

USE OF PULSATING WATER JET TECHNOLOGY FOR REMOVAL OF  
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**Abstract.** High-speed water jet technology is commonly used for removing degraded concrete surface layers selectively in the process of repair of concrete structures. This technology offers number of advantages (such as reduced noise, dust and vibrations, preservation of intact material and thus more delicate intervention into the structure), but it still requires further improvement in terms of productivity and cost effectiveness to be even more competitive to traditional methods of concrete surface layers removal. The impact of a high-velocity liquid drop or bunch of water on a rigid surface generates extremely short high-pressure transients that can cause substantially serious damage to the surface and interior of the solid material. Therefore, the use of pulsating water jets, that are able to generate repeatedly above mentioned high-pressure transients, can lead to higher performance of pulsating high-speed water jets compared to continuous ones under the same operating conditions. A special method of the generation of the high-speed pulsating water jet was developed recently and tested extensively under laboratory conditions. The method is based on the generation of acoustic waves by the action of the acoustic transducer on the pressure liquid and their transmission via pressure system to the nozzle. A series of laboratory experiments was performed to compare effects of pulsating and continuous jets (both rotating and flat fan) acting on concrete surface. A rate of concrete removal was used to evaluate the jet. Results of the study of effects of pulsating and continuous high-speed water jets on concrete surfaces using methods of optical microscopy and image analysis are also discussed in this paper.

**Keywords:** high-speed water jet technology, pulsating jet, rotating jets, removal of concrete layer, concrete repair, rehabilitation of bridges.

## 1. Introduction

High-speed water jet represents a technology that is able to disintegrate even the hardest materials. Water jets are inert to material abrasiveness as there is no mechanical tool-material interaction in the process of disintegration. The erosion capability of the jets is widely used for many applications in modern industry. Water jet cutting and/or cleaning equipment except the pump is lightweight and the whole cutting process can be easily automated. Hydrodemolition (also called water-jet blasting) of concrete structures is typically used where the preservation of the reinforcing steel is desired for reuse in the replacement concrete such as in the rehabilitation of bridges (Fig. 1) and parking garage decks. The method is vibration free; furthermore, reinforcing bars are not cut or damaged (Manning 1991; Kasai 1988). The technology is commonly used in the Czech Republic and neighbouring countries

for treating concrete surface before renovation of concrete structures, in particular bridges and road constructions. For example, Technical Regulations of the Ministry of



**Fig. 1.** Repair of road bridge in Brno (Czech Republic) using hand-held water jet lance tool

Transport of the Czech Republic for construction of roads, TP 120 – Maintenance, Repairs and Renovation of Concrete Bridges, recommend high-speed water jet as a suitable method for removing of damaged layer of concrete.

Although Momber (2001) highlighted that due to operational advantages, such as low cutting forces, selective removal capability, high efficiency, dust-free, heat-free and vibration-free performance, the water jet replaces conventional mechanical techniques, such as sawing, grit-blasting, jack hammering and milling, the performance of water jet techniques is not always competitive with existing conventional mechanical systems yet. Therefore, substantial attention has been paid recently to the development of these methods so it would give us the possibility to improve performance of water jet considerably.

One of the methods is represented by generation of pulsations in high-pressure systems to produce pulsating high-speed water jets. The reason is that the introduction of pulsations into the water jets enables to increase their cutting efficiency due to the fact that the impact pressure (so-called water-hammer pressure) generated by an impact of bunch of water on the target material is considerably higher than the stagnation pressure generated by corresponding continuous jet (Chapter 2). In addition, the action of pulsating jet induces also fatigue and shear stresses in the target material due to the cyclic loading of the target surface and tangential high speed flow across the surface, respectively. This further improves the efficiency of the pulsating liquid jet in comparison with the continuous one (Foldyna *et al.* 2004). Besides, short-time cavitation erosion, as an additionally contributing failure mechanism, seems to be presented very likely in concrete hydrodemolition as indicated by Momber (2000b). Thus, materials can be disintegrated without utilization of abrasives using significantly lower pressure of water than that of continuous jets (usually 5 to 10 times). Pulsating jet escapes from the nozzle as a continuous jet and due to uneven flow velocity it breaks up in air to separate bunches of water. The best performance of pulsed jet can be observed at certain distance from the nozzle exit (in order of centimetres). This phenomenon is very useful in contrast with continuous jet, the highest efficiency of which is close to the nozzle exit and significantly decreases at longer distances due to air friction (jet breakage occurs). From concrete repair point of view it is difficult to maintain the short distance from the nozzle exit in most cases.

