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COMPARISON OF CONTINUOUS AND PULSING WATER JETS FOR REPAIR ACTIONS ON ROAD AND BRIDGE CONCRETE

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Abstract. The concrete samples with various erosion states simulating road or bridge damage were disintegrated by pure continuous water jets generated from pressure 380 MPa and by pulsing water jets generated from low pressure 30 MPa. The erosion states of samples were prepared applying several laboratory techniques simulating the concrete aging under the conditions corresponding to the use in practice. The influence of the erosion state on the disintegration rate was tested because water jet techniques are very effective in selective disintegration of damaged concrete without significant erosion of the unbroken concrete unlike pneumatic drills or other impacting machines usually used for such a work. The comparison of both the depth of penetration and the ratio of volume disintegration regarding the input power is performed. All results are discussed regarding their application in practice and further development of special routings.

Keywords: water jet, depth of penetration, removed volume, concrete erosion, concrete repair, reinforcement purging.

1. Introduction

The research presented in this paper is aimed at better preparation of surfaces during the repair actions on concrete constructions, especially concrete road surfaces and bridges. The new surfaces should be properly structured so that the repairing materials can well adhere to the underlay. Sometimes, the damaged concrete needs to be removed to the reinforcement. The reinforcement can be easily cleaned by water jets and prepared to a subsequent new concreting. Many types of concrete damage are studied on samples prepared in laboratories of the Faculty of Civil Engineering at the Technical University of Brno. The samples include simulation of freezing and thawing cycles, influence of chemical thawing agents, atmosphere in chemical plants, media in sewages, aggressive underground waters and many more corrosive media. Some of the concrete corrosion problems, especially those related to concrete on bridges and road surfaces, were described by e.g. Hääl and Sürje (2006) or Kamaitis and Čirba (2007). It is supposed that together with information about climate changes and evaluation of action of those changes (like described by Laurinavičius *et al.* 2007; Juknevičiūtė, Laurinavičius 2008) it will be possible to repair and protect concrete structures more efficiently. Both the theoretical study presented in this paper and the subsequent water jet efficiency analysis is based on theories prepared by Hlaváč (1992). This theoretical model describing water jet disintegration of brittle materials was derived in late eighties using both some results and theoretical premises prepared by researchers closely adherent to practice (Crow 1973; Rehbinder 1980) and the works of rather theoretically oriented researchers (Hashish, duPlessis 1978; Yanaida 1974). The model was completed later (Hlaváč, Sochor 1995) according to the topical knowledge (Summers, Blaine 1994). Since the end of nineties the Hlaváč's theory is used in our laboratory for analyses, description and prediction of water jet efficiency in air and also in a certain depth under the water level. The submersion is simulated by water overpressure inside a special vessel. The most common concretes used for construction of bridges and roads in the Czech Republic were tested both in air and under the water level in the Laboratory of Liquid Jet at the VŠB–Technical University of Ostrava and in laboratories of the Institute of Geonics CAS, v.v.i. in Ostrava.

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2. Theoretical background

Basic theoretical presumptions related to the water jet attenuation in the medium outside the nozzle and used for analyses presented in this paper were published in nineties (Hlaváč *et al.* 1999). This theoretical background is inspired by theories describing behaviour of the cumulative charge (e.g. Lavrentiev 1957). Considering the medium outside the water nozzle to be the fluid continuum the equation for evaluation of the attenuation coefficient was derived. The uniform equation for evaluation of the coefficient characterizing the attenuation of the liquid jet energy inside any continuum, which it is passing through, was derived. The coefficient was determined from the density of the fluid continuum surrounding the water nozzle, the density of the jet forming liquid and the characteristic jet cross-section dimension:

$$\xi = \frac{C_x}{\mu} \frac{\rho_e}{\rho_o d_o} . \tag{1}$$

The jet-head shape resistance coefficient C_x is a function of the type and pressure of the fluid medium outside the water nozzle, the discharge coefficient μ is determined by the water nozzle geometry. Then the depth of penetration (commonly named depth of cut) can be calculated using the equation derived and presented about twenty years ago (Hlaváč 1992):

$$h = \frac{\pi d_o \sqrt{2\rho_o \mu^3 p^3 \gamma_R^3 e^{-5(\xi L)}} (1-\alpha^2)\cos\theta}{4\chi\rho_M \, \nu^{\frac{\rho_o}{\rho_M}} \left[\alpha^2 e^{-2(\xi L)} \mu p \gamma_R + \frac{\rho_o}{\rho_M} \sigma \right]} . \tag{2}$$

