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NEW POTENTIAL OF HIGH-SPEED WATER JET TECHNOLOGY FOR RENOVATING CONCRETE STRUCTURES

ABSTRACT

The paper discusses the background and results of research focused on the action of a high-speed water jet on concrete with different qualities. The sufficient and careful removal of degraded concrete layers is very important for the renovation of concrete structures. High-speed water jet technology is one of the most common methods used for removing degraded concrete layers. Different types of high-speed water jets were tested in the experimental part. The classical technology of a single continuous water jet generated with one nozzle was tested as well as the technology of revolving water jets generated by multiple nozzles (used mainly for the renovation of larger areas). A continuous flat water jet and pulsating flat water jet were tested the first time, because the connection of a water jet with the acoustic generator of a pulsating jet offers new possibilities for the use of a water jet (see [1] and [2]). A water jet with such a modification is capable of efficient action and can even be used for cutting solid concrete with a relatively low consumption of energy. A flat pulsating water jet which can be newly used for renovation seems to be a promising technology.

1. INTRODUCTION

1.1. High-speed water jet, basic information

The technology of concrete removal has advanced substantially in recent decades. The advancements have been driven by a desire to reduce unit labor costs, improve both worker comfort and safety, and reduce environmental contamination [7]. One possibility is the use of a continuous water jet generated by a single nozzle or the use of a continuous abrasive water jet. A continuous water jet is a stream of liquid flowing at a speed as high as 800 m.s⁻¹ (depending

on the water pressure). Water jet technology (cutting, cleaning and other applications) disintegrates material by means of complicated physical processes through changing the kinetic energy of a water jet to pressuring energy at the point of contact with the surface of the worked material.

The water jet accomplishes its destructive action by means of three separate mechanisms: (1) direct impact, (2) pressurization of cracks, and (3) cavitation [8]. These three processes reach their maximum efficiency when the water jet strikes the concrete paste. The nozzle is thus played rapidly and continually over the area to be removed and excess water is allowed to drain away. Jet efficiency

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KEY WORDS

- High-speed water jet technology,
- concrete repair, degraded concrete,
- single continuous water jet,
- nozzle,
- continuous flat water jet, pulsating flat water jet.

is at a maximum when the jet itself is stable, and the stability is determined by the shape and configuration of the feeding pipe and nozzle, the exit speed of the water, and the distance from the point of impact [7].

The cutting ability of a continuous water jet can be considerably increased by the addition of abrasive particles. Abrasive particles are accelerated by the water up to the final speed they have at the point of contact with the surface of the worked material. Disintegration of the material caused by the action of such a high-speed abrasive jet is similar to high-speed erosion by the abrasion caused by particles colliding with material. Water has the function of accelerating abrasive particles at a medium rate and washing out the abrasive and cut material used so that the water jet is always in contact with the clean surface of the worked material. Figure 1 shows the schemes of a continuous water jet and a continuous abrasive water jet. A multiple water jet is a modification of a single jet; its advantage lies in the possibility of treating a larger area in one pass. Degraded concrete on renovated structures has been successfully removed with multiple jets for many years now. The aim of using multiple nozzles is to treat a larger area in one pass and achieve a uniform distribution of the energy of the water jet on the treated surface. The picture below shows a scheme of the tracks of different types of combined water jets with repeated passes of the jets on a treated surface.

Fig. 1 Basic types of water jet.

1.2. Pulsating water jet

If the aim is to spread the jet's energy to a larger area, either a multiple nozzle set or a flat, fan-shaped jet can be used. The second type of water jet is currently not used for renovation purposes because the energy of the jet is not sufficient. This type of jet is generated by a single nozzle. Since the energy of the jet is spread over a relatively

wide area, currently used jet parameters (water pressure, flow rate) cannot ensure the sufficient disintegration of concrete. A flat water jet is successfully used for special applications (cleaning, removing iron scales). A flat water jet and its energy distribution have to be modified for the purpose of removing relatively strong concrete. This problem has successfully been solved by the Institute of Geonics of the Academy of Sciences of the Czech Republic, v.v.i., in Ostrava. A combination of a standard continuous water jet with an acoustic generator (Fig. 2) of high frequency pulses [3] enables the disintegration of hard concrete by the pulsating jet with the use of standard high pressure devices used for renovation work. The efficiency of the flat water jet can be increased by pulsating as well [4].

