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Fundamental investigations on concrete wear by high velocity water flow

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Abstract

A primary concern in the design of marine constructions is the wear and erosion of concrete structures by high velocity water flow. The mechanism of concrete failure for this type of loading is not well understood. By using high velocity water jets to simulate the loading, the authors observed the general behaviour of concrete during failure and investigated the influence of water velocity and exposure time. The results show that the interface between hardened cement paste and aggregate grains plays the main role in the fracture process. It is found that a critical threshold velocity w_c and a critical threshold exposure time t_c must be achieved in order to induce the erosion process. A mathematical relation between both parameters and the erosion intensity is found through mass removal measurements.

Keywords: Concrete; Water flow; Erosion

1. Introduction

Since concrete is used for marine and hydraulic structures, pipe coating and channel walls, its wear due to the attack of fast flowing water is a problem [1]. The first systematic investigations on the resistance of concrete against wear in marine structures were carried out in the 1940s [2]. The mechanisms which act in this case of loading can be subdivided into three events:

(1) direct action of the high velocity water flow (erosion), which is the topic of the present paper;
(2) action of imploding gas bubbles in high velocity flow (cavitation); and
(3) action of suspended solid particles with high velocities (abrasion).

Studies addressing these wear mechanisms are presented in [2–10], and the results are summarized below. The loading and failure of concrete due to erosive action are localized processes with a dynamic character. It was found that the properties (hardness, weight), as well as the distribution of the inclusions (aggregate materials) in the concrete, have a greater influence on the erosion resistance than the macroscopic material properties. Also, the structural properties of the concrete mixture, such as porosity, permeability and homogeneity influence its erosion resistance. Conventional mechanical properties do not give exact information on the erosion resistance of concrete, but for the case of abrasion the fracture energy of concrete is in good relation with its resistance. It was found that the most important parameters to describe the regime of loading are flow velocity and exposure time, but no work has been carried out to investigate and verify the influence of these parameters. In general, the basic destruction mode of concrete due to high velocity water flow is not well understood, and no satisfactory theories exist to describe the behavior of concrete exposed to erosion, cavitation or abrasion.

These findings suggest two problems. First, when investigating the behavior and resistance of concrete exposed to high velocity water flow, not only must the macroscopic strength properties be addressed, the structure of the concrete material, especially the inclusions must be considered. Wittmann [11] proposed a hierarchic system of three levels for the structural modelling of concrete. The micro-level is concerned with the structure of the hardened cement paste; the meso-level deals with pores, inclusions, cracks and interfaces; the macro-level is related to the structural element (e.g. specimen). The present investigation is based on the assumption that the material characteristics from the meso-level, such as pores, inclusions (aggregates),

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cracks, and interfaces (between aggregates and cement matrix), are most susceptible to the penetration of fluids. These targets for penetration strongly influence the behavior of concrete exposed to erosion by high velocity water flow. Secondly, the investigation of the basic failure mode must be carried out under intensified loading conditions, which means higher flow velocity and shorter exposure time compared with the previous investigations. For these reasons, this present work concentrates on the following problems:

(1) Investigation of the influence of inclusions (aggregate grains), especially of the interface between inclusion and matrix, on the erosion resistance of concrete.
(2) Influence of the erosion attack on the meso-level structure of concrete and derivation of a general failure mode during erosion.
(3) Investigation and quantitative description of the influence of flow velocity and exposure time on the erosion resistance of concrete.
(4) Development of a calculation model for the estimation of concrete erosion due to high velocity water flow.

2. Materials and experimental methods

2.1. Materials

Two different materials, a hardened cement paste and a concrete material, are developed to investigate the influence of aggregate particles and their interfaces with the cement paste. The cement paste is a hardened mixture of water (W) and binding agent (B) in the ratio of W:B = 0.55. A Portland Cement (PZ 35 F) according to DIN 1164 was used as the binding agent. After mixing, this composition was cured and hardened for 28 days. The same procedure was followed for the concrete samples. The concrete mixture consists of water (W), binding agent (B) and limestone grains (G) as inclusions. Fig. 1 shows the distribution of the inclusions. The water to binder ratio was changed depending on the moisture absorbing capacity of the inclusions. General material properties are given in Table 1.