The variables, parameters and coefficients in the Eqs (1) and (2) have the following meanings: α – coefficient of water jet velocity losses in interaction with material; γ_R – compressibility factor; θ – angle of incidence of the water jet measured between the normal to the material surface at the point of jet axis projection and the jet axis, rad; μ – water nozzle discharge coefficient; ξ – coefficient of the jet attenuation caused by resistance of the medium between the nozzle outlet and the target surface, m^{-1}; ρ_0 – water density in a non-compressed state, kg.m^{-3}; ρ_e – density in a non-compressed state of the continuum fluid medium between the nozzle outlet and the target surface; kg.m^{-3}; ρ_M – density of material, kg.m^{-3}; σ – material compressive or combined strength, Pa; χ – coefficient of reflected jet expansion due to mixing with disintegrated material; C_x – coefficient of water jet head shape in the continuum fluid medium between the nozzle outlet and the target surface; d_0 – water nozzle diameter, m; *h* – depth of water jet penetration into material, m; *L* – stand-off distance from the water nozzle outlet, m; *p* – water pressure before the nozzle inlet, Pa; *v* – modified traverse speed, m.s^{-1}.

This theoretical model seems to be quite sufficient for description of the water jet impact on material in gas medium. Using this theory for outflow to liquids it can be mentioned that the density of the fluid continuum surrounding the water nozzle and the density of the jet forming liquid can be of close or even identical values. Then the characteristic size, i.e. nozzle diameter, starts to play the decisive role. The theoretical attenuation seems to increase into very high values and the respective jet radius of action is close to zero. Nevertheless, this conclusion is not verified by experiments. The efficiency of the water jet drops down in water medium, but it is not zero. In fact, there is possible to find out dependence of the attenuation coefficient on the depth of submersion (i.e. pressure inside the water the jet is flowing to). These facts imply that a different expression of the attenuation coefficient is to be prepared. The first suggestion of such a new expression can be as follows. The ratio between attenuation coefficient determined for gas and the one for liquid is set by the fact that an equivalent mass of liquid is to be moved by the one flowing out of the nozzle. Applying the conservation laws of momentum and energy on jet element motion in air and in liquid the ratio *n* is determined and the attenuation coefficient in liquid ξ_{liq} is calculated from this equation:

$$\xi_{liq} = n \frac{C_{xliq}(C)}{C_x} \xi. \tag{3}$$

The jet-head shape resistance coefficient C_{xliq} is a function of the type of liquid and pressure inside it, the jet-head form resistance coefficient C_x is the one used in Eq (1) (usually the one used for air under normal pressure) and attenuation coefficient ξ is calculated from Eq (1).

3. Description of experimental material

The experimental blocks were prepared from a standard concrete grade B30 (according to the Czech norms).

The aggregates of three fractions each one from another Czech locality were used (Table 1). The cubic concrete samples 150×150×150 mm were prepared and, subsequently, they were separated into several groups (Table 2). All samples were progressed to further treatment after 28 days. The water jet testing was started one year later (i.e. the respective samples were stored in corrosive media one year) – the age of all samples was identical.

Table 1. Concrete formula

Component	kg/m^3
Aggregates 0–4 mm Ledce	778
Aggregates 8–16 mm Olbramovice	664
Aggregates 11–22 mm Lomnička	290
Slag cement Mokrá	416
Fluxing agent Sikament 100	3.33
Water	180

The first one was the reference group stored in normal environmental conditions labelled N. The second group of

