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The response of geo-materials to high-speed liquid drop impact

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ABSTRACT

The subject of the investigation is the response of geo-materials, namely rocks and cementitious composites, to the impact of liquid drops at very high velocities. A single drop impact jet apparatus is utilized for the simulation of drop impacts with a velocity of 885 m/s. The response of six materials (igneous, sedimentary and metamorphic rocks; concretes) with defined mechanical parameters is investigated. The removed volume is measured, and it is related to material parameters, namely uniaxial compressive strength, splitting tensile strength, Young's modulus, mode-I fracture toughness, and elastic strain energy density. The highest correlation exists between removed volume and fracture toughness. SEM inspections revealed a variation of brittle failure features, but barely any signs of plastic response. Threshold criteria are derived, which indicate that hard and brittle rocks respond entirely elastically to the impact in the investigated loading case. A brittle material resistance function is derived, which combines fracture toughness, Young's modulus and density. The results of this study can be used to approximate the resistance of geo-material against high-speed liquid impact, when brittle fracture dominates the material removal process.

1. Introduction

The impingement of high-speed liquid jets is a promising non-conventional method for rock excavation and concrete fragmentation [1], which attracted new interest in recent past [2]. The impingement of micro-jets formed during the asymmetric implosion of gas bubbles plays a major role during the cavitation erosion of rocks in hydraulic structures [3]. On the other side, this phenomenon has the potential for high-effective deep drilling applications [4] and for rock comminution processes [5]. Self-resonating cavitating jets are utilized successfully for deep drilling applications, and rock excavation efficiency can be doubled compared with continuous jets [6]. A combination of mechanical drill bits and pulsed cavitating jets can increase the efficiency of well drilling processes up to 30% [7]. Pulsating water jets also offer qualitative and esthetical advantages for stone surface finishing processes [8]. Examples for the potential of impinging/pulsating water jets for the treatment of particular geo-materials are listed in Table 1.

The terms "*water jet impact*" and "*pulsed jet*" are not precisely defined in the engineering literature, and that makes it difficult to compare and interpret results obtained by different authors. A critical parameter is jet length, or pulse duration. The situation for impinging water volumes on a solid surface is schematically illustrated in Fig. 1. Fig. 1a illustrates the impact of a rather long pulse, or water jet. The process consists of the actual impact period (t_P) with very high pressures (p_D) and a stagnation period with rather low pressures (p_B). The situation is typical for "water jet impact". It is characterized by a number of parameters, namely p_B, p_D, t_1, t_2, and t_P, defining the two phases of the impact process. Their meanings are discussed in Chapter 2. Fig. 1b illustrates the impact of a pulsed jet. The jet consists of two consecutive pulses ($N_P = 2$). The pulses are sufficiently long to allow for the formation of a stagnation phase. Pressures vary between p_{DP} and p_B with a given frequency; similar to a fatigue load. Fig. 1c illustrates the impact of a cavitating jet. The gas bubbles, carried with the jet, implode and generate short high-stress pulses. Fig. 1d illustrates the impact of a water drop. This situation does not include a stagnation phase, or the stagnation phase is negligibly short. Previous works in rock removal covered the situations shown in Figs. 1a–c, and only one author [18,19] was concerned with the impingement of water drops without any (or with negligible) stagnation period ($t \leq t_P$). A summary of existing works is provided in Table 2. This paper is concerned with the situation illustrated in Fig. 1d.

The material removal due to drop impact may generally be described as follows:

$$V_M = f(P)f(M)(v_D - v_C)^m \quad (1)$$

This situation is simplified in Fig. 2. In the equation, V_M is the removed volume, v_D is the drop impact velocity, v_C is a threshold velocity, m is a power coefficient, f(P) is a function covering process parameters (namely drop size, pulse length, pulse frequency, and angle of impingement), and f(M) is a function covering target