2.2. Testing equipment and performance

The high speed water flow attack is simulated by a water jet having velocities up to 400 m s^{-1}. Fig. 2 shows the general structure of a water jet. More details of jet generation and action can be found in [12]. The high velocity water jet unit consists of a high pressure water pump (110 kW), hose system, nozzle holder, nozzle, and rotating worktable. The nozzle holder and specimens are located inside a closed plexiglass cell,

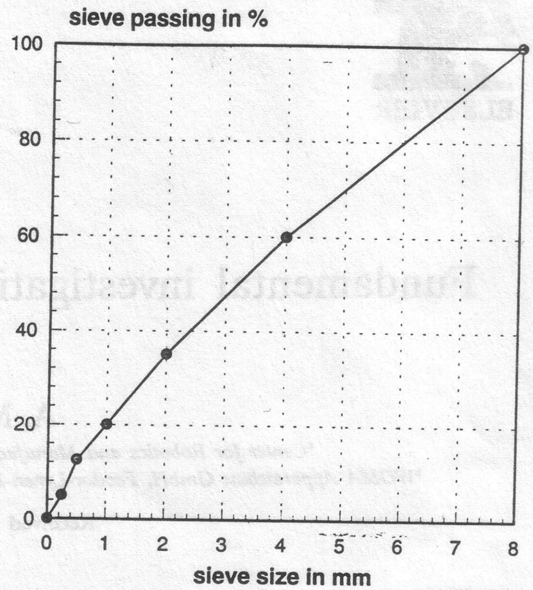

Fig. 1. Distribution of the used aggregate grains according to DIN 4188.

Table 1
Mechanical properties of the investigated concrete mixtures

Property	Concrete 1	Concrete 2
Compressive strength (MPa)	21	39
Young's modulus[a] (MPa)	19930	25463
Bulk density (kg m^{-3})	2070	2290
Absorbed fracture energy[b] (MJ m^{-3})	14.5	65.1

[a]According to DIN 1048.
[b]11th loading cycle according to DIN 1048.

which makes it possible to collect the removed material and weigh it.

The pore and crack systems of the materials, including non-visible structural changes inside the specimens, are detected by a mercury penetration unit. Using Eq. (1) (Washburn equation), one can assume a relation between the pressure (p_m) which is necessary to transport mercury into the structure and the size (diameter in case of pores, length in case of cracks) of the transport paths (r).

$$r = 2\sigma_0 \cos \phi / p_m \quad (1)$$

Here, σ_0 is the surface tension of the mercury and ϕ is the contact angle of the hardened cement matrix. If r represents the radius of a pore and the length of a crack, respectively, and V is the volume of mercury which penetrates the material under a given pressure, a relation can be obtained between the size (r) and the relative fraction ($dV/d \log r$) (see Fig. 3). The processes of preparation and handling of a mercury penetration unit are described by Schneider and Herbst [13] and Momber [14]. Additionally, all samples and

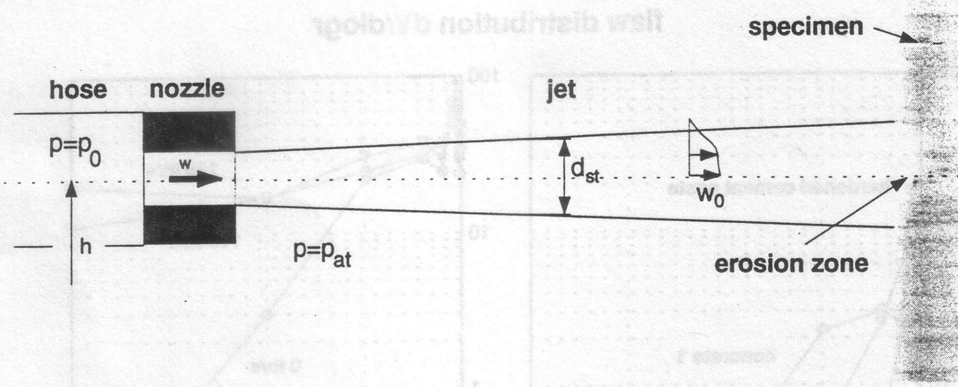

Fig. 2. Fluid mechanical situation during water jet generation.

the removed material are observed using optical and scanning electron microscopy.

3. Results and discussion

3.1. Destruction and failure process

Fig. 3, which is based on Eq. (1), shows a comparison of the mercury penetration results obtained for samples exposed to water jet attack and those which had not been subjected to a water jet. For the loaded samples, all measurements were carried out on areas which did not show any visible damages, so they represent the situation before the visible erosion process starts. In Fig. 3(a) one can find the flaw distribution of an unloaded specimen, which was measured before the erosion process was started. The curve for the plain cement paste exhibits a maximum between 10 nm and 100 nm which is typical for this material and represents the capillary pore system. The addition of aggregates leads to an increase in the number of large flaws (100–1000 nm in length). This range is defined as a microcrack region [13] and describes the influence of the interfaces between cement paste and aggregate grains. The structure of a cement paste/aggregate interface is shown in Fig. 4. As Larbi [16], Alexander [17], and Langton and Roy [18] have shown, this zone is characterized by a high degree of microporosity and reduced strength properties, and can be described as the "weakest link" in concrete with respect to strength. It is expected that these interfacial zones play important roles during water flow erosion. To illustrate this, Figs. 3(b) and 3(c) show the influence of the flow velocity on the flaw distributions of the eroded concretes. It can be noted, that the number of microcracks greater than 100 nm in length greatly increases when the specimen is subjected by the water flow. So one can assume that, starting from the interfacial zone, a network of cracks is formed before the macroscopic and visible erosion process starts. These events can be described as an incubation period. Only the connection of these cracks leads to the removal of material grains and yields a measurable erosion (Fig. 5). The behaviour of the plain cement paste during erosion, which is shown in Fig. 3(d), is somewhat different. The second maximum of the flaw distribution curve (crack lengths between 100 and 1000 nm) is not very significant, which implies that a network of microcracks is not present. The smooth macroscopic surfaces of the failed cement paste sample, which were observed after the fracture, supports this conclusion. Obviously, this material fails suddenly as a result of the presence of only a few large cracks which generate relatively large erosion debris. Whereas the maximum average debris diameter of the concrete specimens was about 8.0 mm, in the case of the hardened cement paste the average debris diameter was about 50 mm. This type of failure could be due to the fact that, in contrast to the concrete, no aggregate grains are present to stop or branch the cracks so they are able to penetrate the material.