Table 2. Concrete samples – division into tested groups and their labelling

Group	Reference	Nitrates	Sulphates	Chlorides	Gas CO_2	Chemical thawing lotion	Frost
Label	N	NH_3^-	SO_4^{2-}	CL^-	CO_2	CHRL25, CHRL50, CHRL75, CHRL100	M50, M100
Total number of samples	10	10	10	10	10	40	10
Number of samples tested by water jets	5	5	5	5	5	20	5

samples was stored in the lotion with a high concentration of the NH_3^- ions (up to 4%) simulating aggressive media in chemical industry or in sewage canals and other structures (marked NH_3^-). The third group of samples was stored in the lotion with the Na_2SO_4 (concentration of the Na_2SO_4 was 51.2 grams per litre of water) simulating thus media in chemical plants or sewerage plants and influence of the aggressive groundwater rich in concentration of sulphates (label SO_4^{2-}). The fourth group of samples (marked Cl^-) was stored in the solution of the NaCl in water (100 grams per litre) simulating the thawing agents, aggressive media in the sewerage plants, in the water treatment plants or in the pools with the chlorinated water. The fifth group of samples was stored in a special container with a high concentration of the CO_2 gas and the relative humidity 90% – these conditions simulate the process of concrete carbonation in air due to the CO_2 action in combination with the air humidity or they simulate activity of the aggressive CO_2 from the groundwater, their label is CO_2. The sixth group of samples was exposed by several tenths of freezing and thawing cycles with applied chemical thawing lotion (3% thawing salt) – samples are marked CHRL25, CHRL50, CHRL75 and CHRL100, where numbers mean the number of freezing and thawing cycles. The limit temperatures in the cycle were +20 °C and –15 °C. Only one side of the cubic sample was exposed into approximate depth 50 mm. Samples of the seventh group were frozen and thawed in wet state in many cycles. These samples were labelled M50 or M100 and the limit temperatures in the cycle were +20 °C and –20 °C. The duration of the one freezing – thawing cycle was approx 48 h for both groups of sample. The lotions were changed each two months and their pH factors were tested each fourteen days.

It should be taken into account that concretes are very heterogeneous materials. Therefore, the local strength can substantially differ from the declared average values. Moreover, the aggressive media demote the cement based aggregates binder faster than the material of aggregates itself. Hence, the local depths of water jet penetration into the concrete samples can analogically differ from the average values calculated from the theoretical equations.

4. Experimental procedure

The first aim of experiments with high-velocity continuous water jets was to prove some differences in concrete response regarding sample storage, i.e. application of various chemical lotions and physical conditions. The second aim was to test possibilities of concrete preparation for repair action under the water level. Concrete samples were tested in the overpressure vessel produced and described several years ago (Hlaváč *et al.* 2001). The dimensions of the blocks were approx 150×100×50 mm. They were sawn from respective original blocks by diamond saw. In the beginning of each experiment the respective sample was fixed into the support of the motional device inside the pressure vessel (Fig. 1).

The vessel was closed and filled with water except the cases when comparative tests were performed in air. Water inside the vessel was either without any pressure or pressurized. The overpressure was usually set to values from 0.2 MPa up to 1.4 MPa with the 0.2 MPa step. Pressure of the water inside the vessel was regulated by the inflow from the cutting nozzle and the regulation overflow valve. The water overpressure inside the vessel was measured using the mechanical pressure meter installed on the vessel body. The operator checked the value during each cut made in material. The kerfs were performed at various traverse speeds. The pump pressure was 380 MPa, the nozzle diameter was 0.25 mm, the stand-off distance was 10 mm (from the nozzle outlet) and the angle between the jet axis and the normal to the impingement surface of the samples was 0π.

The depths of the kerfs were measured in five points assigned on the respective sample surfaces. Then the average values for all kerfs were evaluated by the standard processing of measured data. Illustrative photo of several concrete samples after their testing in the overpressure vessel is presented in Fig. 2. It demonstrates variation in the water jet effects and the influence of the water overpressu-

Fig. 1. Support with a sample in front of the pressure vessel

re on the water jet penetration into the concrete structure. It can be seen that the high-pressure generated water jet is rather cutting than breaking and extracting large volumes.

The experimental results are compared with curves calculated from the theoretical equations in Fig. 3 for two extreme samples (one more resistant and the second less resistant) and the reference sample stored in normal environmental conditions. The results of the other damaged concretes lay in between the extremes except the samples submitted to the freezing and thawing cycles in the wet form. These samples were totally destroyed during the first water jet pass – they were fragmented into several pieces. Therefore, it was not possible both to continue experiments on these samples and to determine the depth of jet penetration. It was concluded that the selected numbers of freezing – thawing cycles for the wet samples, i.e. 50 or 100, were too overestimated. The experiments investigating the influence of the freezing – thawing cycles quantity on the concrete samples consistency in water jet cutting tests are suggested as an important part of the project prepared as a continuation of presented research.

