DEVELOPMENT OF A NEW METHOD FOR AGGREGATE QUALITY CONTROL IN ROCK QUARRIES

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ABSTRACT

A great amount of aggregate is utilized in civil engineering applications such as road construction, railway infrastructure, concrete production, etc. Igneous rocks are the preferred raw material due to their high strength and abrasion resistance. Rock quality assurance is a key factor and has great influence on the quality of constructions in civil engineering. One of the major problems encountered by both the producers and users of igneous aggregate rock is the fact that, with the passage of time, some specific rocks lose their strength, up to a complete loss of structure, i.e. disintegrate and degrade. This phenomenon has a great influence on the quality, strength and durability of aggregates. In the last decades, different methods and procedures such as the glycol test, the methylene blue dye test, as well as the Los Angeles test, have been introduced to distinguish rock properties, and to identify these problems. However, as these wet-chemical methods are time consuming, hard to perform, only to be applied to hand-piece samples, requiring special laboratory equipments, and are only possible to be accomplished under laboratory conditions, their application has always been severely limited. To address this widespread quality management problem of the quarry industry, a relatively quick, easy and user-friendly approach is necessary. It calls for a systematic solution with a device that can simply be used in the day-to-day routine of a mine for quality control of the quarry´s daily production. Our research is concentrated on developing a systematic method for early recognition and diagnosis of rock quality, in order to control and manage the quality of the quarry production in advance. Our new approach is based on two rock parameters: magnetic susceptibility and loss on ignition. The measurement of these parameters provides reliable information on the quality of the rock and allows the quality control process to be accomplished and performed at the borehole location. Our new approach has been assessed through extensive field and laboratory studies and has been implemented on the drill-cuttings of a basaltic andesite quarry. The results of the experiments are discussed in detail, including their impact on increasing resources and environmental protection.

KEYWORDS

Aggregate, Rock quality, Weathering, Magnetic susceptibility, Loss on ignition, Glycol test, Methylene blue dye test

INTRODUCTION

On exposure to weathering, many igneous rocks tend to partially decompose. This phenomenon, which is known in the aggregate industry under the collective term of “basaltic sunburn”, leads to the problem that certain quality requirements for products, such as railroad ballasts, asphalt and concrete, cannot be met. This results in complaints by end users, and may endanger both the existence of a mining company and the sustainability of the raw material production itself.

Although this phenomenon has been known for a long time, until today there is no simple method or device that would allow for on-site quality control and early warning. The established methods (e.g., the boiling test in glycol and the methylene-blue test) only allow investigations on hand-sized samples and provide results, at the soonest, within one day after sampling (DIN EN 1097-2, 1998; DIN EN 1367-3, 2001 & 2004; Kühnel et al., 1994; Pham & Brindley, 1970; Prudêncio et al., 2002; Stapel & Verhoef, 1989). Apart from the fact that the test preparation is time-consuming, the results only provide selective information on the quality of the already produced/extracted raw material and the results are not fully reliable. By both methods, the reaction of different clay minerals is measured. A sample that disintegrates on weathering can be regarded as suitable in one of these tests and can be judged as unsuitable in other tests. Regardless of this unsatisfactory state, these wet-chemical methods cannot be applied for online quality control and are not suitable for the quality management of the mining process, as during blasting, loading, transporting and processing of the rock.

The aim of the investigation documented in this paper was to find a systematic quantitative approach for in-situ quality control applicable to quarrying of igneous rocks. Based on these investigations, a new procedure and a device for on-line quality control in aggregate mining was developed.

PROCEDURE

To develop a method and a device for quality assurance in rock quarries for aggregate production, a systematic multi-stage approach is required. Reconnaissance work on the mineralogical nature of the rock and its alteration, as performed by multi-element geochemical and petrographic studies, form the first part of this research. A large number of tests define the quality requirements, whereby reference tests by means of accepted and approved standard methods are used for comparison. In a subsequent large-scale field test, the reproducibility of results and the field suitability of the selected methods are to be verified. In addition, from the statistical point of view, a large number of measurements are performed to assure the validity of the method.

