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Influence of the Mineralogical Composition and Textural Properties on the Quality of Coarse Aggregates

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To evaluate the influence of the petrographic variables on the quality of coarse aggregates consisting of granitoid (granite to tonalite) rocks, 17 samples selected from the Swedish part of the Baltic shield have been studied concerning their petrographic properties, for example, mineral composition, grain size, grain boundaries, and the frequency of micro-cracks. All of the samples selected also have been studied in mechanical tests used to evaluate the quality of aggregates in Sweden. The quality has been determined by means of flakiness, impact value, abrasion value I, and abrasion value II. An analysis of the influence of the mineral composition and textural properties on the aggregate quality has been performed using statistical correlation and linear models. The results indicate that an increasing content of feldspar negatively influences the strength against impact, while an increasing content of mica (tested to 35 vol.%) combined with a diminishing grain size and more irregular grain boundaries has a positive influence on the resistance of granitoids to mechanical impact. Abrasion value II seems to be mainly influenced negatively by an increasing frequency of micro-cracks. The practical implementation of the results is suggested.

Keywords: aggregates rock material, image analysis of microscopic images, mechanical properties

1. Introduction

1.1 Background

Knowledge of the influence of petrographic variables, such as rock structure, mineral composition, grain size, grain boundaries, and micro-cracks, on the mechanical properties of coarse aggregates is highly significant for the modeling of the rock fragmentation processes (e.g., drilling, blasting, and crushing) used by the aggregate industry and the mining industry.

These subjects have been previously studied by several researchers.[1-9] All the researchers have stated that the physical and mechanical properties of rocks are a function of their mineralogical, structural, and textural properties.

The results of all previous investigations indicate also that the mechanical properties of different rock types are influenced by different petrographic variables. This fact makes it difficult to draw general conclusions concerning the influence of petrographic variables on the mechanical properties of the rocks. Another conclusion is that the selected rock types should be studied separately and systematically with regard to their origin and petrographic variations, for example, the structure, rate of crystallization, grain size, grain distribution, and content of mica.

1.2 General Goal of Project and Aim of Study

The general goal of this project was the systematic study of selected rock types that are frequently used as raw materials in the production of aggregates, with particular attention to their variations in mechanical properties and suitability for different purposes.

To study the origin of variations in mechanical properties of granitoid rocks (granites to tonalites), 17 samples were selected, and their petrographic and mechanical properties were analyzed.

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2. Experimental Testing Methods

2.1 Selection and Collection of Rock Samples

The selection of granites focused on variations in their mica content, grain size, and the frequency of their micro-cracks. The choice of representative samples was based on information from geologic bedrock maps of Sweden (scale 1:50 000) that included petrographic analyses of the selected rock types. Brief characterizations of the rock samples are presented in Table 1. The collection of representative rock samples was performed with the help of a geologic sledgehammer and wedge. Each sample consisted of about 40 kg of non-weathered rock.

2.2 Estimation of Mineralogic and Textural Variables

Each sample was analyzed to determine its mineral composition, textural properties (i.e., grain size, grain boundaries, micro-cracks), and mechanical properties (i.e., flakiness, impact value, abrasion value I, and abrasion value II, as shown in Table 2).

2.2.1 Mineral Composition. The mineral content was calculated using the point count method.[10] Approximately 500 points were counted in each thin section. For rocks with a grain size larger than 5 mm, two or three thin sections were used to estimate the mineral composition. To focus on the main minerals that influence the mechanical properties of the rock, sim-