Fig. 2. Selected samples of construction concretes cut in the overpressure vessel by a high-pressure generated water jet

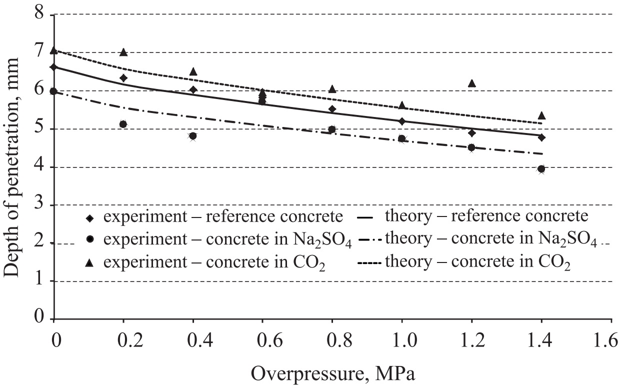

Fig. 3. Graphical presentation of results – depth of water jet penetration relationship on the overpressure in the vessel for two extreme concrete samples and the reference one (curves are calculated from theory and the value at zero overpressure)

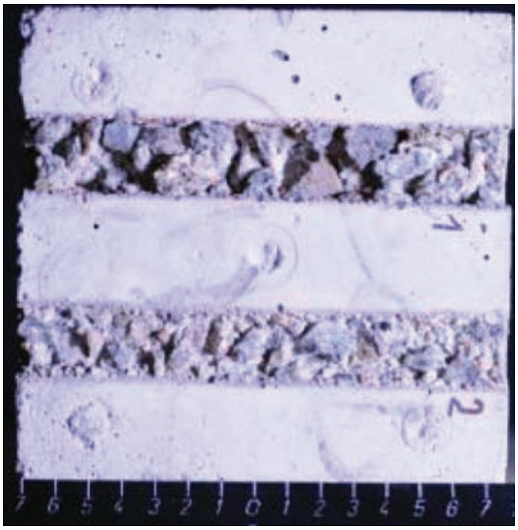

Fig. 4. An example of the trace of the wide operating fan nozzle used for concrete demolition: top kerf – one pass of pulsing jet, bottom kerf – one pass of continuous jet (both generated by identical nozzle with the identical water pressure)

Simultaneously with experiments in the overpressure vessel, some experiments with the low-pressure based water jets were performed with nozzles Lechler 1508 having the following parameters: the vertex angle of the outlet jet – 30°, the nozzle outlet diameter – 2.05 mm, the nozzle inlet diameter – 4 mm, water pressure – 30 MPa, the stand-off distance – 40 mm and the amplitude of vibrations if applied – 7 μm. The experiments were performed with traverse speeds 100, 200, 400 and 1000 mm/min under the normal air conditions. The disintegrated volumes were determined for the "cutting" length 150 mm (the edge dimension of the original cubic sample). Typical width of the jet trace on the material surface was 22 mm. The depth of penetration altered from approximately 1mm without pulsing up to more than 10 mm with pulsing switched on. An example of sample prepared using fan water jets is presented in Fig. 4.

5. Discussion

Some of the results were anticipated. The decrease of the depth of penetration with increasing overpressure inside the vessel is one of the most expected ones. Nevertheless, the efficiency decrease is rather inexpressive. The increasing overpressure inside the vessel influences primarily the type of the disintegration. While in low overpressures the cutting effect in dominant, the large volume disintegration occurs when the overpressure increases (it can be mentioned also in Fig. 2). Then the measurement of the depth of penetration of water jet into the concrete sample is very difficult. Nevertheless, the standard measurement uncertainty A determined for data is about 15% that is conformable with the values of inaccuracies of some parts of the experimental system and applied procedures. The sample was driven in the overpressure vessel by a hydraulic motor that is temperature dependent. The temperature was changing during its operation and the values of the traverse speed were influenced by this fact. In spite of the effort to keep the oil temperature stable the traverse speed was fluctuating ± 15%. Simultaneously, the transfer valve used for automatic regulation of the overpressure worked within the range up to ± 15% from the set up one. Therefore, the experimental results presented in Fig. 3 as points, are considered to correlate with the values calculated from the theoretical model and represented by curves. Each one point is determined as an average from five values measured at five points along the individual kerf.