3.2. Influence of flow velocity

As was previously pointed out, the water flow velocity is an important influence parameter in the erosion process. Using Bernoulli's law of pressure constancy according to Fig. 2 and Eq. (2), the velocity of the water jet, w_0, can be estimated from Eq. (3)

$$g\,dh + \rho_w^{-1}\,dp + d(0.5w^2) = \text{const.} \tag{2}$$

$$w_0 = \mu p_v \sqrt{2p_0/\rho_w} \tag{3}$$

The parameters μ and p_v define velocity losses due to friction on the nozzle walls (μ) and in the transport hoses (p_v), respectively. The factor μp_v was estimated by measurements to be 0.9. Fig. 6 shows the relation between the pressure of the water pump and the mass loss due to erosion. According to Eq. (3) one can expect a linear correlation between the square of the flow velocity and the mass loss due to erosion. This relation is given in Fig. 7. The function can be described

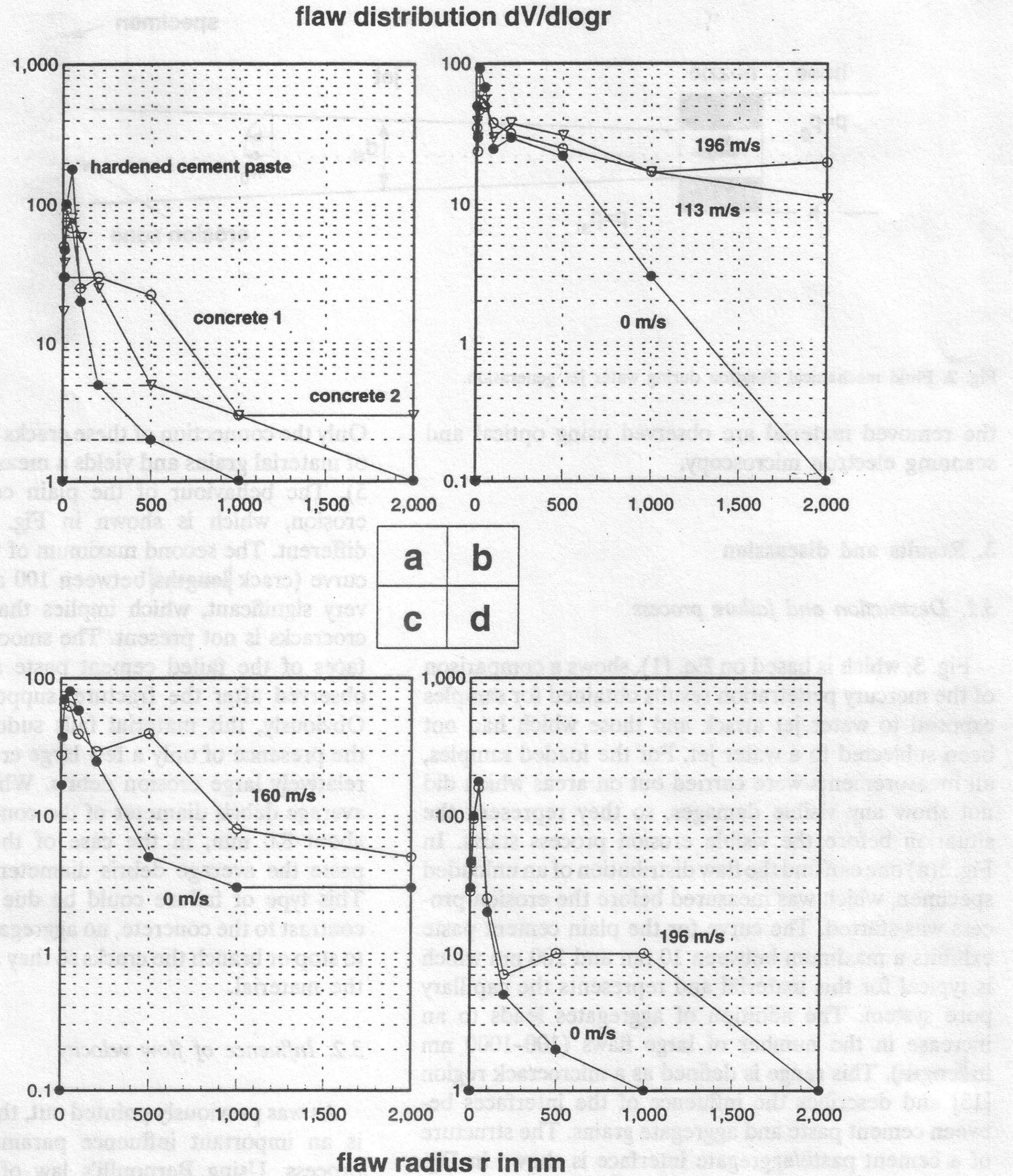

Fig. 3. Mercury penetration measurements on plain and eroded material samples [14]: (a) all materials, uneroded; (b) concrete 1, eroded; (c) concrete 2, eroded; (d) hardened cement paste, eroded.

by

$$m = C_1(w_0^2 - w_c^2) \tag{4}$$

The parameter w_c can be taken as a critical threshold velocity which is needed to induce the destruction of the material. Below this threshold value no visible erosion occurs, however an invisible network of cracks is still