Multi-element geochemical and petrographic work and magnetic susceptibility measurements (Phase 1)

In this phase of the project, representative samples of different rock varieties were selected for mineralogical and geochemical investigation. The quality of the samples was firstly determined by the mine operator, based on a visual assessment process. For geochemical analysis, the milled samples were sent for multi-elemental analysis.

Table 1 shows a summary of the multi-elemental analysis of some samples from the same andesitic basalt quarry. The analyses show a significant difference in content of CaO, Na_2O and K_2O, including the content of volatile components defined by the LOI value (loss on ignition), i.e. the loss of weight of a dry, powdered sample by heating up to 850°C.

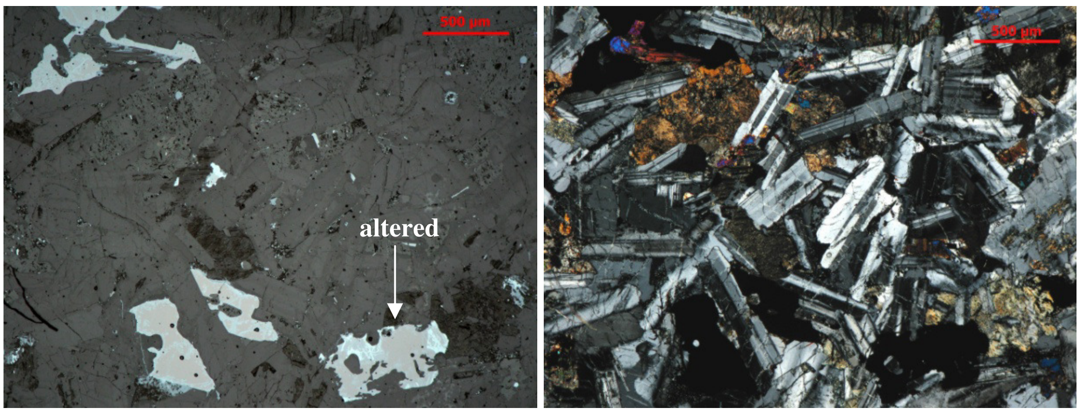
Table 1 – Results of the multi-elemental analysis of three representative basaltic rock samples. Significant variations between fresh and altered samples are shown in grey shading.

Analyte	SiO_2	Al_2O_3	Fe_2O_3(T)	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total
Unit	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
Detection Limit	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.005	0.01		0.01
Analytical Method	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP
S3-1	52.34	16.99	8.09	0.13	4.63	7.84	3.09	1.71	1.126	0.28	2.17	98.39
S4-1	52.44	17.73	6.78	0.12	4.83	7.68	3.22	1.84	1.182	0.25	3.50	99.58
S4-2	54.63	16.94	8.28	0.13	4.20	6.66	3.46	2.52	1.199	0.33	1.48	99.83

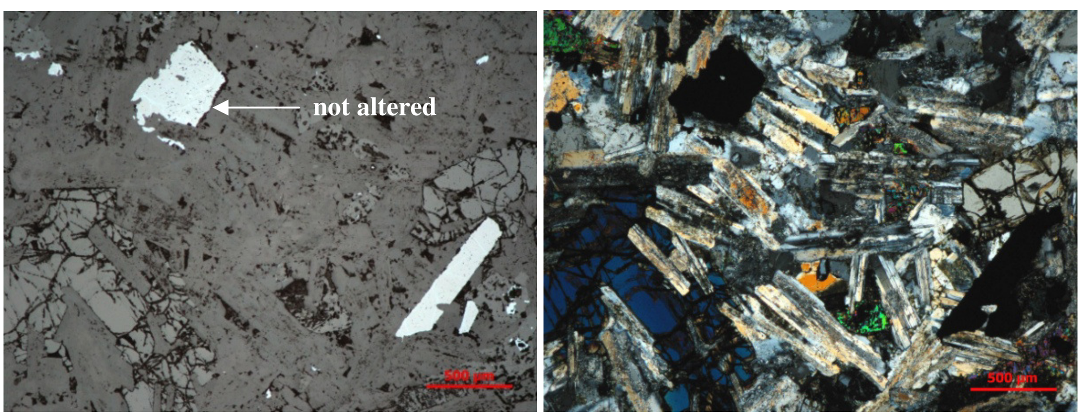
In the low quality rock samples S3-1 and S4-1, as identified by visual assessment of the operator, an enrichment of CaO and a depletion of Na_2O and K_2O is recognizable. These two samples also have up to twice the amount of volatile components (LOI) compared to sample S4-2.