No one sample of construction concrete seemed to be extremely weakened by influence of the aggressive solutions used for simulation of the concrete aging from the water jet cutting point of view. Some differences were mentioned (see difference between any two samples presented in Fig. 3), but they lay within the range of measurement uncertainty for any of tested concretes. Maybe, the period of the sample preparation in aggressive media was too short, although they were exposed to the aggressive solutions one year. On the contrary, the samples repeatedly frozen and thawed in wet state were damaged during the first water jet pass to such an extent that the testing used for other samples could not be applied – these samples were so crumbly that they were completely disintegrated and could not be analysed like the rest ones.

The appropriate method for correlation of the high-pressure and the low-pressure generated water jets was searched for. The depth of penetration (the depth of kerf) is one of possibilities. Nevertheless, the applied experimental conditions are quite different and the resulting effects on material are not easily comparable. The disintegrated volume is another quantity that can be used for comparison of high- and low-pressure generated water jets. Therefore, the disintegrated volume of concrete was measured and the surface structure was studied. The aim is to prepare the measurement method ensuring determination of the surface preparation sufficient for a good adhering of the reconstruction materials. However, the single disintegrated volume was not sufficient for comparison of water jet efficiency when water jet parameters diverge substantially. Therefore, it was necessary to introduce the parameter making possible to compare these profoundly different cases of water jets. It is supposed that the energy per disintegrated volume can play this role satisfactorily.

The comparison of the specific energy per volume unit is calculated from the water pressure, the nozzle geometry and the measured volume. The trends of this physical quantity should be identical for any type of pure water jets. The average values determined from five measuring points on investigated samples are presented in Fig. 5 as points in corresponding individual traverse speeds used in tests. The exponential curve is determined by regression included in Microsoft® Excel. Similar procedure has been used for all tested concrete groups. The regression formulae were determined in Excel from four experimental points corresponding to traverse speeds used in experiments. Each point was determined as an average from five measured values on respective samples. Subsequently, these formulae, determined for individual concrete groups, were used for calculation of the specific energy of the low-pressure generated water jets at traverse speed identical with the one used for high-pressure water jets. Comparison of values calculated from regression equations is summarized in Table 3. It shows that specific energy necessary for disintegration of the unite volume by low-pressure water jets is from 20% up to 80% lower than the one of the high-pressure generated ones. Moreover, the efficiency of the pulsing jets is in average about 4 times higher than the one of the continuous jets with the same energy. This fact is demonstrated in Fig. 6 through the dependence of the disintegrated volume on the traverse speed on concrete samples stored in NaCl lotion. All other tested samples show similar trends both in comparison of continuous with pulsing jets and in traverse speed dependence.

Table 3. Comparison of water jets generated by low and high pressure from the energy consumption point of view

J/mm^3	CHRL 100	NaCl	SO$_4^{2-}$	reference sample
low pressure	18.7	27.0	42.4	50.9
high pressure	27.9	49.0	59.8	61.2
energy consumption increase	49%	82%	41%	20%

The results were determined for the traverse speed 1.5 m/min.

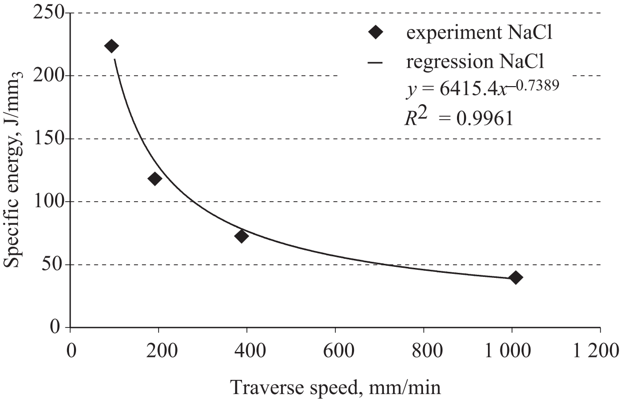

Fig. 5. Trend of the specific energy respective to traverse speed for concrete samples stored in NaCl lotion

