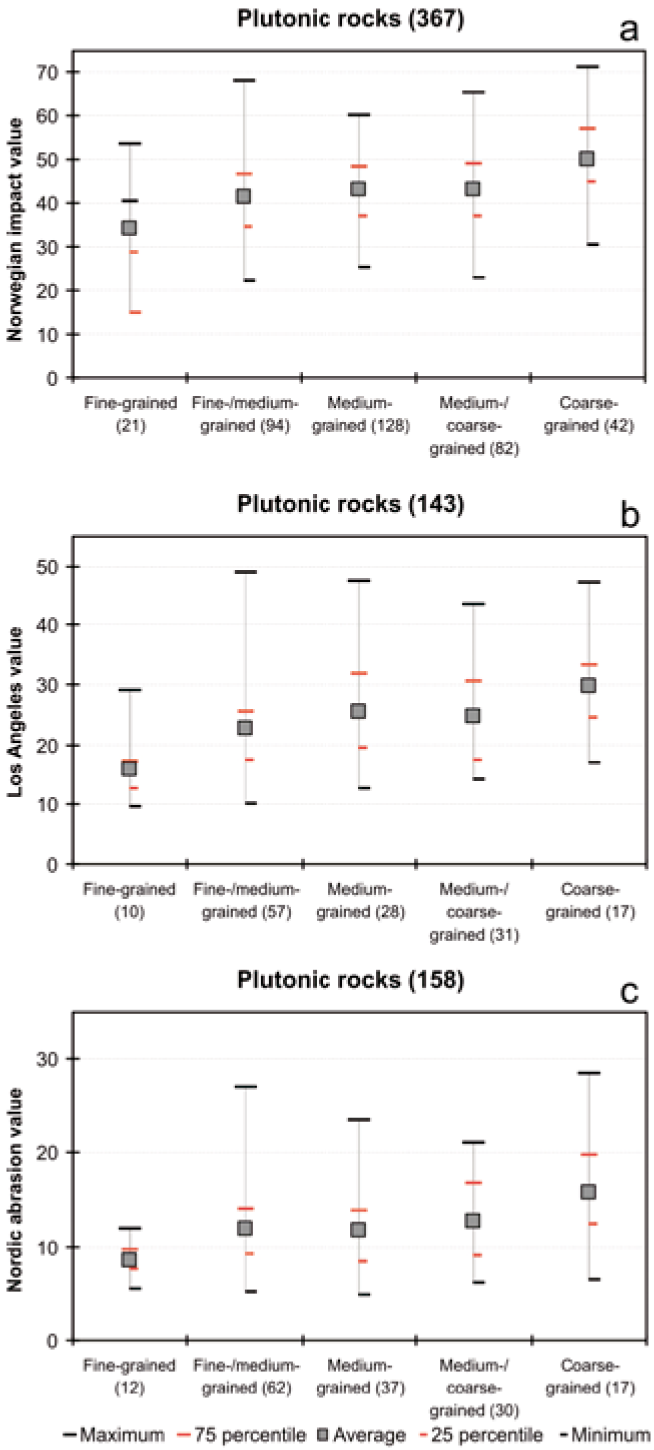

Figure 9. Variation in (a) the Norwegian impact value, (b) the Los Angeles value, and (c) the Nordic abrasion value with grain size for plutonic rocks. Number of analyses in parentheses.

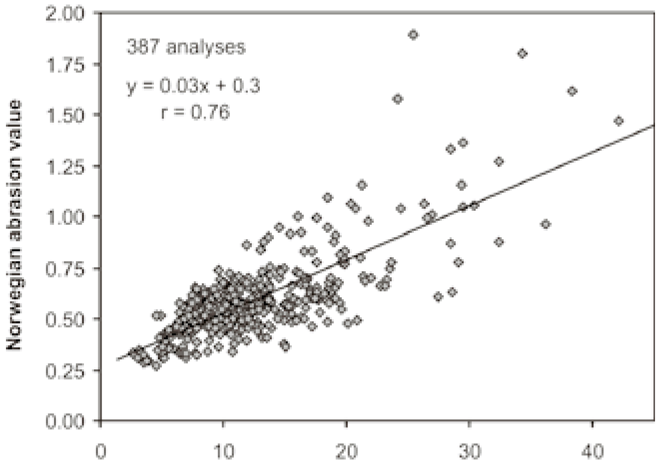

Figure 10. Nordic abrasion value vs. Norwegian abrasion value. Analyses from NGU's Database for hard-rock aggregates.