Table 1 Description of the Selected Samples

Sample	Rock Description	Grain Size mm
G1	Granite, massive, medium-grained, not even-grained	0.5-2
G2	Orthogneiss, slightly foliated, medium-grained, not even-grained	0.5-3
G3	Orthogneiss, slightly foliated, medium-grained, not even-grained	0.5-2
G4	Granite, massive, medium- to coarse-grained, not even-grained	0.6-6
G5	Orthogneiss, slightly foliated, medium-grained, not even-grained	1 to 2
G6	Granodiorite, massive, medium-grained, even-grained	0.5-3
G7	Granite, massive, medium-grained, even-grained	0.4-2
G8	Granite, massive, fine-grained, even-grained	0.5-1.5
G9	Granite, massive, fine-grained, even-grained	0.3-1
G10	Granite, massive, medium-grained, not even-grained	0.5-5
G11	Orthogneiss, slightly foliated, medium-grained, not even-grained	0.2-5
G12	Orthogneiss (granodiorite), slightly foliated, medium-grained, even-grained	0.5-2
G13	Granodiorite, massive, fine- to medium-grained, even-grained	0.1-1
G14	Granodiorite, massive, medium- to coarse-grained, not even-grained	0.1-6
G15	Granodiorite, massive, medium-grained, not even-grained	0.1-4
G16	Dark tonalite, massive, coarse-grained, even-grained	1-8
G17	Tonalite, massive, fine-grained, even-grained	0.1-1

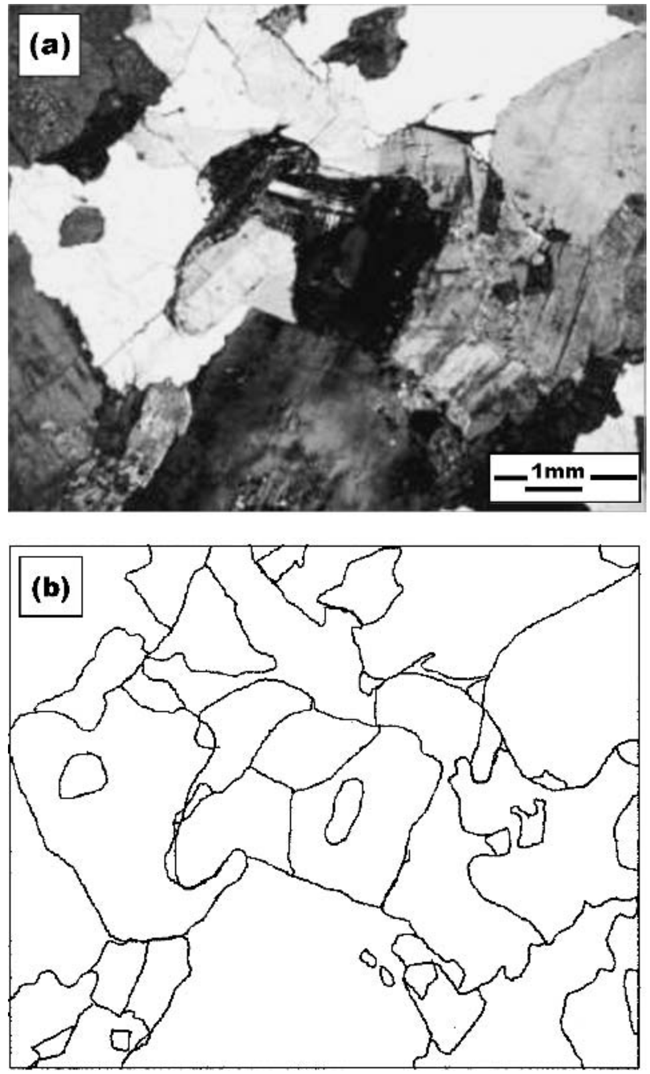

Fig. 1 **(a)** Microscopic image of the rock type G6, and **(b)** the image of the rock texture after the manual segmentation

plifications were made concerning the mineral composition. Biotite, muscovite, and chlorite were included in the determination of mica content. Determination of the feldspar content included both K-feldspar and plagioclase.

2.2.2 Textural Parameters. The texture of the granitoids was quantified through the morphologic parameters of the rock minerals such as grain size, grain boundaries, and micro-cracks. A large variety of parameters are used to characterize the morphologic parameters of texture.

2.2.3 Estimation of Textural Parameters Using Image Analysis of the Thin Sections. The method for estimating the grain size index was a modification of the method of Chayes.[10] The number of mineral grains was counted along the 40 mm line in the thin sections under a polarizing microscope. To avoid the influence of slight foliation in the orthogneisses, the grain size evaluation was performed along two perpendicularly oriented lines. The grain size index then was calculated as an average value of the two measurements. An increasing value in the grain size index indicates a diminishing grain size.