In geochemistry, this phenomenon is known as alteration, caused by hot or cold water passing through joints and weak zones of the rock from its post-magmatic (hydrothermal) up to the youngest weathering history. By this water-rock interaction the original rock is pervasively modified and its mineralogical and geochemical composition changes according to the physicochemical variation in the fluid phase. In particular, hydrous minerals are formed at low temperature from anhydrous minerals that formed during the magmatic stage. The chemical analysis shows that several components are modified during alteration. The simplest indicator for this process is the LOI value, which can be measured in a short time and at low cost.

Following the results of multi-elemental analysis, polished thin section microscopy was performed on the samples. The microscopical study in reflected light shows that the alteration is associated with a change of magnetite [Fe_3O_4] to hematite [Fe_2O_3], i.e. oxidation. The more advanced the alteration process, the more magnetite is converted to hematite. The samples with higher LOI values have a greater transformation of magnetite to hematite. Accordingly, a second independent parameter is identified, i.e. the amount of magnetite in the rock, which can be determined by measurement of the magnetic susceptibility. In Figure 1, the two samples, S4-1 and S4-2, are shown in reflected and transmitted polarized light, respectively.



(a)



(b)

Figure 1 – Photomicrographs of polished thin sections of samples S4-1 (a) and S4-2 (b) in reflected light (left) and transmitted light (right). Sample S4-1 is altered, as seen by the decomposition of igneous magnetite to haydrothermal hematite, while sample S4-2 has igneous magnetite preserved, i.e. is much less altered. Magnetite in reflected light is brownish-grey while hematite is bluish-light grey. Both magnetite and hematite are opaque and appear black in transmitted light.

Project relevance is achieved by the fact that the magnetic susceptibility can be determined relatively simply and quickly by means of a hand-held magnetic susceptibility meter. These devices have been introduced in petrology and mineral deposit sciences for some time and are utilized in field surveys to collect data about the alteration zones. In Figure 2, such an instrument is shown.

Figure 2 – The hand-held magnetic susceptibility meter (Georadis s.r.o. & Terraplus Inc.)

To check the suitability of the magnetic susceptibility measurements as a quality indicator, the magnetic susceptibility of the samples was measured repeatedly, using the featured handheld instrument. The magnetic measurements showed a good correlation with the results of the microscopic work, and with the LOI values from the multi-elemental analysis. Rock samples of low quality have a much lower magnetic susceptibility value. The comparison of LOI and magnetic susceptibility shows that an increase of volatile components is associated with a decrease in magnetic susceptibility (Figure 3). In conclusion, these two quantitative parameters can be used as indicators for rock quality.