## 2. Jet impact on the target

Analysis of jet impact on the target was presented for instance by Foldyna *et al.* (2001): when a continuous water jet impinges normally on a flat rigid surface at the velocity of  $v_0$ , the max pressure (based on Bernoulli's law) at the point of impact is the stagnation pressure  $p_s$ , given by:

$$p_s = \frac{1}{2} \rho v_0^2, \quad (1)$$

where  $\rho$  represents water density. However, if a drop or a bunch of water strikes the same target at the same veloc-

ity of  $v_0$ , the initial impact pressure will be much higher. So-called water-hammer pressure developed by the initial impact of a water jet can be determined as:

$$p_i = \rho v_0 c_0, \quad (2)$$

where  $c_0$  is shock wave velocity in water. Thus pulsing the jet leads to an amplification of the impact pressure

$$\frac{p_i}{p_s} = 2 \frac{c_0}{v_0}. \quad (3)$$

Since velocities of continuous jets currently used for removal of concrete layers and surface treatment, respectively, do not exceed  $700 \text{ ms}^{-1}$ , the impact pressure of pulsed jet will be at least 4 times higher at the same velocity and therefore significant improvement in cutting performance can be expected. Similar relationships were published also by Vijay (1994) and Momber (2005). Momber states that amplification ratio  $\frac{p_i}{p_s}$  could be about 11 for water pressure as low as 30 MPa. This ratio challenges the use of mechanisms able to produce high-speed fluid bunches.

Several types of devices intended for generation of high-frequency pulsating liquid jets were investigated in the past, such as internal mechanical flow modulators (Nebeker 1987), Helmholtz oscillators (Shen, Wang 1988), self-resonating nozzles (Chahine *et al.* 1983) and ultrasonic nozzles (Vijay 1992) and (Vijay, Foldyna 1994). Low lifetime of the equipment and/or low depth of modulation represent main shortcomings of the above mentioned principles.

## 3. Pulsating jet with acoustic generator of pressure pulsations

A special method of the generation of the pulsating liquid jet was recently developed and tested extensively under the laboratory conditions. The method is based on the generation of acoustic waves by the action of the acoustic transducer on the pressure liquid and their transmission via pressure system to the nozzle. Efficient transfer of the high frequency pulsation energy to longer distances in the high-pressure system was studied by Foldyna *et al.* (2007). The high-pressure system with integrated acoustic generator of pressure pulsations consists of a cylindrical acoustic chamber connected to the liquid waveguide. The liquid waveguide is fitted with pressure liquid supply and equipped with the nozzle at the end. The acoustic actuator consisting of piezoelectric transducer and cylindrical waveguide (Fig. 2) is placed in the acoustic chamber. Pressure pulsations generated by the acoustic actuator in the acoustic chamber filled with pressure liquid are amplified by the mechanical amplifier of pulsations and transferred by the liquid waveguide to the nozzle. Liquid compressibility and tuning of the acoustic system are utilized for effective transfer of pulsating energy from the generator to

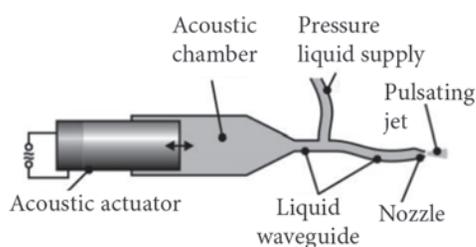


Fig. 2. Schematic drawing of the high-pressure system with integrated acoustic generator of pressure pulsations

the cutting head where pressure pulsations transform into velocity pulsations. The device based on the above mentioned method of the pulsating liquid jet generation can be used to produce pulsating single jets as well as pulsating multiple jets. At present, an extensive research program is in progress to understand the basic principles of the process of generation and transfer of pulsation in water jet cutting system.

