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A transition function for the solid particle erosion of rocks

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ABSTRACT

A simple two-parameter model $K_1 = 1 - \exp\ [-(\lambda \cdot \chi)^b]$ is derived, which can describe the response of rock materials during the erosion through rounded solid particles at normal incidence. A procedure for estimating the distribution parameters λ and b is proposed, and the procedure is applied to four rock materials (rhyolite, granite, limestone, and schist). Erosion experiments with quartz particles are performed in order to estimate K_1 numbers for the rock materials. It is shown that the model covers different types of material response. The parameter K_1 can be linked to general rock classification schemes.

1. Introduction and procedure

The impingement of solid particles on brittle materials is associated with a number of failure modes, namely plastic deformation, ring or cone crack formation, and radial or lateral crack formation. The former mode is usually referred to as ductile failure, whereas the latter modes are referred to as brittle failure (elastic failure or elastic–plastic failure). Additionally, erodent particle fragmentation occurs. The occurrence of an individual failure mode is governed by threshold, or transition, conditions [1].

In an earlier issue of this journal [2], the author applied an erosion model [3], which combines erosion due to plastic deformation (E_R^P) and due to lateral cracking (E_R^L) to geomaterials

$$E_R = K_1 \cdot E_R^P + K_2 \cdot E_R^L \tag{1}$$

A procedure for the estimation of the two parameters K_1 and K_2 does not exist yet. This communication deals with a calculation procedure for rock materials. The first step is the reduction to a single-parameter model. This can simply be done for the condition $K_2 = 1 - K_1$, which delivers

$$E_R = K_1 \cdot E_R^P + (1 - K_1) \cdot E_R^L \tag{2}$$

The constant K_1 balances the amount of either erosion mode. The following conditions apply: For $K_1 = 0$, lateral cracking dominates the erosion process, and elastic–plastic erosion models shall be valid. For $K_1 = 1$, ductile erosion modes (ploughing, lip formation, platelet formation) dominate the erosion process, and erosion models for ductile materials (like soft metals) shall be valid. For values $0 < K_1 < 1$, mixed mode erosion occurs. A criterion for the transition from plastic response to lateral cracking for geomaterials is presented earlier [2]; it reads like follows:

$$\chi = K_{\mathrm{Ic}}^{12/4} / \sigma_{\mathrm{C}}^{23/4} \tag{3}$$

In the equation, χ is a transition number, K_{Ic} is target material fracture toughness, and σ_C is target material compressive strength. Numbers for the ratio $K_{Ic}^{12/4}/\sigma_C^{23/4}$ are provided in Table 1 for relevant materials. Low numbers characterize a preference for lateral cracking [$K_1 \rightarrow 0$ in Eq. (2)], and vice versa. Fracture toughness becomes the dominating erosion resistance parameter if χ decreases. For high χ-numbers, other resistance parameters become important, namely hardness, respectively compressive strength. Compressive strength is also the governing parameter in Eq. (3) because of its higher power exponent.

For the three frame conditions: (i) $K_1 = 0$ for $\chi = 0$; (ii) $K_1 = 1$ for very high χ-numbers; (iii) inflection point between erosion modes, the relationship between χ and K_1 can be approximated with a two-parameter Weibull distribution function [8]

$$K_1 = 1 - \exp[-(\lambda \cdot \chi)^b] \tag{4}$$

In that equation, λ is a scale parameter, and b is a shape parameter. A method for the estimation of λ and b is provided in [9]

$$\ln\left(\ln \frac{1}{1-K_1}\right) = b \cdot \ln \chi - \underbrace{b \cdot \ln\left(\frac{1}{\lambda}\right)}_{A}; \tag{5.1}$$

$$\lambda = \exp\ \left(-\frac{A}{b}\right) \tag{5.2}$$

Shape and scale parameter can be estimated if Eq. (5.1) is fitted to experimentally estimated K_1-values. Values for K_1 for particular materials and erosion conditions can be estimated through microscopic inspections of eroded surfaces. The following simple

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Table 1
Numbers for the transition criterion $\chi = K_{Ic}^{12/4}/\sigma_C^{23/4}$ for different geomaterials. Values for σ_C and K_{Ic} are taken from [2,4–7].

Material	σ_C (MPa)	K_{Ic} (MN/m$^{3/2}$)	χ (MPa$^{-11/4}$ m$^{3/2}$)
Arenaceous shale	143	2.12	3.85×10^{-12}
Argillaceous schist	50	2.70	3.35×10^{-9}
Äspö diorite	219	3.83	1.96×10^{-12}
Aue granite	166	2.38	2.31×10^{-12}
Basalt	274	2.27	1.12×10^{-13}
Basalt	120	1.80	6.46×10^{-12}
Basalt	187	3.01	2.36×10^{-12}
Carrara marble	101	2,44	4.34×10^{-11}
Coral limestone	59	1.32	1.51×10^{-10}
Dolomite	95	1.47	1.35×10^{-11}
Dolostone (Falkirk)	172	1.66	6.40×10^{-13}
Dolostone (Kankakee)	152	1.66	1.30×10^{-12}
Dolostone (Markgraf)	177	1.80	6.92×10^{-13}
Dolostone (Oatka)	142	1.78	2.37×10^{-12}
Dolostone (Remeo)	264	2.47	1.70×10^{-13}
Granite (Newhurst)	175	1.75	4.90×10^{-13}
Granite (Portuguese)	160	0.80	1.09×10^{-13}
Flechtinger sandstone	96	1.15	6.08×10^{-12}
Jurassic limestone	55	1.21	1.74×10^{-10}
Marble (coarse)	40	1.12	8.63×10^{-10}
Mizunami granite	134	1.60	2.41×10^{-12}
Ogino tuff	55	0.60	3.83×10^{-11}
Porphyric rhyolite	240	1.17	3.30×10^{-14}
Rüdersdorf limestone	40	1.11	8.63×10^{-10}
Ruhr sandstone	95	1.28	8.91×10^{-12}
Ryefield sandstone	35	1.04	1.49×10^{-9}
Sandstone (coarse)	33	0.27	4.07×10^{-11}
Siltstone	51	0.80	7.78×10^{-11}
Syenite	233	1.73	1.68×10^{-13}
White limestone	50	1.38	4.47×10^{-10}