An analysis of the grain boundaries and micro-cracks was carried out using an image analysis of the microscopic images. To quantify the textural parameters, the following steps were performed:

1) Capture of microscopic images with a digital camera installed in a polarizing microscope and connected to a computer. Three microscopic images were taken from each thin section of each sample. The images were taken with crossed nicols (Fig. 1a).
2) Delimitation of the rock texture. The extraction of the grain boundaries was performed manually on top of the microscopic image. The image of the mineral boundaries (Fig. 1b) then was used for the further textural analyses.

The micro-cracks are discontinuities that are associated with the mineral cleavage and the grain boundaries. At the micro-scale, the micro-cracks appear as straight lines. The width of the micro-crack line is 0.0043 mm. The identification of the micro-crack analysis proceeded as follows:

1) Straight lines were traced when micro-cracks were observed in the microscopic image.
2) The micro-cracks were counted. The microscopic image on which the micro-cracks were traced and numbered was recorded.

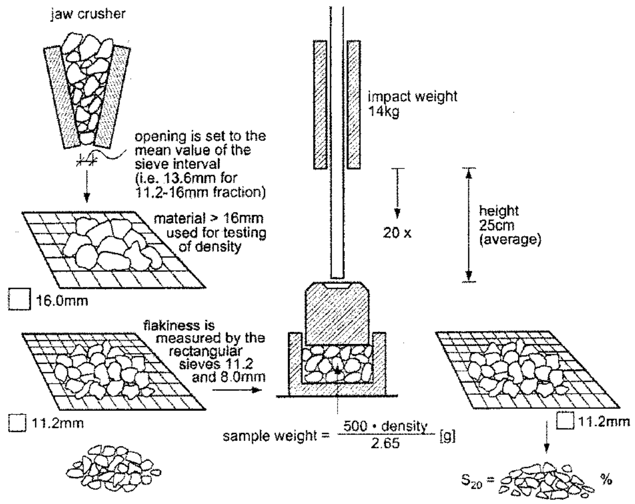

Fig. 2 Schematic representation of impact value test procedure (Gertsch et al., 2000)[13]

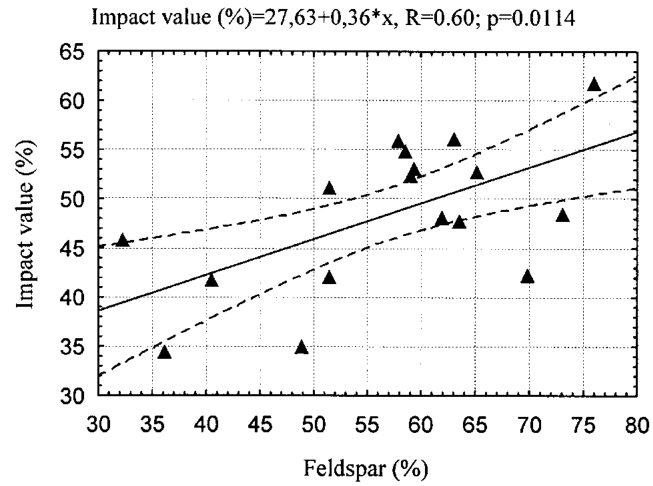

Fig. 3 Linear correlation between the feldspar content and the impact value

Table 2 Mineralogic Composition and Mechanical Properties of the Investigated Granitoid Rocks