#### 4. Water jets in the process of concrete disintegration

High-speed water jet technology is nowadays closely connected to repair and maintenance of concrete structures as well. It is used for removal of corroded concrete layers and preparation of surface for concrete replacement or protection. Unlike classical continuous jets generated by single nozzle, rotating jets generated by multiple nozzles mounted into a carrier (rotating head) are commonly used for repairs of larger concrete areas. Hlaváč *et al.* (1993) showed that rotating nozzles (unlike single jet) cover wide area and thus pressure energy of the jets is distributed on larger disintegrated surface. Specific energy is not evenly distributed over the surface; its distribution depends on nozzle configuration and rotating head movement (Momber 2005). A model of estimation power distributions of rotating water jet tools is provided by Blades (1994).

So-called flat jet (or fan jet in some literature) represents another possibility of spreading the jet energy on the larger area. It is generated by a single nozzle and its energy is spread to great width. Flat jets are not commonly used in concrete repair processes yet because such a jet is unable to disintegrate the concrete sufficiently with standard jet operating parameters. Flat jets were developed formerly for special applications like cleaning, removal of hot iron scales etc. Summers (1995) recommended use of rotating water jets at greater stand-off distances instead of flat jet due to its very low efficiency. However, if high frequency acoustic pulsations are implemented to flat jet via acoustic generator, completely different situation occurs: pulsating flat water jet is capable of disintegrating hard concrete layers using ordinary high-pressure equipment for concrete repair and treatment.

Research on disintegration of concrete by high speed water jets is very extensive and frequently published in the literature. Momber (2000a), for instance, indicated the inf-

luence of interfaces, cracks, and inclusions on the failure of concrete materials due to penetrating water flow at velocities of several hundred meters per second: the predominant mechanisms of the concrete failure are the propagation and intersection of existing microcracks. It was found that the destruction process due to the high-speed water flow is introduced in the interfaces between the matrix and the aggregate grains which are characterized by a high degree of porosity and pre-existing microcracks. Inside a crack, the water is pressurized which leads to forces acting on the crack wall surface. If the generated stresses exceed critical material values, for example the critical stress intensity factor, the crack starts to grow. The crack growth is controlled by the interaction between cracks and aggregate grains. It was found that inclusions in the material act as crack arresters and energy dissipaters. The intersection of several single cracks leads to a macroscopic material removal and, finally, to the generation of fine-grained erosion debris. The main conclusion from Momber's investigations is that the concrete hydrodemolition is a fracture mechanics process which involves the generation, propagation and intersection of cracks. Probably the most comprehensive summary of knowledge in the area of concrete hydrodemolition was published in the book by Momber (2005).

However, only a few studies were performed to test using of pulsating water jets on concrete. One of them was published by Yan *et al.* (2004) in paper on delaminated concrete removal by forced pulsed water jet. The use of pulsed technique resulted in saving of \$200 per m<sup>2</sup> compared to the techniques used earlier (chipping and sandblasting). Nebeker (1984) found that pulsating water jets have higher hydrodemolition efficiency than non-affected jets. He observed that the aggregate grains in the investigated concrete specimen were broken in the case of pulsating jets. In contrast, grains remained undamaged after conventional water jet attack.

#### 5. Experimental work

Disintegration effects of water jets were tested in the laboratory to verify their performance in concrete cutting and removal of concrete layers. Results of disintegration of non-degraded concrete specimens stored in normal environment by pulsating flat high-speed water jet are presented. For comparison, additional tests were performed by continuous flat jet and multiple water jets generated by rotating nozzles (both pulsating and continuous) commonly used in building constructions repair, cleaning and removal of surface layers. Results are presented in following sections.

##### 5.1. Properties of tested concrete specimens

Experimental research on concrete disintegration was conducted on special made specimens. Blocks with approximate dimensions of 150×150×700 mm were prepared from concrete of class C45/55 – XF4 and left to cure for 28 days. Table 1 gives exact composition of concrete specimens.