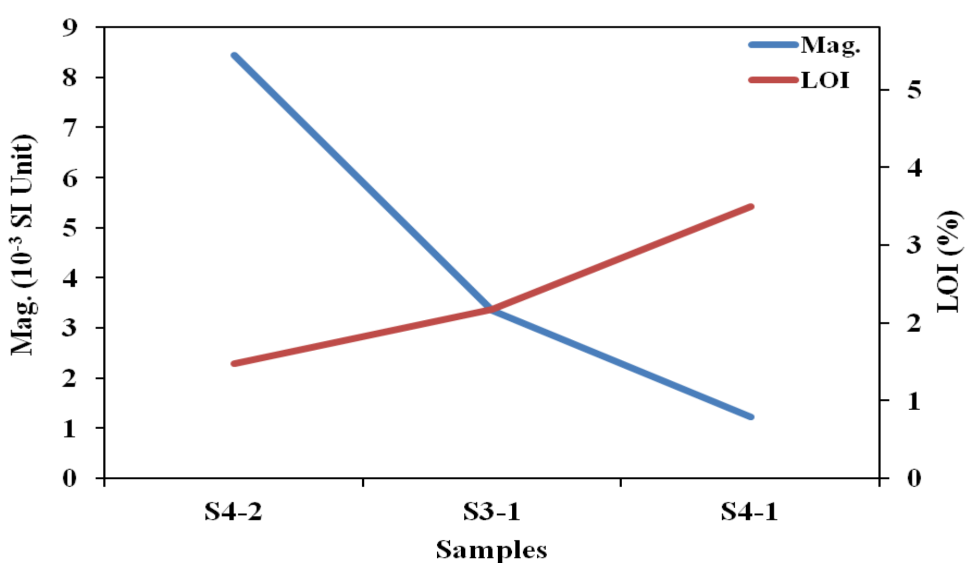


Figure 3 – LOI vs. magnetic susceptibility (Mag.) for three representative rock samples

Reproducibility of the method and determination of quality limits (Phase 2)

In the second phase of the project, 29 rock samples were taken from the quarry for further investigation. Based on the results of the first phase of the project, these samples were examined with respect to the indicators already identified. For this purpose, the volatile content and the magnetic susceptibility of each sample were determined. Furthermore, thin sections were prepared and a microscopic study was carried out. To determine the accuracy of this method, as well as for detecting and fixing the indicator limits, the same samples were subjected to the glycol test. The glycol test provides data on the percentage of rock disintegration, for the determination of the quality limits (Figure 4). The analysis of the measurements of the volatile components showed a range between 1.26 and 3.84 wt% LOI.

The range of measured magnetic susceptibilities of the studied samples is 1.47 to 10.2 ($\times 10^{-3}$ SI Unit). The wide spectrum of the magnetic susceptibility values of the samples, compared with the LOI values, permits an easier and more practical determination of the quality threshold or limiting value. Small deviations would not lead to a relevant change in quality.

The investigations of the second phase of the project confirm the assumption that the rock quality is associated with the intensity of alteration, and that it is correct to use values of the volatile components and the magnetic susceptibility as indicators. Rocks, which have a low magnetic susceptibility and a high value of volatile substances, are of low quality. They disintegrate after the glycol test either completely or into smaller pieces.

(a) (b)

Figure 4 – Results of the glycol test. (a) before the glycol test, (b) after the glycol test (Glycol test=69.73%, LOI=2.57 wt%, Magnetic susceptibility=1.55×10^{-3} SI Unit)

Field measurements in combination with laboratory studies (phase 3)

This phase of the project was initiated with the objective of checking the transferability of the procedure and the analytical device into practice. At the same time, based on a large number of measurements, the reproducibility of the results was to be investigated through a statistically reliable data collection method.

During a test phase of several months length in the quarry and in the laboratory, thousands of measurements were conducted. The measurements in the quarry were made bench by bench in a narrow measuring grid on all current mining walls. The magnetic susceptibility of the rock was recorded at least 5 times at 1,530 points. Figure 5 shows this approach as an example.

Figure 5 – Field test. Numbers are referring to magnetic susceptibilities of the bench´s wall. Magnetic measurements were taken nearly every 10 cm along each bench´s wall

In parallel with these measurements, samples were taken from those areas having a significant change in magnetic susceptibility in order to determine the volatile components in the laboratory. A total of 152 samples were analyzed for the LOI value. The magnetic susceptibilities of these samples were also measured. The statistic evaluation of the test results and the comparison of the respective values of the volatile components and the magnetism confirm the usefulness of the selection of the two indicators as quality criteria and underlines that the mentioned indicators in the first and second phases of the project are strongly inversely correlated. It is confirmed that magnetic susceptibility increases with the decrease of LOI values (Figures 6 and 7).