Fig. 2 Scheme of a high-pressure system integrated with an acoustic generator of pressure pulses.

Fig. 3 Pulsating water jet.

Tab. 1 Example of concrete sample mix-design.

	Mix-design No. 1 Concrete C25/30	Mix-design No. 2 Concrete C35/37
Cement CEM I 42.5 R Mokrá	380 kg	480 kg
Sand 0 – 4 mm, Žabčice site	860	820 kg
Aggregate 8 – 16 mm, Želešice site, amphibolite aggregate	970 kg	926 kg
Water	209 kg	208 kg
Water / Cement ratio w	0.55	0.43
Consistency – degree of slump	S3	S3
Compressive strength after 28 days	28 MPa	39 MPa

Figure 3 shows a pulsating water jet. The structure of the jet shows distinct areas of the bulging of the liquid due to the different speeds of the flowing particles caused by the pressure pulses in a high-pressure system. The individual bulges of the liquid cause a short-term increase in pressure up to the so-called impact pressure at the point of the impact onto the surface of the worked material. The impact pressure is several times higher than the stagnation pressure caused by a continuous jet. The cyclical high frequency (20KHz) loading of the surface of the worked material by the pressure changes causes its disintegration at a water pressure several times lower (30MPa) than the pressure currently used (150 – 200 MPa).

2. EXPERIMENTAL TESTS

2.1. Properties of concrete samples

It was necessary to select representative concrete samples before performing the experimental disintegration. Samples were prepared so that their corrosion load was in accordance with the actual corrosion common for renovated concrete structures.

Different types of concrete samples were prepared. The samples were made from the concrete classes C25/30 and C 30/37 in order to include commonly used material. The samples then matured for 28 days in standardized conditions. After 28 days, the referential concrete samples were placed in a normal environment; other samples were exposed to the above-mentioned types of corrosive environments. The controlled degradation of the prepared concrete samples was based on all the information available on the input material, the manufacturing process of the samples and the conditions of the corrosive action. The selected types of corrosion load were: CO₂ combined with high humidity, SO₂ combined with high humidity, a sulphate solution, a chloride solution, a nitrate solution, frost, cyclical freezing, frost and chemical de-icers. Then, the properties of the concrete samples were described (both the

reference and degraded samples). Their physical-mechanical and chemical properties were defined in terms of the compressive strength, tensile bending strength, tensile strength of the surface layers, volume weight, water-absorbing capacity, pH value, X-ray diffraction analysis, differential thermal analysis, content and distribution of air pores, degree of degradation of the samples, degree of carbonation, degree of sulphation and other additional tests according to the type of corrosive environment. All the information gained served in the formulation of the mathematical model of the material's disintegration.

The material for testing the physical-mechanical properties of the concrete was taken from two areas of all the corroded samples:

One sample was taken from the surface layer of a concrete sample – a max. of 5 mm deep.

The other sample was taken from the area of the high-pressure water jet cut. The cuts were 20 mm deep (measured from the sample's surface).

The properties of the samples of this layer confirmed the fact that the physical-mechanical properties of the concrete actually change on the cross-sectional area. The tests also determined the properties of the layer remaining after the application of the water jet and verified that the cut was deep enough to reach the material with satisfactory physico-mechanical properties.

2.2. Apparatus used for high-speed water jet technology

An experimental device from the Institute of Geonics in Ostrava was used for disintegrating the concrete in laboratory conditions. The high-pressure plunger pump KUNZ Hranice was used for lower pressures and higher flow rates (continuous and pulsating rotating and flat jets). The device is capable of supplying high-pressure water at a rate of 45 liters per minute and a pressure of 120 MPa. A PTV pump based on the Flow Systems pressure multiplier with a maximum level of pressure of 415 MPa was used for the