Sample No.	Mineralogic Composition, %			Mechanical Properties of Aggregates			
	Quartz	Feldspar	Mica	Flakiness	Impact Value %	Abrasion Value I, %	Abrasion Value II, %
G1	25.4	73.1	1.5	1.39	48.4	2.1	7.7
G2	22.1	75.9	2	1.28	61.8	2.4	17.1
G3	31.9	63	4.8	1.32	56.1	2.4	12.7
G4	36.7	57.9	4.9	1.22	56.0	2.0	17.6
G5	28.2	65.2	5.2	1.27	52.7	2.2	12.8
G6	35.3	59.1	5.6	1.33	52.4	1.9	10.0
G7	31.9	62	6.1	1.27	48.2	2.3	8.3
G8	22.4	69.9	6.6	1.35	42.3	1.9	8.0
G9	28	63.6	8.4	1.34	47.8	1.8	8.4
G10	31.2	59.4	8.6	1.35	53.1	1.8	11.4
G11	34.2	51.5	14	1.38	51.1	2.1	9.1
G12	20.5	58.6	17	1.27	54.8	2.2	19.7
G13	15.6	48.9	25	1.37	34.9	3.0	12.0
G14	32.7	40.5	27	1.36	41.7	2.2	11.0
G15	19.5	51.5	27	1.34	42.1	2.4	15.0
G16	16.9	32.3	31	1.32	45.8	2.7	19.0
G17	22.9	36.1	33	1.39	34.5	2.7	12.0

The micro-crack index was defined as the number of micro-cracks found in the three images.

2.3 Mechanical Tests of Coarse Aggregates

The quality of coarse aggregates is determined by laboratory tests. The test methods used in the present investigation concerned flakiness, impact value, abrasion value I, and abrasion value II. These tests are the standard Swedish methods for testing the mechanical properties of aggregates and are similar to European standards.

2.3.1 Flakiness. The flakiness value describes the shape of the aggregates after the rock material has been fragmented. Thin and elongated particles indicate the durability and strength of aggregates for later use. Thin or elongated particles break more easily than cubical particles. The values of flakiness vary from 1-2. The low flakiness value refers to the cube-like form of the particle. The laboratory procedure of the Swedish Asphalt Pavement Association[11] is similar to the European norm.[12]

2.3.2 Impact Value. The impact value is a measure of resistance to wear by impact. It is determined through the brittleness test (Fig. 2) and gives a very good measure of the ability of the rock to resist crushing by repeated impacts. Several modifications of the test have been made and are used in several European countries. The sample volume corresponds to 500 g of grain density at 2.65 g/cm^3 from fractions of 5.6-8, 16-11.2, or 11.2-8 mm. The brittleness value equals the percentage of the material that passes an 11.2 mm mesh after the aggregate has been crushed by 20 impacts. The brittleness value is the mean value of 3-5 parallel tests.[14] A lower impact value indicates a rock that is more resistant to impact.[4] The laboratory procedure of the Swedish Asphalt Pavement Association[15] is similar to the method described in the British Standard.[16]

2.3.3 Abrasion Value I. Abrasion value I provides an estimate of the surface wear properties. Thirty-six representative particles that are 8-11.2 mm in size are held together against a rotating lap for some 500 revolutions. Abrasion powder is fed into the front of the sample. The weight of the original sample minus the loss of weight during the test, all divided by the grain density of the sample, gives the Swedish abrasion value,[17] which is similar to that derived by the British method.[18] A low numerical value indicates a rock that is more resistant to abrasion.

2.3.4 Abrasion Value II. Abrasion value II measures the resistance of the aggregates to abrasion caused by the impact of steel balls. A charge of 500 steel balls and 2 L of water are rotated in a steel cylinder. The rotation causes attrition through mutual tumbling and impact. After the test, the sample is screened on a sieve with a 2.0 mm aperture. The fine fraction is weighed, and the loss of weight, as a percentage of the original weight, is the abrasion value. A low numerical value indicates a rock that is more resistant to abrasion combined with impact. The laboratory procedure was carried out according to the method of the Swedish Asphalt Pavement Association,[19] which corresponds to the Studded Tyre Test method.[20]

2.4 Correlation Analysis

Correlation analysis was used for the estimate of the influence of petrographic factors on the mechanical properties of the investigated granitoid rocks. With regard to the statistical data obtained, the Spearman correlation analysis was chosen for the statistical evaluation of the results.

2.4.1 Spearman Correlation. An analysis of the statistical relationship was performed by means of the Spearman correlation.[21] Results showing a p value of <0.1 are considered to be statistically significant at a confidence level of 90%. The values that slightly exceed 0.1 are considered as indications of correlation between the parameters.