**Table 1.** Composition of tested concrete samples

Concrete class	Composition and properties (1 m <sup>3</sup> of fresh concrete mixture)
C45/55 XF4	Fine aggregate 0–4 mm (extracted; 732 kg)*, coarse aggregate 4–8 mm (crushed; 183 kg)**, coarse aggregate 8–16 mm (crushed; 914 kg)**, cement CEM I 42.5 R (440 kg), water (166 l), plasticiser Glenium ACE 40. Mixing period 90 sec. Water/cement ratio 0.38, density 2 440 kg·m <sup>-3</sup>

\* washed aggregate mined from water; composition: quartz grains with an admixture of feldspars, micas and rock debris;

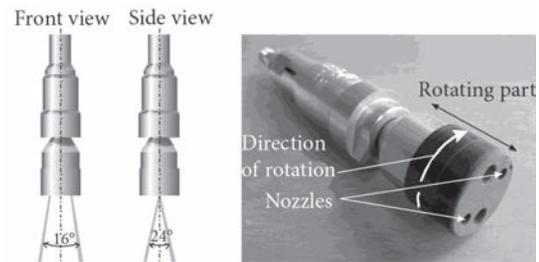
\*\* granodiorites with an admixture (ca 20%) of granitized biotitic gneisses (Martinec et al. 2008) for aggregate properties.

## 5.2. Experimental arrangement and procedure

The laboratory experimental apparatus consisted of a high-pressure water supply system, a system for generation of pressure pulsations and an X-Y table for traversing of the cutting nozzle/nozzles over testing specimens.

High-pressure water was supplied to the flat or rotating nozzles by a plunger pump capable of delivering up to 43 l·min<sup>-1</sup> of water at pressure up to 120 MPa. Pressure pulsations were excited by acoustic generator with operational frequency of 20 kHz and max power of 630 W. Flat nozzle with spraying angle of 15° was used to generate flat jet. Self-rotating 2-jet nozzle with centrifugal rotation speed control was applied to generate rotating jets. Self-rotation of the nozzle is produced by the inclination of jets from the axis of rotation (Fig. 3). Calibrated pressure sensor (gauge) placed at high-pressure system was used for measurement of operating water pressure. Image processing software and optical microscope equipped with the motorized scanning stage and the CCD camera were used for the reconstruction of slot image.

Both single flat and multiple rotating jets cut slots in specimens during the tests. In order to compare the performance of pulsating jets with the continuous ones, tests with the latter were performed using the same values of operating parameters. In addition, the flat jets were used for treatment of larger area of concrete by way of three passes of the jet close to one another with respect to visual aspects in the case of larger area concrete removal by flat jet.

**Fig. 3.** Self-rotating 2-jet nozzle

Equivalent diameter of flat nozzle used during experiments was 2.05 mm, self-rotating nozzle was equipped with two nozzles with diameter of 1.19 mm. All tests were performed at pressure of 30 MPa. Rotating speed of the rotating nozzle was 1020 RPM at this pressure. The stand-off distance from the nozzle exit using flat jets (pulsating and continuous) was 40 mm. Stand-off distance was 20 mm using rotating continuous jet and 40 mm using rotating pulsating jet due to higher efficiency of such jet in longer distances from the nozzle because of jet breaking-up into bunches of water. The ultrasonic power was set to 630 W (max) when cutting with pulsating jets. Traversing velocity was 0.2 m·min<sup>-1</sup>. Process parameters for different jet types are summarized in Table 2. Disintegrated volume was used as a measure of performance of the jet. Macros-

**Table 2.** Process parameters for different jet types

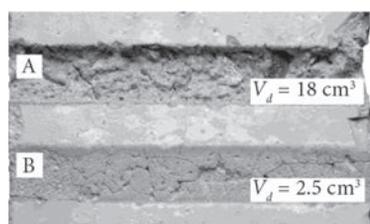
Jet type	Water pressure, MPa	Type of nozzle/nozzles	Number of nozzles	Nozzle diameter, mm	Spraying angle, °	Rotating speed, RPM	Stand-off distance, mm	Traversing velocity, m·min <sup>-1</sup>	Frequency of acoustic generator, kHz	Acoustic power, W
Flat pulsating	30	flat	1	2.05 (equivalent)	15	-	40	0.2	20	630
Flat continuous	30	flat	1	2.05 (equivalent)	15	-	40	0.2	-	-
Rotating pulsating	30	round	2	1.19	-	1020	40	0.2	20	630
Rotating continuous	30	round	2	1.19	-	1020	20	0.2	-	-

scopic as well as microscopic analyses of newly created concrete surface after water jet treatment were performed on selected slots by means of methods of optical microscopy and image analysis. The microscopic thin section was prepared from the concrete sample situated perpendicular to the slot. A large microscopic image was acquired from every thin section by automatic planar composition of 6 times 5 (11 times 4, respectively) image fields.