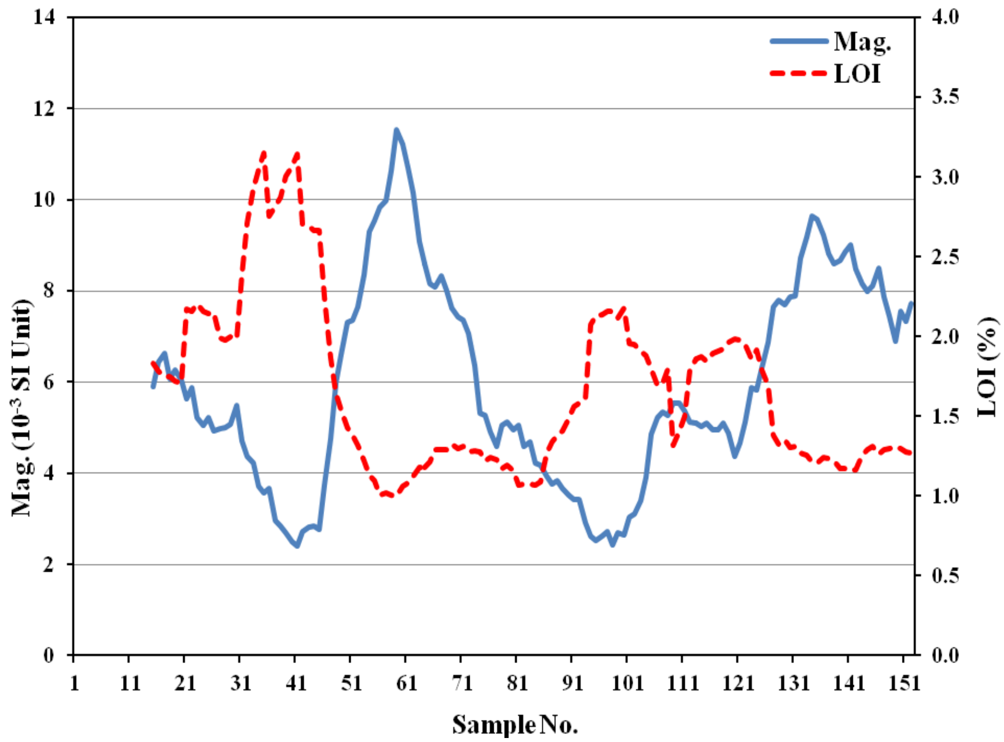


Figure 6 – Dependence of magnetic susceptibility and LOI for individual rock samples

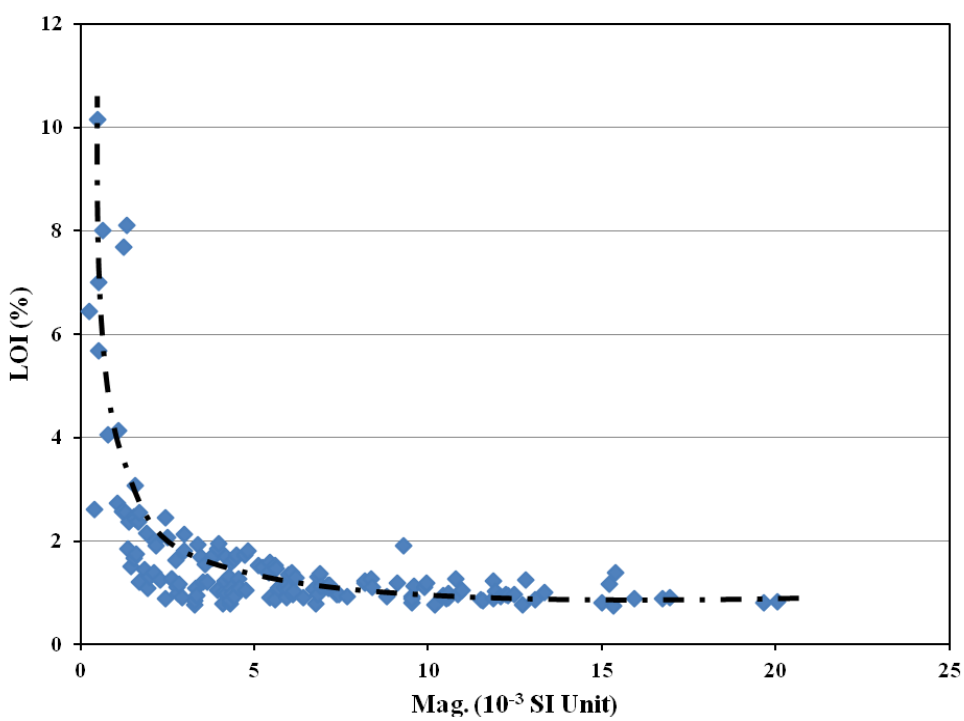


Figure 7 – Variability of magnetic susceptibility versus LOI (rock samples)

Checking the quality distribution in the quarry by reference boreholes (phase 4)

To check or visualize the determined quality distribution along the mining benches, 20 boreholes in four separate groups were drilled, each consisting of five boreholes. The drilling locations were chosen, based on the results of the quality distribution, in such a way that two zones with low rock quality and two zones with high rock quality were to be explored.