generated in the material (Figs. 3(b)–3(c)). It was shown by water jet cutting investigations on rocks [19] that this parameter is related to the stress intensity factor of the materials. It will be seen that the progress of the function, $C_1 = \mathrm{d}m/\mathrm{d}w_0^2$, is constant over the entire velocity range. Contrary to the cement paste samples the concrete specimens were not destroyed completely at high flow velocities, but a continuous material removal was observed. This behaviour illustrates again that unrestrained cracks can not be the source of the erosion of concrete. Obviously, the crack growth has been interrupted due to events of energy dissipation and toughening mechanisms. Mechanisms related to the concrete can be: crack shielding, crack deflection, crack arresting, crack bridging, and crack progress through aggregate grains [20]. Several of these phenomena were observed during water jet cutting of concrete materials

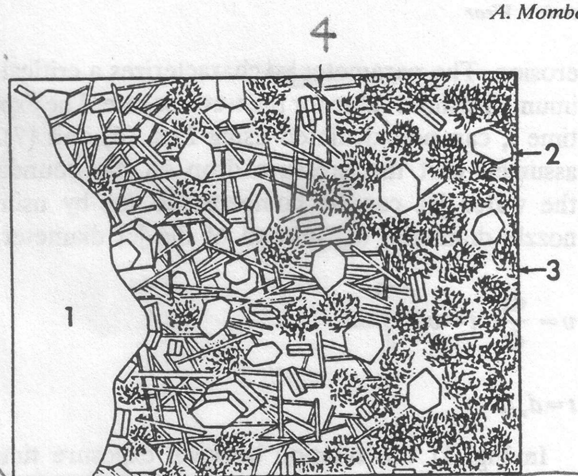

Fig. 4. Grain size structure of eroded particles ($w_0 = 226$ m s^{-1}).

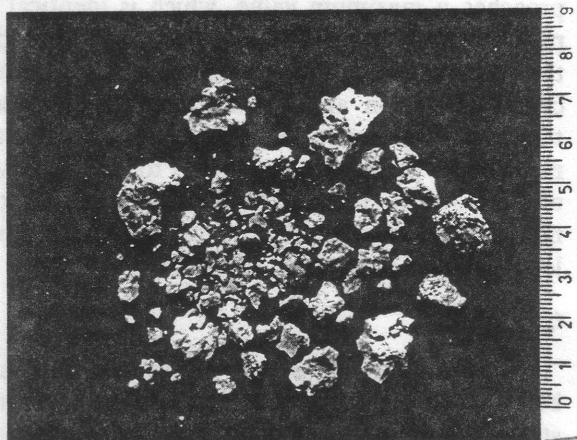

Fig. 5. Structure of the interface between hardened cement paste and aggregate grain [15]: 1, aggregate grain; 2, $Ca(OH)_2$; 3 C–S–H; 4, ettringite needles.

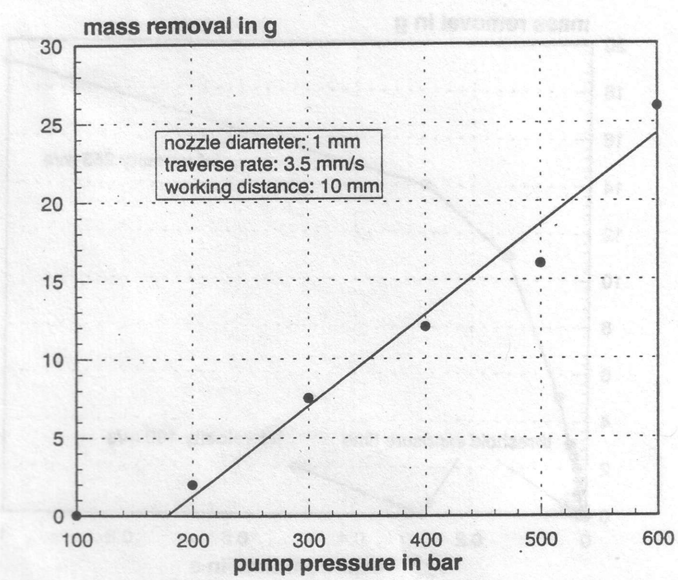

Fig. 6. Relation between pump pressure and mass loss due to erosion (concrete 1).