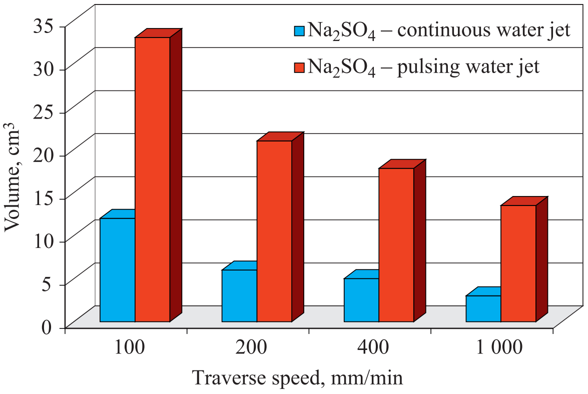

Fig. 6. Comparison of disintegrated volume for continuous and pulsing water jets on samples stored in Na_2SO_4 lotion

The efficiency of the pulsing jets, firstly used for development of a commercial tool in 1998 (Vijay 1998), demonstrated on concrete samples evokes some new trends in water jet applications in practice. It should be very positive when this tool is used instead the classical impacting machines and tools especially on bridges and slab blocks or other concrete structures that can be endangered by internal micro-cracks induced by extreme dynamics. It is also very efficient in selective disintegration of material (Vijay *et al.* 2008), especially the brittle one with internal cracks, failures and defects, many times caused by rusting of reinforcing steel structures. Application of water jets in the preparation stage of concrete repair for dismantling of the damaged concrete should ensure either disintegration of failed layer without violence of the rest material or breaking-out the concrete and purging of the reinforcement without inducing further failures into the concrete matter or taking out more steel matter than the rusty one. In fact, the brittle and non-homogeneous materials like concrete or rust are much less resistant to water jet impact than steels as mentioned also Campbell and Fairfield (2008). Therefore, the application of water jet for selective disintegration of concrete and removing of concrete from steel reinforcement is very efficient. Together with the recent techniques of concrete repair (Issa *et al.* 2007; Issa *et al.* 2008) this tool may ensure a very high standard of road and bridge maintenance and reconditioning.

6. Conclusions

It was confirmed that artificial concrete erosion used for preparation of samples is a good method for research acceleration.

Depth of penetration that is a very useful parameter for evaluation of high-pressure generated water jets is insufficient quantity for low-pressure generated water jets because they rather fragment than cut material; therefore, the disintegrated volume needs to be measured.

The disintegrated volume represents a quantity necessary for evaluation of the efficiency of concrete removing; it can be applied for comparison of water jets generated from various pressures.

A specific parameter – energy per disintegrated volume – has been introduced; comparison of results based on this parameter shows that even continuous low-pressure generated water jets are more efficient than the ones generated from a high-pressure.

The efficiency is much more increased when pulsing is induced into the water flow.

The pulsing water jet is a befitting tool for concrete disintegration during preparation of constructions for repair or reconditioning, especially on roads, bridges and high-rise buildings because levels of the vibrating energy transferred to the concrete are very low.

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References

Campbell, S. A.; Fairfield, C. A. 2008. An Overview of the Various Techniques Used in Routine Cleaning and Maintenance of Clay, Concrete and Plastic Drains, *Construction and Building Materials* 22(1): 50–60. http://dx.doi.org/10.1016/j.conbuildmat.2006.05.046

Crow, S. C. 1973. A Theory of Hydraulic Rock Cutting, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 10(6): 567–584. http://dx.doi.org/10.1016/0148-9062(73)90006-5

Hashish, M.; duPlessis, M. P. 1978. Theoretical and Experimental Investigation of Continuous Jet Penetration of Solids, *Transactions of ASME – Journal of Engineering for Industry* 100(1): 88–94. http://dx.doi.org/10.1115/1.3439351

Hääl, M.-L.; Sürje, P. 2006. Environmental Problems Related to Winter Traffic Safety Conditions, *The Baltic Journal of Road and Bridge Engineering* 1(1): 45–53.