The cuttings of each borehole were examined for their magnetic susceptibility through systematic sampling and preparation in the laboratory. The amount of volatile components (LOI) was also measured for the same samples. As an additional reference test in the laboratory, the so-called methylene-blue test was applied. These experiments were extended to another 250 borehole cuttings samples that were present in the laboratory as reference samples for documentation of previous boreholes.

The evaluation of the measurement results completely confirmed the results of the first three phases of the project. The two parameters (1) value of volatile components and (2) magnetic susceptibility are applicable to the cuttings as quality features. The interlinkage between the indicators is in accordance with all previous test results. Again, as the LOI value increases, the value of the magnetic susceptibility decreases in parallel (Figure 8).

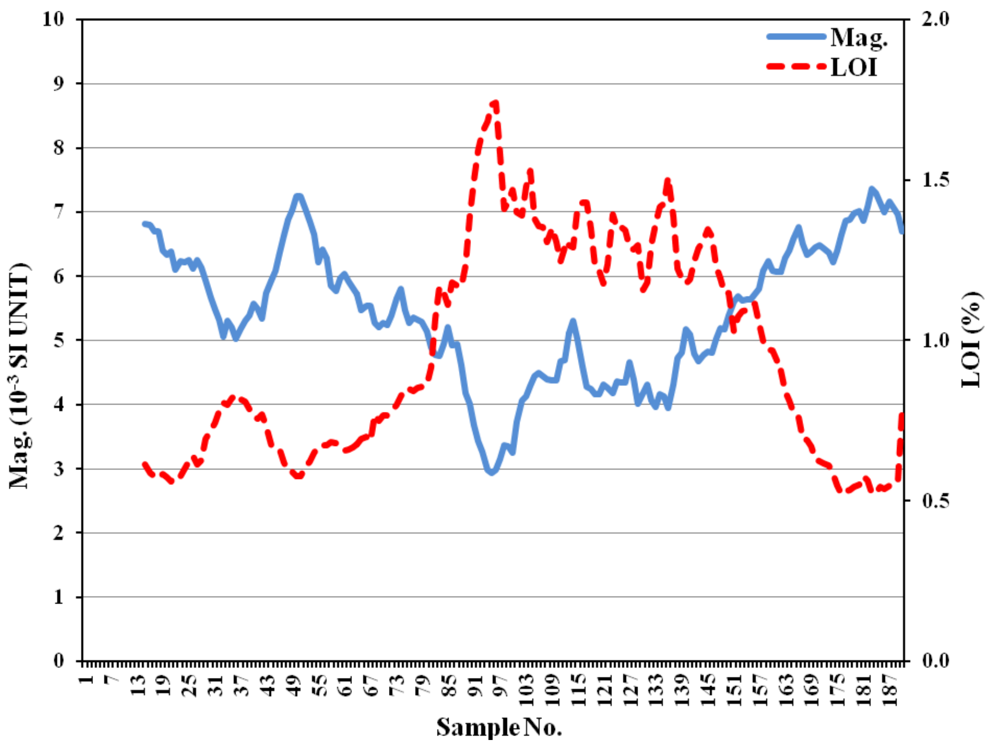


Figure 8 – Dependence of magnetic susceptibility and LOI (borehole cutting analysis)

SELECTION OF THE RIGHT INDICATOR

As explained before, the main reason for disintegration of the studied rocks is summarized under the process of alteration. There are many kinds of alteration, and, knowing the specific type of alteration gives us the right clue for selecting the most suitable parameter. Although, in our case, both criteria are leading to the same result and therefore the selection of either of them is satisfactory, it may also happen that one of these parameters could lead to a better solution and be more effective. The key factor in being able to find the right answer to this question is to determine the mineralogical geochemical alteration type.