Tab. 2 *Parameters of water jets.*

Parameters of continuous water jet		
Pressure [MPa]	Diameter of water nozzle [mm]	
350	0.1	
250	0.1	
Parameters of flat high speed water jet (continuous and pulsating)		
Pressure [MPa]	Flat nozzle Lechler equivalent diameter [mm]	
30	2.05	
Parameters of rotating high speed water jet (continuous and pulsating)		
Pressure [MPa]	Barracuda head – 2 nozzles diameter [mm]	Rotating rate [rpm]
30	1.19	1020

high pressures and lower flow rates. Different types of nozzles were used to generate the high-speed water jets as cutting instruments. A conventional round jet was generated by the standard water nozzles; a Lechler flat nozzle, type 602571, with a spray angle of 15° was used for generating the flat jets; a Barracuda (StoneAge) rotating cutting head with two water nozzles inclined from a vertical axis was also used (Fig. 4). An acoustic pulse generator with a frequency of 20 kHz was alternatively used for all the types of nozzles. The movement of the water jet above the worked samples was controlled by an X-Y table.

The kerfs on the concrete samples were cut by a continuous water jet, a pulsating water jet, rotating continuous and rotating pulsating

water jets, and flat continuous and flat pulsating jets. The distance of the worked concrete from the nozzle was 40 mm for both the pulsating and continuous flat jets. The distance between the concrete and nozzle for the continuous rotating jet was 20 mm and 40 mm for the pulsating jet because the efficiency of the pulsating jet is higher at this distance due to the breaking up of the jet into slugs of water. The ultrasonic output was set to the maximum during the cutting by the pulsating jet. The cutting rate differed according to the jet used (from 0.1 m.min⁻¹ to 5 m.min⁻¹); the cutting rate was the same for the kerfs created by both the continuous and pulsating water jets. The volume of material that disintegrated from the kerfs or the depth of the cut was measured. The cut surfaces were macroscopically analyzed.

3. RESULTS

The findings about the disintegration of concrete with a high-speed water jet resulted from lengthy and extensive research. The extent of this paper is limited; therefore, only the typical or particularly interesting examples are mentioned. The most important conclusions are stated at the end of the paper. The photographs give an illustrative picture of the results of the concrete disintegration with different types of high speed water jets (e.g. Figures. 5 and 6). The surface of the worked concrete was evaluated visually (using a microscope with various magnifications), and

Fig. 4 *Barracuda™ rotating cutting head with two water nozzles.*

Fig. 5 *Kerf created by a pulsating oscillating jet on a road panel. The kerf was created by an Aqua Cutter Robot HVD-6000. The swinging motion of the nozzle was used. The compressive strength of the concrete was 40 MPa.*

Fig. 6 Kerfs created in class C40/45 concrete with the top layer made from material with worse properties (class C20/25 concrete with a high dose of mixing water). The influence of the traversing velocity on the depth of the cut and the disintegrated volume – rotating jet (1 – continuous, traversing velocity: $0.5 \text{ m} \cdot \text{min}^{-1}$, 2 – pulsating, traversing velocity: $0.5 \text{ m} \cdot \text{min}^{-1}$, 3 – pulsating, traversing velocity: $0.3 \text{ m} \cdot \text{min}^{-1}$, 4 – pulsating, traversing velocity: $0.2 \text{ m} \cdot \text{min}^{-1}$, 5 – pulsating, traversing velocity: $0.1 \text{ m} \cdot \text{min}^{-1}$, 6 – continuous, traversing velocity: $0.1 \text{ m} \cdot \text{min}^{-1}$).

the volume of the disintegrated concrete or depth of the cut was measured. The surrounding area was examined with respect to the presence/absence of cracks.

Figure 6 shows examples of kerfs cut by a rotating water jet in concrete made from two considerably different layers. The properties of the top layer (without pigment) were intentionally worsened by a high dose of the mixing water in the course of the manufacturing process of the sample.

4. CONCLUSIONS

Different types of concrete samples were tested in a series of extensive disintegration experiments in laboratory conditions. Concrete placed in a normal environment was used for the reference samples. Other concrete samples were then subjected to the action of different types of corrosive environments (CO_2 , SO_2 combined with high air humidity, chlorides, sulphates, nitrates, cyclical freezing, and freezing combined with the action of chemical de-icers). The advantage of the experiments with the *concrete - high-speed water jet* interaction was testing different types of high-speed water jets. The classical technology of a single continuous water jet generated with a single nozzle was tested as well as rotating water jets generated by multiple nozzles (used mainly for the renovation of larger areas). A flat continuous water jet, flat pulsating water jet, rotating continuous water jet and rotating pulsating water jet were tested for the first time. The results of the experimental disintegration with different types of jets were compared and

evaluated. The complex results of the experimental work are being processed and will be used for the formulation of a model of the disintegration of degraded construction material with water jets.