approaches can be utilized:

$$K_1 = \frac{N_P}{\sum_{i=1}^{n} N_i} \tag{6.1}$$

$$K_1 = 1 - \frac{N_L}{\sum_{i=1}^{n} N_i} \tag{6.2}$$

In the equation, N_L is the number of impact sites showing lateral cracking, N_P is the number of impact sites showing ductile erosion, i is the number of inspected impact sites. With known numbers for K_1 (from the counting procedure) and for χ (from materials testing; see Table 1), values for λ and b can be estimated, and Eq. (2) can be quantified for different erosion conditions.

2. Experimental procedure

Experiments were performed on four rock materials, namely rhyolite, granite, limestone, and schist. Their mechanical properties are listed in Table 2. The granite was Portuguese granite with a crystalline structure. The rock forming minerals were mica, quartz and feldspar. The structure was dense. The fracture behaviour was dominated by the cleavage of the minerals. Due to tectonic loading, a pronounced pre-existing micro-crack net was formed in the material. The porphyry was a porphyric rhyolite, consisting of a matrix (approximately 50 vol%) and embedded coarse particles. Major mineral components were potassium feldspar, sodium feldspar and quartz. The non-crystalline matrix was dense and fine-grained (average matrix particle size about 0.1 mm). The inclusions had a maximum grain size of about 13 mm. The limestone was a sedimentary Jurassic limestone consisting of a fine-grained matrix with an average grain size in the 1/10-mm-range and embedded broken shells. These organic inclusions may lead to local strength reduction. However, the calcitic matrix was very dense. The schist was argillaceous schist with a layered structure. The layers could be identified as a white, quartz-rich pale-band, and a dark band containing a high amount of mud and organic substances. Pronounced cleavage could be noticed as the specimens were loaded parallel to the layers. The properties listed in Table 2 were estimated perpendicular to the layer structure.

Erosion conditions and erodent properties are listed in Table 3. The feeder mechanism of the erosion device allowed steady and reproducible particle delivery. Erodent particles entered into the stream of air under the suction provided by a constriction in the inlet section. The particles were then accelerated by the air flow up to an appreciable fraction of the air speed. The particle velocity was calibrated through the pressure of the air delivery system. The targets were mounted a fixed distance from the end of the blasting nozzle, allowing precise control over the exposure position and the impact angle. An impact angle of 90° was applied for all experiments. The exposure time was 30 s, which was in the range of steady-state erosion. Three erosion spots with a cross section of 0.78 cm², generated at an impingement velocity of 140 m/s, were inspected under scanning electron microscopes at magnifications between 10 × and 40,000 × . Two types of SEM were used. The first microscope was type “JEOL 840 SEM” with the following parameters: scanning distance 3.9 mm; voltage 15 kV; electric current 6×10^{-9} A. The second microscope was type “Zeiss Supra VP55” with the following parameters: scanning distance 4–9.8 mm; voltage 10 kV; electric current 10^{-9} A. The samples were sputtered with gold (5–8 nm). Each spot was separated into four sections, and each section was inspected in detail in terms of erosion modes (see Figs. 1a, 2a, 3a and 4a). A total of 250 individual impact sites were

Table 2
Properties of the investigated rock materials.

Material	Splitting tensile strength[a] (MPa)	Density (kg/m³)	Fracture toughness[b] (MN/m$^{3/2}$)	Compressive strength[c] (MPa)	Young's Modulus[d] (GPa)
Granite	10.7	2,500	0.80	160	52
Limestone	10.7	2,500	1.21	55	82
Rhyolite	12.2	2,700	1.17	240	45
Schist	–	2,600	2.70	50	–

[a] Brazilian disc splitting tensile test.
[b] Notch bend three-point bending test.
[c] Uniaxial cylinder test.
[d] Slow-deformation three-point bending test.

Table 3
Experimental conditions and erodent properties.

Parameter	Value
Nozzle diameter	10 mm
Stand-off distance	80 mm
Erodent mass flow rate	0.45 g/s
Angle of impingement	90°
Impingement velocity	140 m/s
Erodent type	Quartz sand
Particle size	0.3–0.6 mm
Particle roundness[a]	1.32
Erodent density	2,650 kg/m³
Erodent indentation hardness[b]	12 GPa
Erodent fracture toughness[b]	1.6 MPa m$^{1/2}$
Erodent Poisson's ratio[c]	0.17
Erodent Young's modulus[c]	87 GPa

[a] Elongation ratio.
[b] Ref. [10].
[c] Ref. [11].