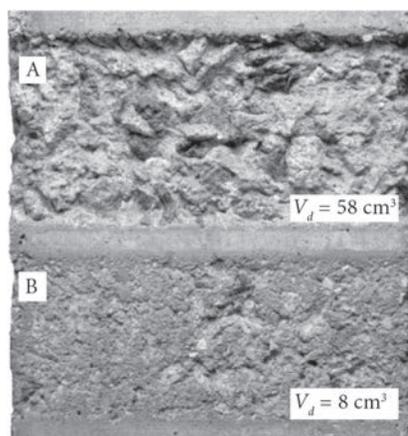
### 6. Results and discussion

Examples of slots appearance after cutting by both continuous and pulsating flat water jets as well as values of disintegrated volume  $V_d$  of particular slots are shown in Figs 4 and 5. Similarly, slots created by rotating water jets (pulsating and continuous) are displayed in Fig. 6. Microscopic images of selected slots can be seen in Figs 7 and 8.

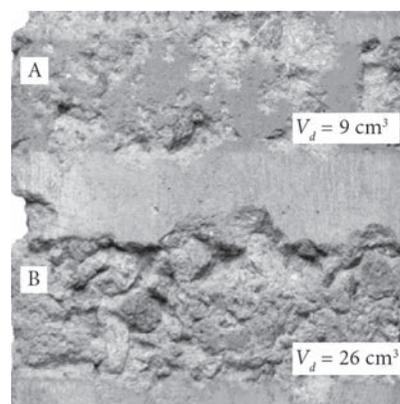
It is evident from experimental set of slots created in tested specimens that pulsating jet always disintegrates larger volume of concrete under the same operating conditions compared to the continuous one. Results show that pulsating flat jet disintegrated approximately 7.2 times higher volume of concrete under the same operating



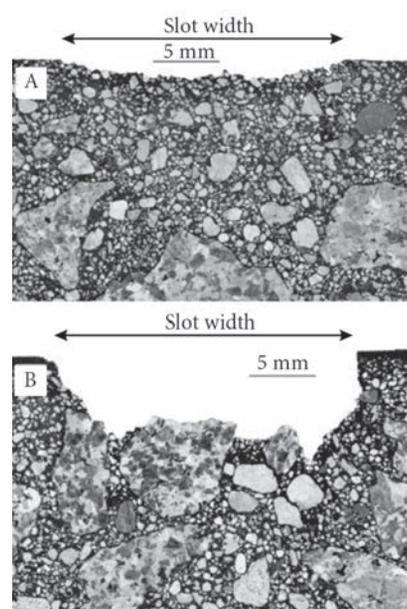
**Fig. 4.** Example of slots created by flat pulsating jet (A) and flat continuous jet (B) in C45/55 concrete ( $V_d$  – disintegrated volume, water pressure: 30 MPa, equivalent nozzle diameter: 2.05 mm, standoff distance: 40 mm, traversing velocity: 0.2 m.min<sup>-1</sup>)



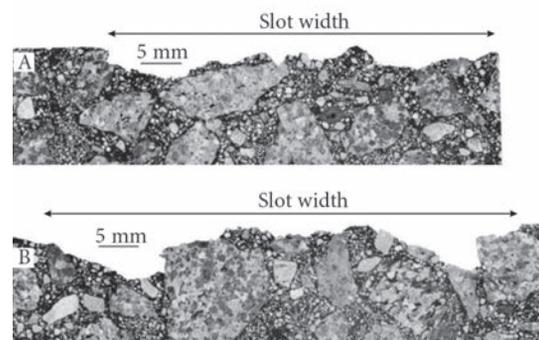
**Fig. 5.** Example of larger areas processed by flat pulsating jet (A) and flat continuous jet (B) in C45/55 concrete ( $V_d$  – disintegrated volume, water pressure: 30 MPa, equivalent nozzle diameter: 2.05 mm, standoff distance: 40 mm, traversing velocity: 0.2 m.min<sup>-1</sup>)