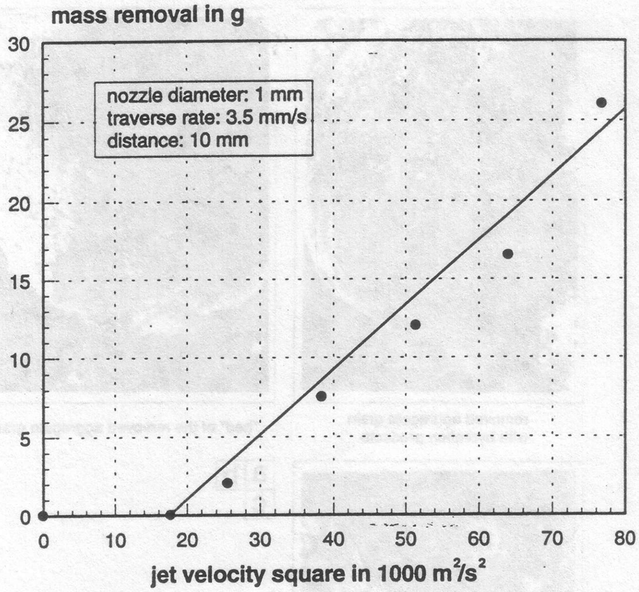

Fig. 7. Relation between quadratic flow velocity and mass loss due to erosion (concrete 1).

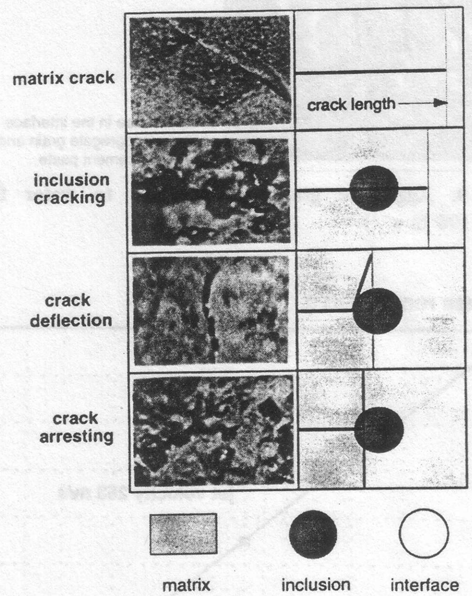

Fig. 8. Toughening mechanisms in concrete removal by water jet attack [21]: matrix crack (×20), inclusion cracking (×11), crack deflection (×11), crack arresting (×11).

by Momber and Kovacevic [21] (Fig. 8). Fig. 9 shows an example of a single aggregate grain removed by interfacial fracture, which is related to crack deflection and crack bridging.

4. Influence of exposure time

The second important influence parameter, exposure time t, is simulated in this study by the traverse rate of the nozzle holder, v. Fig. 10 shows the relation between traverse rate and mass removal due to erosion

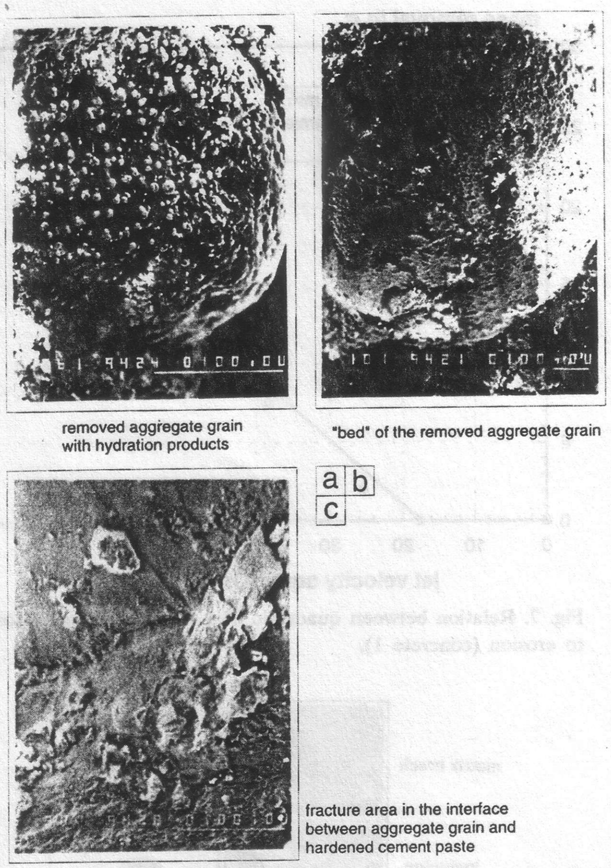

Fig. 9. Aggregate grain removal due to water flow erosion ($w_0 = 196$ m s^{-1}).