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Nomenclature

c_D	speed of sound in water
c_M	speed of sound in target material
c_S	shock wave velocity target material
c_W	shock wave velocity water
d_D	drop diameter
E_D	drop kinetic energy
E_M	Young's modulus target material
E_T	cracking energy
f(M)	target material parameter function
f(P)	process parameter function
f_S	stress wave transfer coefficient
f_Y	plastic target parameter function
H_M	indentation hardness target material
I_M	sound impedance target material
k_1	energy transfer coefficient
K_{Ic}	fracture toughness target material
m	power coefficient
M	target material parameter
m_D	drop mass
n	power exponent
p_B	stagnation pressure
p_D	impact pressure
r	radial direction vector
r_C	contact radius
r_D	drop radius
R_P	stress magnification factor
SE_M	elastic strain energy density target material
t	exposure time
t_1	pulse stage duration
t_2	radial flow stage duration
t_P	pulse period
v_C	threshold impact velocity
v_D	drop velocity
v_E	threshold velocity crack formation
V_M	removed volume
V_P	removed volume (plastic)
V_W	removed volume (brittle)
v_Y	threshold velocity plastic deformation
z	axial direction vector
Δm	mass loss
$\dot{\varepsilon}$	strain rate
γ_M	specific surface energy
η	erosion model parameter
ρ_D	drop density
ρ_M	density target material
σ_C	compressive strength target material
σ_P	pulse stress
σ_T	tensile strength target material
σ_Y	yield strength target material

material properties. For $v_D < v_C$, material removal does not occur. For brittle materials, v_C is mainly related to fracture toughness of, and sound velocity in, the target material [26]. Effects of impact velocity in that period on the crack morphology in rocks and cementitious composites, impinged by simulated water drops, are quantified in detail in references 18 and 19. Reference 18 also verified the contribution of lateral jetting to the damage process. Threshold conditions for the damage of rock materials due to impinging water drops as well as an elastic–plastic transition criterion for rock materials are derived in reference 27. The function f(P) is specified for two rock materials in reference 28, where effects of pulse length and pulse frequency are investigated. Ni et al. [16] discussed the effects of pump pressure, jet length, nozzle diameter, impact velocity, impingement time, and pulse frequency on the rock excavation performance of pulsating jets. Lu et al. [29] investigated the effect of water jet impact velocity on the material removal process in sandstone. They noted a linear relationship between damage depth and impact velocity. The authors also investigated the crack morphology, and they found that cone crack length increases, and cone crack angle decreases, with increasing impact velocity. The function f(M) is investigated in reference 18 for the range $v_D \approx v_C$, and it is found that the dimensions of crack rings, formed during liquid impact, depend on fracture toughness of rocks.

Investigations for f(M) for rocks and rocklike materials for the situation $v_D >> v_C$ (thus, for the actual material removal phase) are only a few. They are summarized in Table 2. They basically apply to the case of liquid segments with a notable stagnation period ($t > t_P$), but not to the case of drop impact (see Fig. 1). Gnirk and Grams [21] proposed a second-power inverse relationship between removed volume and tensile strength for numerous rocks. Farmer and Attewell [23] and Labus [22] suggested inverse power relationships between removal depth and compressive strength of geo-materials, whereas the power coefficient was –0.95 for rocks and –0.25 for concrete. Singh and Huck [20] found a reverse power relationship between removal depth and compressive strength for a number of rocks. Cooley [30] suggested using the "specific fracture energy" (Eq. 15) of rocks to characterize their resistance against impinging water slugs. [More precisely, this is *elastic strain energy density*.] This parameter was utilized for characterizing the response of geo-materials to impact and erosion [31,32]. However, references 20–23 and 30 rather utilized water jets, or pulses, with a stagnation phase. Preliminary results on the effects of fracture toughness and sound impedance are provided in reference 33; this author reported a negative power function for either parameter, but neither quantified nor analyzed the results. For a related material type, brittle ceramics, a relationship $V_M \propto K_{Ic}^{-7.9}$ was found [34]. Fracture toughness seemed to have an extraordinarily high effect on the removal process for this material type.

Analysis of Table 2 reveals two gaps in the existing literature:

(1) No investigation has been performed for a wider variation of geo-materials, including cement-based composites and layered rocks.
(2) No investigation has been performed that covers the situations $t \le t_P$, $v_D > v_C$, and $N_P = 1$ for geo-materials.

The objectives of this paper are:

- to quantify target material property effects on the material removal process;
- to quantify material failure modes for geo-materials; and
- to introduce a detailed expression for the target material function f(M).

2. Loading due to liquid drop impingement

Drop impact can be considered a tribological process, and it can be expressed in a tribological system. The tribological system for water drop impact is schematically shown in the upper image of Fig. 3. It features the loading collective, the wear parameters, the surrounding medium, and the bodies involved in the process. The *loading collective* for $t \le t_P$ is denoted f(P) in this paper. The *material loss* is characterized through the removed volume V_M (mm^3) in this study. *Surface modifications* are discussed in Section 4. The *surrounding medium* is air. The term *basic body* characterizes the geo-materials; it is denoted f(M) in this paper. The term *reverse body* characterizes the impinging drops.