**Fig. 6.** Example of slots created by rotating continuous jet (A) and rotating pulsating jet (B) in C45/55 concrete ( $V_d$  – disintegrated volume, water pressure: 30 MPa, nozzle diameter: 2×1.19 mm, standoff distance: 20 mm (continuous) and 40 mm (pulsating), traversing velocity: 0.2 m.min<sup>-1</sup>)



**Fig. 7.** Cross-section of slots created by flat continuous jet (A) and flat pulsating jet (B) in C45/55 concrete

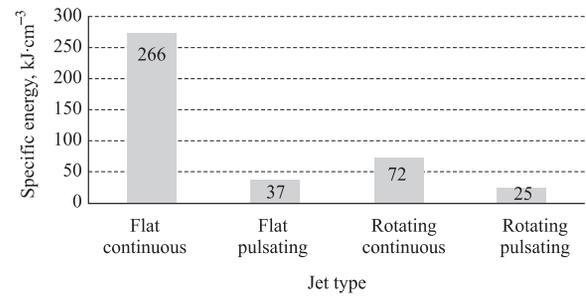


**Fig. 8.** Cross-section of slots created by rotating continuous jets (A) and rotating pulsating jets (B) in C45/55 concrete

conditions. The ratio of the performance of pulsating rotating jet vs. continuous rotating jet is about 2.9. Sitek *et al.* (2003) found that average depths of cut with pulsating single round jet were approx 1.5 times higher compared to those cut with continuous jet during concrete cutting. Although the brittleness of a tension-softening material (e.g. concrete) could be serious barrier against water jet erosion as was found by Momber (2003), pulsations in the jet successfully assist in disintegrating brittle materials because of intensive cyclic loading of the surface by impact pressure. Thus a net of individual microcracks is drastically generated in the structure due to pulsating water jet attack (Momber 2000a).

Fig. 9 represents specific energy necessary for disintegration of 1 cm<sup>3</sup> of test concrete. Based on hydraulic power of individual nozzles and work necessary for creating the slot, the values of specific energy were calculated for every tested jet type. Comparison of efficiency of flat pulsating jet with rotating continuous jet commonly used in concrete repair is interesting. Flat pulsating jet is able to disintegrate approximately twice as large volume with the same energy intensity. Since acoustic energy required for the creation of pulses in pulsating jet represents negligible portion of energy necessary for jet generation (roughly 1% to 2%), it seems that pulsating flat jet might be serious competitor of continuous rotating jets in the future.

Results of both macroscopic and microscopic analyses of newly created surface after cutting by every jet type are given in Table 3. Whereas continuous jets remove only upper part of hardened cement paste or partly uncover aggregates within the concrete, respectively, pulsating jets remove cement paste and aggregates expose as a relief from newly created surface. In addition, some grains are broken,



**Fig. 9.** Specific energy required for disintegration of 1 cm<sup>3</sup> of concrete for tested jet types (water pressure: 30 MPa, traversing velocity: 0.2 m.min<sup>-1</sup>)

which confirms the assumptions in the phenomenological model presented by Momber (2000a).

Type of concrete failure also vary with various jets: continuous jets cause bowl-shaped failure, while pulsating jets cause triangular failure. Surfaces treated by pulsating jets show larger effective area compared to those treated by continuous jet.

Generally speaking, repair materials better adhere to rough surface. Toutanji and Ortiz (2001) reported that surface treatment by water jet produces a better bonding strength than surface treatment by sander. It was found (Sitek *et al.* 2002) that the pulsating jet produces more “rough” surface with larger effective surface area compared to continuous one. The shape of slots created by pulsating jet could be suitable in particular in applications where good adhesion both in tension and shear is needed (such as surface preparation for coatings and/or preparation of stonework and concrete surfaces before application of repair materials).