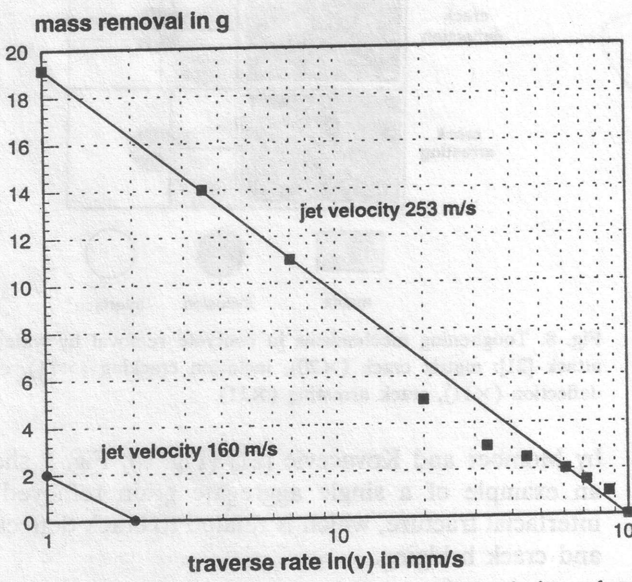

Fig. 10. Relation between traverse velocity, flow velocity and mass removal due to erosion (concrete 1).

for different jet velocities. The function is in good agreement with Eq. (5).

$$m = m_{v=0}[-(\ln v/\ln v_c)+1] \quad (5)$$

Here, $m_{v=0}$ is the mass loss for the case of stationary erosion. The parameter v_c characterizes a critical maximum threshold value for the traverse rate. The exposure time t, can be calculated using Eqs. (6) and (7). It is assumed that the pressure drop on the boundary of the water jet can be compensated for by using the nozzle diameter, d_n, instead of the jet diameter.

$$v = \frac{dx}{dt} \qquad t = v^{-1}\int_0^{d_n} dx \quad (6)$$

$$t = d_n/v \quad (7)$$

In Fig. 11 the relation between exposure time and mass removal due to erosion is plotted based on Eq. (7). One can notice a threshold exposure time t_c, which is necessary to induce damage in the material. Also, this figure shows that the function asymptotically approaches a maximum value, which is identical to the parameter $m_{v=0}$ in Eq. (5). It was found in section 3.1 that the erosion process consists of several events of crack generation and propagation. This suggest that the critical exposure time, t_c, can be related to a fracture-mechanical parameter, especially to the crack velocity of the material (v_{cr}), and that the duration of exposure must be long enough to generate a certain critical crack length (l_{cr}). This can be expressed by Eq. (8).

$$t_c = l_{cr}/v_{cr} \quad (8)$$

To verify this assumption, a comparison is made between a measured threshold exposure time from this study and results of a previous study (Momber [27]). The crack velocity of concrete, v_{cr}, can be estimated using Eq. (9) [22,23].

$$v_{cr} = 0.25\sqrt{E_m/\rho_m} \quad (9)$$

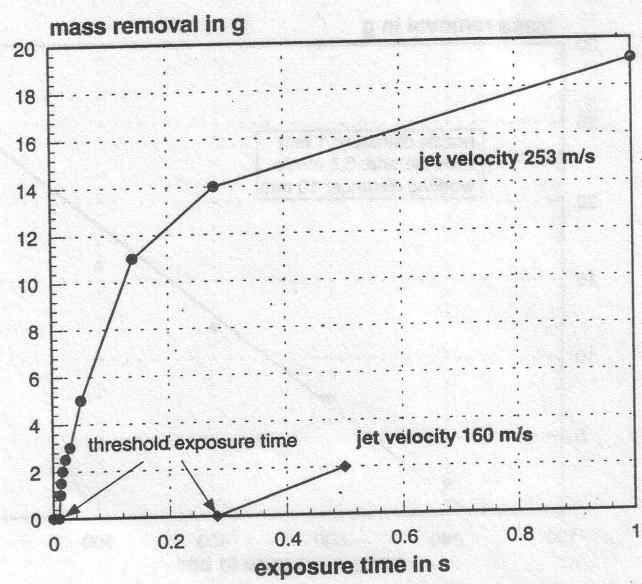

Fig. 11. Relation between exposure time, flow velocity and mass removal due to erosion (concrete 1).