Hlaváč, L. 1992. Physical Description of High Energy Liquid Jet Interaction with Material, in *Geomechanics 91*. Press: Taylor & Francis, 341–346. ISBN 9054100397

Hlaváč, L. M.; Hlaváčová, I. M.; Mádr, V. 1999. Quick Method for Determination of the Velocity Profile of the Axial Symmetrical Supersonic Liquid Jet, in *Proc. of the 10th Conference American Waterjet WJTA*. St. Louis, Missouri, 189–199.

Hlaváč, L. M.; Hlaváčová, I. M.; Kušnerová, M.; Mádr, V. 2001. Research of Waterjet Interaction with Submerged Rock Materials, in *Proc. of the Conference American Waterjet WJTA*, vol. 2. St. Louis, Missouri, 617–624.

Hlaváč, L. M.; Sochor, T. 1995. Modelling of Rock Excavation by High Energy Water Jet, in *Mechanics of Jointed and Faulted Rock*. Rotterdam: Balkema, 847–852. ISBN: 9054105410

Issa, M. A.; Alhassan, M. A.; Shabila, H. I. 2008. High-Performance Plain and Fibrous Latex-Modified and Microsilica Concrete Overlays, *Journal of Materials in Civil Engineering* 20(12) 742–753. http://dx.doi.org/10.1061/(ASCE)0899-1561(2008)20:12(742)

Issa, M. A.; Alhassan, M. A.; Shabila, H. I. 2007. Low-Cycle Fatigue Testing of High-Performance Concrete Bonded Overlay-Bridge Deck Slab Systems, *Journal of Bridge Engineering* 12(4): 419–428. http://dx.doi.org/10.1061/(ASCE)1084-0702(2007)12:4(419)

Juknevičiūtė, L.; Laurinavičius, A. 2008. Analysis and Evaluation of Depth of Frozen Ground Affected by Road Climatic Conditions, *The Baltic Journal of Road and Bridge Engineering* 3(4): 226–232. http://dx.doi.org/10.3846/1822-427X.2008.3.226-232

Kamaitis, Z.; Čirba, S. 2007. A Model for Generating Multi-Layer Anti-Corrosion Protection for Road, *The Baltic Journal of Road and Bridge Engineering* 2(4): 141–146.

Laurinavičius, A.; Čygas, D.; Čiuprinskas, K.; Juknevičiūtė, L. 2007. Data Analysis and Evaluation of Road Weather Information System Integrated in Lithuania, *The Baltic Journal of Road and Bridge Engineering* 2(1): 5–11.

Lavrentiev, M. A. 1957. Kutulyativny zared i principy iego raboty, Uspiechi Matematicinkish Nauk 12 (4): 41–56.

Rehbinder, G. 1980. A Theory about Cutting Rock with Water Jet, *Rock Mechanics and Rock Engineering* 12(3–4): 247–257. http://dx.doi.org/10.1007/BF01251028

Summers, D. A.; Blaine, J. G. 1994. A Fundamental Tests for Parameter Evaluation, in *Geomechanics 93*. Rotterdam: Balkema, 321–325.

Vijay, M. M. 1998. Design and Development of a Prototype Pulsed Waterjet Machine for the Removal of Hard Coatings, in *Proc. of the 14th International Conference on Jetting Technology*, BHR Group Conference Series Publication, vol. 32. London: Professional Engineering Publishing, 39–57.

Vijay, M.; Tieu, A.; Yan, W.; Daniels, B.; Randolph, J.; Laquines, F.; Crawford, D.; Pessetto, C.; Merril, J.; Eybel, R.; Bucknor, K.; Game, M. 2008. Demonstration, Validation and Certification of Forced Pulsed Waterjet Technique for the Removal of Coatings from Aircraft/Aerospace Components, in *Proc. of the 19th International Conference on Water Jetting.* BHR Group. Cranfield: Bedford, 203–216.

Yanaida, K. 1974. Flow Characteristics of Water Jets, in *Proc. of the 2nd International Symposium on Jet Cutting Technology*, BHRA, Cambridge, England, 19–32.

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