3. Results

The results of the petrographic and mechanical analyses and the statistical evaluations of the influence of mineralogic and textural parameters on the mechanical properties of the granitoid rocks are presented below.

3.1 Mineralogic Composition of the Granitoid Rocks Investigated

The results obtained for the mineralogic composition and its influence on the mechanical properties of the aggregates are

Table 3 Spearman Correlation Analysis Concerning the Mineralogic Composition and Mechanical Properties

Mineralogic Composition	Flakiness	Impact Value	Abrasion Value I	Abrasion Value II
Quartz	−0.14	0.36	−0.57	−0.32
p value	0.60	0.153	0.02	0.22
Feldspar	−0.23	0.53	−0.42	−0.34
p value	0.38	0.03	0.09	0.18
Mica	0.35	−0.72	0.38	0.21
p value	0.17	0.00	0.14	0.41

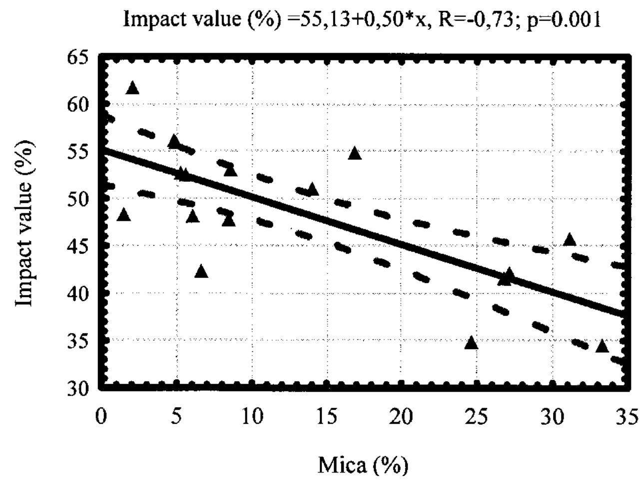

Fig. 4 Linear correlation between the mica content and the impact value

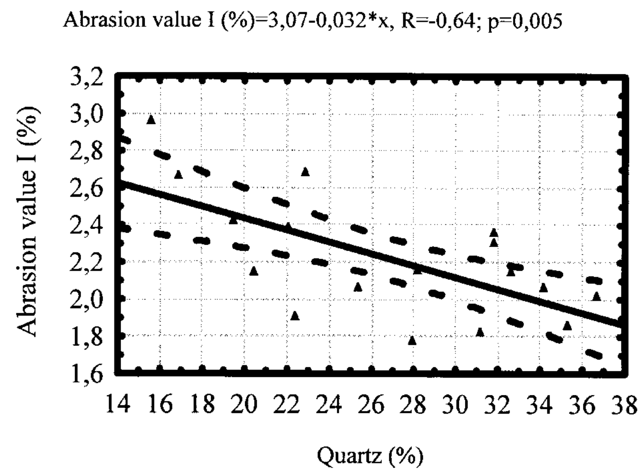

Fig. 5 Linear correlation between the quartz content and abrasion value I

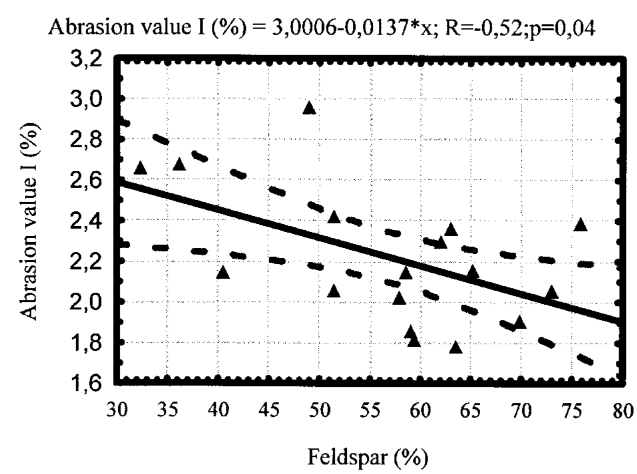

Fig. 6 Linear correlation between the feldspar content and abrasion value I

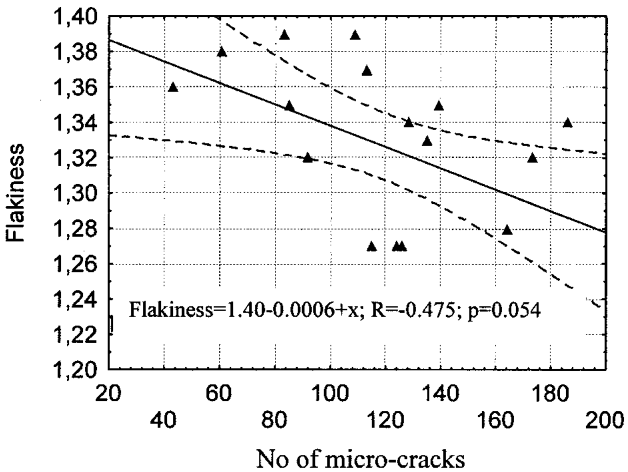

Fig. 7 Linear correlation between the number of micro-cracks and flakiness

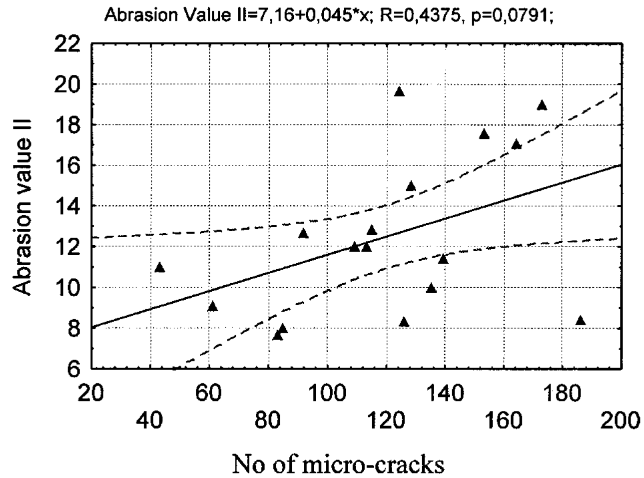

Fig. 8 Linear correlation between the number of micro-cracks and abrasion value II

Table 4 Textural Indices and the Mechanical Properties of the Granitoid Rocks