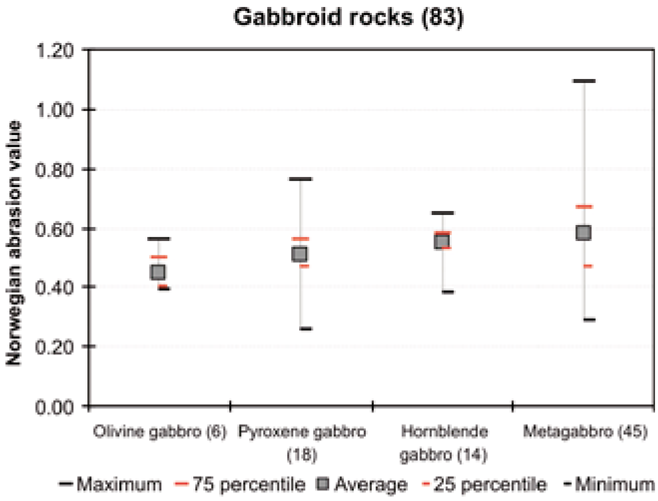

Figure 11. Effect of alteration on the Norwegian abrasion value for gabbroid rocks. Number of analyses in parentheses.

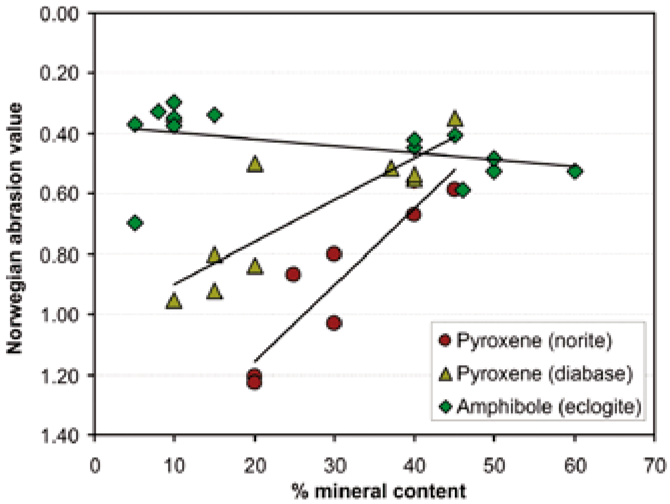

Figure 12. Variation in the Norwegian abrasion value depending on the mineral content for different rock types.

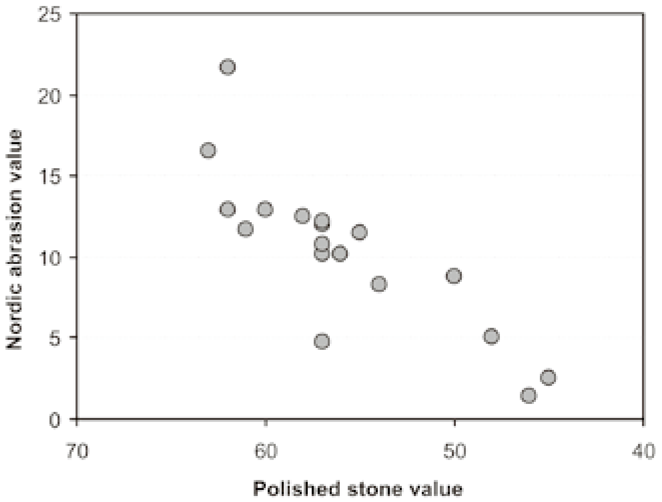

Figure 13. Polished stone values vs. Nordic abrasion value for sandstones.

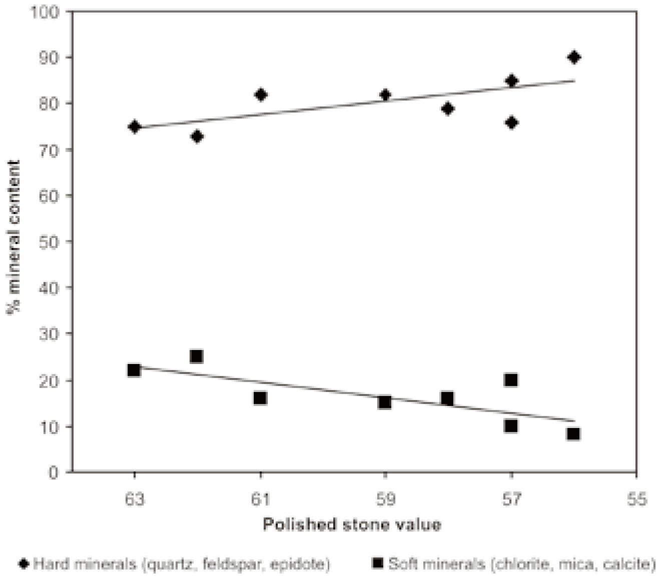

Figure 14. The variation in the polished stone value for Devonian sandstones depending on the mineral content.

Sedimentary rocks resist polishing best. Especially for Devonian sandstone, a suitable mix of hard and soft minerals increases the polishing resistance.

For sand and gravel deposits, different investigation methods are necessary to record both volume and the quality of the aggregate. A good documentation of the variation in the deposit, as shown for the Gardermoen superficial deposit, is fundamental for all sustainable planning.

For areas with a complex geology like Såt, it is crucial to have good geological control before sampling is carried out for examination of the mechanical properties.

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