Using the comminution model of proportionality between applied energy and surface generation [24], the length of a crack network, l_{cr}, can be written as:

$$l_{cr}=\sqrt{0.5S_e} \quad (10)$$

The surface of the eroded material, S_e, can be estimated by different graphical and numerical methods [25,26]. Eqns. (8)-(10) lead to Eq. (11) for the calculation of t_c.

$$t_c=2.83\sqrt{S_e\rho_m/E_m} \quad (11)$$

Using the mechanical material parameters in Table 1 and surface values of removed concrete grains, which Momber [27] has estimated by applying a RRSB-grain-distribution network, the calculated threshold exposure time according to Eq. (11) is 0.02 s for a jet velocity of 253 m s^{-1}. This is in good qualitative agreement with Fig. 11.

5. Equation for the erosion of concrete due to high velocity water flow

Fig. 11 shows that a dependence exists between exposure time and jet velocity. Based on tests results, the authors found a relation according to Eq. (12).

$$w_c=at^{-b} \quad (12)$$

This qualitative relation is in good agreement with the experimental data from [28]. It was also found that the constant C_1 in Eq. (4) is independent of exposure time and traverse velocity, which is in correspondence with observations made in high velocity abrasive wear investigations [29]. Using Eqs. (4) and (12), the material mass loss due to high velocity water flow erosion can be calculated by Eq. (13).

$$m=C_1[w_0^2-(at^{-b})^2] \quad (13)$$

Fig. 12, which is the graphical interpretation of this equation, shows that a minimum flow velocity and a minimum exposure time are needed to start the erosion of the investigated concrete mixture. Below these critical values, which are characterized by the line $m=0$ g, an erosion-free zone exists. The figure also illustrates the dominating influence of the flow velocity on the erosion performance.

6. Conclusions

The present investigation leads to the following conclusions.

(1) A high speed water jet was used for the fast simulation of concrete behaviour in hydraulic structures.

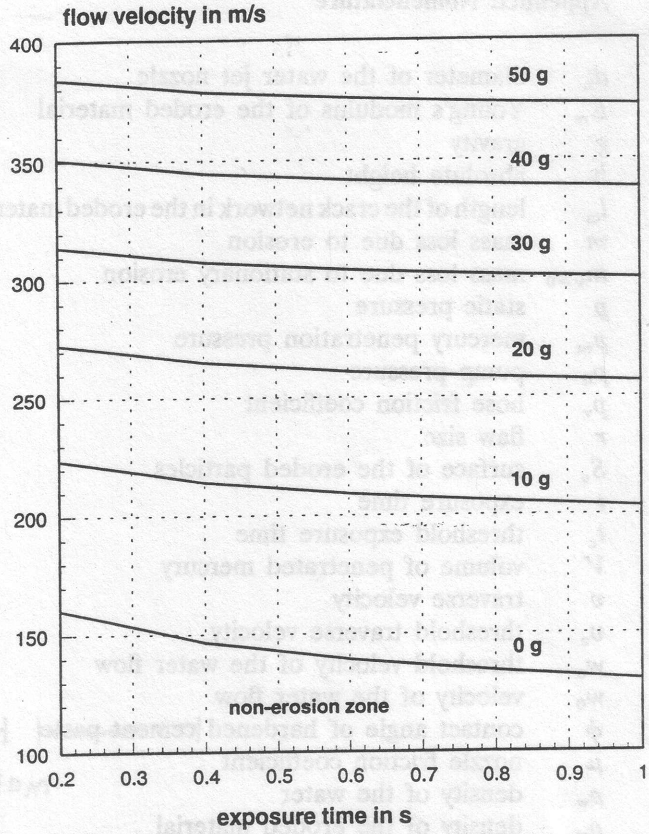

Fig. 12. Calculated mass loss values using Eq. (12) (concrete 1).

(2) The erosion of concrete by high velocity water flow is caused by the generation and widening of microcracks.

(3) The erosion process is induced at the interface between hardened cement paste and aggregate grains.

(4) The erosion progress is controlled by toughening mechanisms, mainly caused by the aggregate–crack interaction.

(5) A critical flow velocity w_c is needed to start the erosion process. This parameter is related to the fracture mechanical properties of the eroded material and

(6) A critical exposure time t_c is also needed, to start the erosion process. This parameter is related to the crack velocity in the eroded material.

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Appendix: Nomenclature

d_n	diameter of the water jet nozzle
E_m	Young's modulus of the eroded material
g	gravity
h	absolute height
l_{cr}	length of the crack network in the eroded material
m	mass loss due to erosion
$m_{v=0}$	mass loss due to stationary erosion
p	static pressure
p_m	mercury penetration pressure
p_0	pump pressure
p_v	hose friction coefficient
r	flaw size
S_e	surface of the eroded particles
t	exposure time
t_c	threshold exposure time
V	volume of penetrated mercury
v	traverse velocity
v_c	threshold traverse velocity
w_c	threshold velocity of the water flow
w_0	velocity of the water flow
ϕ	contact angle of hardened cement paste
μ	nozzle friction coefficient
ρ_w	density of the water
ρ_m	density of the eroded material
σ_0	surface tension of mercury

References

[1] A.P. Davis, Safe velocities of water on concrete, *Engng. News*, (1912) 20–21.