There are different types of alteration of igneous rocks (e.g., mainly propylitic, potassic, phyllic, argillic, or simple weathering) each of which has its own characteristics. In some alteration types (such as for the quarry studied here), the magnetite content of the rock is changed to hematite and, as a result, the magnetic susceptibility of the rock is modified. In parallel, the LOI of the rock increases due to the formation of hydrous minerals. In this type of alteration, both indicators are really linked together. There exists also other types of alteration where the magnetite content remains more or less constant while the volatile content of the rock increases. Such alteration happens when the water-rock interaction develops under magnetite-stable conditions as, for instance, the propylitic alteration with the stable hydrothermal mineral assemblage of chlorite-carbonate-magnetite. In other words, although the rock may be heavily altered, its magnetic susceptibility does not vary that much (or may even increase), but the LOI of the rock increases invariably. In this case it is suggested that the LOI value be used as the main indicator to determine rock quality, although its measurement is not as fast as the magnetic susceptibility.

In our case, based on the existing type of alteration, it is possible to determine the rock quality by measurement of the magnetic susceptibility of the drill cuttings alone. As a result of the constant observation of the direct relationship between magnetic susceptibility and the amount of volatile components of the rock, for the purpose of quality assurance, the measurement of the magnetic susceptibility on borehole cuttings is sufficient here. The measurement of the LOI value can be omitted, once this relationship has been established (For other information on weathering/alteration process, please refer to Bourne, 1993; Ng et al., 2001; Shaw, 1997).

DISCUSSION AND CONCLUSION

This paper documents tests on a basaltic-andesite deposit with the objective of developing a procedure and a device for early quality detection and control. The need for implementation of this project results from the fact that, in the course of time, igneous rocks partly undergo a structural loss and may disintegrate after their extraction from the quarry and their storage. This quality defect is not visible during mining. Common methods of quality analysis have various disadvantages. They are time-consuming and provide only selective information on the quality of the deposit. In addition, the results of these procedures are not congruent. The objective of our new approach is not only to increase the profitability of raw material operations, but also to help the sustainability of the use of the deposit.

The disintegration process is mainly due to mineralogical-geochemical alteration processes. Determination of the specific alteration type can lead to a better understanding of this degradation process and allows identifying the essential parameters to measure rock quality. The alteration processes affect any rock due to inevitable interaction with hot or cold water after its emplacement and is controlled by permeability, i.e. channelled by weak zones of intrusions/volcanic rock sequences.

Already, in the first phase of the project, on the basis of geochemical and mineralogical methods, it was verified that the rock quality can be measured in the form of changes in volatile content (LOI) and magnetic susceptibility. The reference experiments with glycol and methylene-blue dye tests confirm the link between these parameters and rock quality. All experiments have shown that a direct correlation exists between the respective indicators. The 3,000 measurements conducted consistently display that the decrease of magnetic susceptibility is associated with the rise in volatile components.

The alteration type has a decisive role in defining the right quality-control parameter. For example, in propylitic alteration, there is no such systematic trend between magnetic susceptibility and LOI. The magnetic content and the corresponding magnetic susceptibility of the samples remain almost constant during the alteration process. Therefore, for this type of alteration, it is recommended to take LOI as the main indicator. On the other hand, for the argillic alteration in the case studied, it has been shown that both LOI and magnetic susceptibility can be used as a measure of rock quality. As a result, in all stages of the project, we observed a direct correlation between the magnetic susceptibility and the amount of volatile components in the rock. Therefore, magnetic susceptibility alone is sufficient to define the rock quality here. The magnetic susceptibility measurements can be carried out on drill cuttings using a handheld instrument. This approach allows the early and rapid determination of rock quality. The transferability of the results on other deposits is the subject of current research. Based on current results, it can be assumed that, with the help of this new method, an online quality control program with the aim of increasing the profitability and sustainability of quarry-production is possible. At the time being, this method is being implemented in 3 quarries in Germany.

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