Sample No.	Textural Indices: Grain Boundaries, mm	Grain Size, No.	Microcracks, No.	Mechanical Properties of Aggregates: Flakiness	Impact Value, %	Abrasion Value II, %	Abrasion Value II, %
Gr1	1.12	87	83	1.39	48.4	2.1	7.7
Gr2	1.04	101	164	1.28	61.8	2.4	17.1
Gr3	0.99	103	92	1.32	56.1	2.4	12.7
Gr4	1.86	88	153	1.22	56.0	2.0	17.6
Gr5	0.91	93	115	1.27	52.7	2.2	12.8
Gr6	1.58	70	135	1.33	52.4	1.9	10.0
Gr7	1.06	128	126	1.27	48.2	2.3	8.3
Gr8	1.07	160	85	1.35	42.3	1.9	8.0
Gr9	0.98	129	186	1.34	47.8	1.8	8.4
Gr10	1.40	47	139	1.35	53.1	1.8	11.4
Gr11	1.69	180	61	1.38	51.1	2.1	9.1
Gr12	1.25	129	124	1.27	54.8	2.2	19.7
Gr13	0.98	114	113	1.37	34.9	3.0	12.0
Gr14	1.10	217	43	1.36	41.7	2.2	11.0
Gr15	1.27	114	128	1.34	42.1	2.4	15.0
Gr16	1.71	55	173	1.32	45.8	2.7	19.0
Gr17	1.27	231	109	1.39	34.5	2.7	12.0

presented in Table 3 and Fig. 3-6. The statistical evaluation of the rock samples analyzed pointed out the following relations concerning the influence of the mineral composition on the mechanical test methods:

- It was established that a rising content of quartz and feldspar causes a decrease in abrasion value I. This means that the resistance of the granitoid rocks to abrasion increases with an increasing amount of quartz and feldspar.
- There is a slight indication that an increasing content of mica causes a slight deterioration of the rock resistance to abrasion.
- It is significant that an increasing amount of mica (i.e., 0-35 vol.%) improves the resistance of granite to the effects of impact, while an increasing amount of feldspar has the opposite influence.