[2] W.H. Price, Erosion of concrete by cavitation and solids in flowing water, *J. ACI Proc., 43* (1947) 1009–1023.

[3] J.R. Graham, Erosion of concrete in hydraulic structures, in *Manual of Concrete Practice, Part 1*, American Concrete Institute, Detroit, 1988, 210, pp. R1–R22.

[4] M.G. Pat and H.W. Reinhardt, Erosion of concrete, *Heron, 24* (1979) 5–24.

[5] J. Mirza, S. Turenne and J. Masounare, Influence of structural parameters on the abrasion–erosion resistance of various repairing mortars, *Can. J. Civil Eng., 17* (1990) 12–17.

[6] X.H. Zhang and Y. Huang, Fundamental study on the abrasive behaviour of concrete, *Fracture Mechanics and Fracture Energy of Concrete*, Elsevier, Amsterdam, 1986, pp. 561–564.

[7] T.F Fwa and W. Low, Laboratory evaluation of wet and dry abrasion resistance of cement mortar, *Cement, Concrete and Aggregates, 12* (1990) 101–106.

[8] R.K. Dhir, P.C. Hewlett and Y.N. Chan, Near surface characteristics of concrete: abrasion resistance, *Mater. Structures, 24* (1991) 122–128.

[9] S.H. Dahir, Relative resistance of rained-on concrete pavements to abrasion, skidding and scaling, *Cement, Concrete and Aggregates, 3* (1981) 13–20.

[10] K. Walz and G. Wischers, On the resistance of concrete against high speed water flow (in German), *Beton*, (1969) 403–405, 457–460.

[11] F.H. Wittmann, Structure of concrete with respect to crack formation, *Fracture Mechanics of Concrete*, Elsevier, Amsterdam, 1983, pp. 43–74.

[12] A. Momber, *The Basics of Water Jet Cutting Technology* (in German), Beton, Dusseldorf, 1993.

[13] U. Schneider and H.J. Herbst, Porosity parameters of concrete (in German), *TIZ Int., 113* (1989) 311–321.

[14] A. Momber, Mercury penetration measurements on concrete samples after water jet cutting (in German), *Materialwiss. Werkstofftech.* (1992) 283–286.

[15] P.K. Metha, *Concrete: Structure, Properties and Materials*, Prentice Hall, 1986.

[16] J.A. Larbi, Microstructure of the interfacial zone around aggregate particles in concrete, *Heron, 38* (1993) 3–69.

[17] M.G. Alexander, Two experimental techniques for studying the effects of the interfacial zone between cement paste and rock, *Cement Concrete Res., 23* (1993) 567–575.

[18] C.A. Langton and D.M. Roy, Morphology and microstructure of cement paste/rock interfacial regions, *Proc. 7th Int. Congress on the Chem. of Cement, 1980, Paris*, Vol III, pp. VII127–VII132.

[19] J. Wiedemeier, High velocity fluid jets and fracture kinetics of brittle materials (in German), *Diss. thesis*, Univ. of Hannover, 1981.

[20] S.P. Shah and C. Ouyang, Toughening mechanisms in quasi-brittle materials, *J. Eng. Mater. Technol., 115* (1993) 300–307.

[21] A. Momber and R. Kovacevic, Removal of brittle multiphase materials by high energy water jet, paper submitted to *J. Mater. Sci.*, 1994.

[22] H. Blumenauer and G. Pusch, *Technical Fracture Mechanics* (in German), VEB, Leipzig, 1987.

[23] M. Curbach and J. Eibl, Crack velocity in concrete, *Eng. Fracture Mech., 35* (1990) 321–326.

[24] F.C. Bond, Calculation method for fine comminution (in German), *Aufbereitungstechnik*, (1964) 211–218.

[25] H. Rumpf and K.F. Ebert, Grain size distributions and calculation of specific surfaces (in German), *Chemie-Ing. Techn., 36* (1964) 523–537.

[26] H. Schubert, *Processing of Solid Minerals*, Vol. 1, VEB, Leipzig, 1989.

[27] A. Momber, Investigations in the behaviour of concrete during water jet processing (in German), *VDI Fortschrittsber. 109*, 1992 (VDI, Dusseldorf).

[28] F. Erdmann-Jesnitzer, H. Louis and J. Wiedemeier, The action of high speed water jets on materials – measurement methods and their practical application, *Proc. 5th Int. Symp. on Jet Cutting Techn.*, Paper B3, Hannover, 1980, pp. 75–86.

[29] H. Blickwedel, Generation and action of high pressure abrasive jets (in German), *Diss. thesis*, Univ. of Hannover, 1990.