**Table 3.** Description of newly created surface after water jet treatment

Jet type	Surface characteristics	Macroscopic/microscopic description
Flat pulsating	Cement paste removed to aggregate, aggregates form relief. Presence of narrow cracks in cement paste. Max depth of the slot 8.1 mm	Coarsened surface of aggregates, roughness is formed by grains of quartz and feldspar, cement paste completely removed from surface of grains. Grains are morphologically contoured and partly exposed as relief. Foliation of gneiss created by orientation of biotite slices is emphasized. Some grains are broken off voluminously along foliation planes. Cement paste is intensely eroded and removed from sand grains vicinity. Roughness of this surface is formed by sand grains. There is sharp interface between cement paste and aggregate, surface contraction cracks are emphasized. Granodiorite aggregate grains protrude above the slot relief; the grains are exposed of cement paste (fully on the top grain face, partially on grain sides); the top layer of minerals is removed from the naked grain faces. Cement paste is removed deeply along the vertical sides of aggregate grains. Material between aggregate grains is removed. Type of the failure: triangular.
Flat continuous	Removed only upper part of cement paste with frequent contraction cracks. Max depth of the slot 1.5 mm	Coarsened surface of aggregates, roughness is formed by grains of quartz and feldspar, cement paste completely removed from surface of grains. Only one grain is exposed. Cement paste is slightly broken, only thin film of washed cement is removed from surface. Erosion of cement paste with emphasized sand grains occurs on approx 1/4 of surface. There is no exposure of interface between cement paste and aggregates. Surface contraction cracks are emphasized strongly. Slot relief formed by cement paste and quartz sand grains; Type of the failure: bowl-shaped.

Continued Table 3

Jet type	Surface characteristics	Macroscopic/microscopic description
Rotating pulsating	Medium-deep eroded surface with partial exposure of aggregate inside concrete. Aggregate grains “amputated” on their top faces. Cracks are not presented in cement paste, material between aggregates is not washed out. Max depth of the slot: 6.8 mm	Coarsened surface of aggregates, roughness is formed by grains of quartz and feldspar, cement paste completely removed from surface of grains. Some aggregate grains are broken off along crack planes. Grains are partly exposed to approx 1/5 of height, morphologically as relief. Foliation of gneiss created by orientation of biotite slices is emphasized. Cement paste is removed markedly from vicinity of aggregate grains, it is intensely eroded. It is removed completely from vicinity of sand grains. Roughness of this surface is formed by sand grains. After water jet treatment, interface between cement paste and aggregate is not sharp-edged, aggregates are well joined to cement paste.  Granodiorite aggregate grains protrude slightly above the slot relief; the grains are exposed from cement paste on the top face and on one of the grain sides; slot relief is positive in areas with the cement paste. Narrow deep kerfs are not presented. Type of the failure: triangular.
Rotating continuous	Approximately 50% of original surface preserved, rest of surface slightly eroded with fractional exposure of aggregate inside concrete. Narrow kerfs are not presented in the cement paste, washing out of material between coarse aggregate grains is not significant. Max depth of the slot: 3.9 mm	Coarsened surface of aggregates, roughness is formed by grains of quartz and feldspar, cement paste completely removed from surface of grains. Some grains are only exposed or broken off. Foliation of gneiss created by orientation of biotite slices is emphasized. Part of cement paste is not damaged. If destructed, cement paste is shallowly removed from aggregate grains vicinity and it is eroded. Cement paste is removed from vicinity of sand grains, too. Roughness of this surface is formed by sand grains. After water jet treatment, interface between cement paste and aggregates is not sharp-edged, there is no morphological conturation of the aggregate grains, aggregates are joined to cement paste matrix. There are some isolated, thin cracks emphasized by water jet effects.  Granodiorite aggregate grains do not protrude above the slot relief; grains are not fully exposed from the cement paste. Slot relief is positive in areas with cement paste. Type of the failure: bowl-shaped.

## 7. Conclusions

New knowledge gained in research on disintegration of hard concrete by high-speed flat water jets and rotating water jets can be summarized into following points:

1. Pulsating jet achieved higher efficiency in comparison with corresponding continuous one in every configuration tested. Volume of concrete disintegrated by pulsating jet was approximately 2.9 to 7.9 times higher than that disintegrated by continuous jet under the same operating conditions.

2. Required energy for disintegration of unit concrete volume by flat pulsating jet is roughly one half of energy consumed by rotating continuous jets generated by rotating head (with two nozzles) commonly used in removal of concrete layers.

3. Continuous jets remove only upper part of hardened cement paste under given testing conditions, pulsating jets penetrate deeper and remove cement paste to granodiorite aggregates, breaking some of them. Type of failure depends on jet type: continuous jets cause bowl-shaped failure of concrete, pulsating jets triangular one.

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