3.2 Influence of Texture on the Mechanical Properties of Granitoid Rocks

The results of measurements of the textural indices and the mechanical properties are presented in Table 4. Their influence on the mechanical properties of the aggregates is presented in Table 5, and Fig. 7 and 8.

The statistical evaluation of the rock samples analyzed pointed out the following relations concerning the influence of the textural indexes on the mechanical test methods:

- There is an indication that a diminishing grain size causes a slight decrease in the impact value. This means that the resistance of the granitoid rocks to the effects of impact slightly increases with a decreasing grain size.
- It was statistically established that the main factor that influences abrasion value II is the propagation of micro-

Table 5 Spearman Correlation Analysis Concerning the Textural Indices and Mechanical Properties

Textural Indices	Flakiness	Impact Value	Abrasion Value I	Abrasion Value II
Grain size	0.33	−0.48	0.14	−0.24
p value	0.85	0.13	0.68	0.66
Grain boundaries	0.09	−0.26	0.23	−0.20
p value	0.34	0.32	0.38	0.45
No of micro-cracks	−0.55	0.29	0.10	0.42
p value	0.02	0.25	0.70	0.09

cracks. The strength of the rock against the abrasion decreases with an increasing frequency of micro-cracks.

- The results of the correlation analysis pointed out that the flakiness value is positively influenced by an increasing frequency of micro-cracks.

4. Discussion and Conclusions

The study presented has pointed out the main factors that influence the mechanical properties of aggregates consisting of granitoid rocks. The influence of mica on the impact value and the effects of micro-cracks on abrasion value II are the most important results of the study.

To draw practical conclusions, the test methods used in this investigation have to be discussed. They have been applied as the Swedish standards for testing the quality of aggregates for several decades. Some of these methods have been replaced and are not used any more. Abrasion value I was replaced by abrasion value II 10 years ago. Abrasion value II is going to be replaced by the Micro-Deval method in 2004. One of the important issues is the way in which the test methods correspond to the mechanical stress caused by actual traffic. The impact value corresponds most to the brittleness of the rock, while abrasion value I represents static wear, and abrasion value II corresponds to responses to wear and impact combined.

However, it is important to be aware that the mechanical properties of aggregates are indices that are influenced by different petrographic properties of the rock, as has been proved in this study.

The influence of the petrographic properties of the granitoid rocks on the mechanical properties of the aggregates can be summarized as follows:

- Flakiness is influenced positively mainly by the frequency of micro-cracks. It is important to stress that all of the flakiness values tested concerned particles with a cube-like form. All of the test values are under the limit for flakiness according to the Swedish norms for aggregates.
- The impact value is negatively influenced by an increasing feldspar content. Increasing mica content (to about 35%) and a decreasing grain size influence the impact value in a positive way. The lack of coarse-grained samples in the material studied probably impaired the results of the statistical evaluation of the grain size and its influence on the impact value compared with the results expected and known from the industrial production of aggregates.
- Abrasion value I depends mainly on the quartz and feldspar content, while the mica content is of secondary importance.
- Abrasion value II is influenced negatively mainly by an increasing frequency of micro-cracks.
- One of the practical applications of the results of this study is that the incautious blasting of granitoid rocks can cause considerable deterioration of the rock material due to the increasing propagation of micro-cracks.

With respect to the results of this study, it can be expected that increasing mica content will improve the resistance of coarse aggregates consisting of granitoids against mechanical impact. This phenomenon probably can be explained by the elasticity of mica crystals, which moderates the effects of mechanical impact. The practical application of this result would be to permit a higher content of mica in granitic rock materials used for the construction of railways. The limit for the mica content is presently restricted to 10% by Swedish authorities.

Acknowledgments

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