4.1. Disintegration of concrete with a single water jet (continuous and pulsating)

A single water jet was mainly used for the laboratory and experimental purposes. Its efficiency is easy to evaluate by measuring the depth of the cut. This type of water jet is not suitable for working larger areas of concrete. A single water jet with an oscillating or swinging movement is used for demolishing thicker layers. The efficiency of a pulsating water jet is always higher when compared to a continuous jet; the kerf created (depending on the type and strength of the concrete and the parameters of the water jet) is approximately 1.5-2 times deeper. A continuous water jet breaks out pieces of concrete; kerfs created by a pulsating jet are more regular and without larger amounts of chipping. The bottom surface of the kerfs cut by the pulsating water jet is rougher than the surface of a kerf cut by a continuous jet. This can be used for applications requiring the good adhesion of coats, layers or new material.

4.2. Disintegration of concrete with rotating jets (continuous and pulsating)

Rotating jets are a commonly used technology for treating larger areas of concrete, e.g., cleaning or removing surface layers. The simplest solution is a rotating head with two nozzles; however, there

Fig. 7 Specific energy necessary for disintegrating 1 cm³ of concrete by the stated types of water jets (water pressure 30 MPa, cutting rate 0.2 m.s⁻¹).

are tools with several nozzles. A higher number of nozzles leads to the problem of the proper position of the nozzles to distribute the energy of the jets as regularly as possible, depending on the movement of the heads. It was verified that a rotating, pulsating water jet disintegrates a higher amount of concrete than a continuous jet under the same conditions; the amount is approximately 2.3 – 6.3 times higher. The cutting rate has a particularly great influence: the energy of a continuous water jet with a higher cutting rate is not sufficient for the disintegration of a surface layer, whereas a pulsating water jet is capable of a reasonable level of disintegration.

4.3. Disintegration of concrete with a flat water jet (continuous and pulsating)

This type of water jet has not been used for the renovation of concrete due to its low degree of efficiency. However, the results of the laboratory experiments show that the disintegrating power of a flat pulsating water jet is approximately 7.2 times higher than that of a flat continuous water jet under the same conditions. A comparison of the efficiency of a flat pulsating jet and a rotating continuous jet commonly used for renovation (Fig. 7) is rather interesting. A flat pulsating jet can disintegrate about twice as much concrete with the same amount of energy consumption. Since the acoustic energy for the generation of pulses in a pulsating water jet

is negligible compared to the total energy necessary for generating the jet (cca 1-2%), it seems that a flat pulsating jet can become a serious competitor of rotating heads [4].

4.4. Disintegration of degraded or disturbed concrete layers

The technology of a high-speed water jet is selective; if properly adjusted, it removes only a corroded or degraded layer of concrete and saves any compacted material. Another advantage of this technology is that it does not create any cracks which could possibly weaken the whole structure. This property is common to both pulsating and continuous water jets; however, a pulsating jet can remove a degraded layer much faster under the same working conditions. The determining factors for disintegrating different types of degraded concrete were the parameters of the top layer (particularly, the occurrence of cracks), the erosion of surface layers or, on the contrary, the action of corrosive agents with the effect of the partial encapsulation of the surface pores. Compact concrete manufactured without any technological defects shows the highest resistance to the penetration of a water jet (both continuous and pulsating). The lowest level of resistance was found with concrete exposed to different weather effects and concrete with a high amount of mixing water.

4.5. Quality of a treated concrete surface

The action of a pulsating water jet is also positive with respect to the quality of the treated concrete surface. A continuous water jet only removes the surface layer of a cement stone; a rotating continuous jet can only partially uncover the aggregate inside concrete, but a pulsating water jet can remove cement stone to the surface of the aggregate, which creates a relief rising from the new surface. According to [5] or [6], renovation mortars adhere to surfaces treated with water jets very well. Since the surface created with pulsating jets has a larger actual area than a surface created with continuous jets, it can be assumed that the adhesion of renovation mortars will be even higher.

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