EFFECTS OF WATER JETS ON CNTS/CONCRETE COMPOSITE

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Results of the resistance of carbon nanotubes concrete composite (CNTs/concrete composite) to the action of pulsating and continuous water jets are presented in this paper. This work brings advanced results of fully hydrated CNTs/concrete composite (after 28 days) and it follows up the research of this composite hydrated 7 days. The experiments were focused on the determination of erosion effects of both types of water jets impinging the surface of reference (concrete) and CNTs/concrete composite samples. Erosion effects of water jets were evaluated in terms of material removal rate. Tests were performed at various operating parameters of continuous and pulsating water jets.

KEYWORDS

CNTs/concrete composite, continuous and pulsating water jet, material removal

1 INTRODUCTION

In recent years, concrete was used worldwide in the field of civil engineering [Li 2015]. The ma jor advantages of cement based composites are: low cost, ease of construction, room temperature setting, and the ready availability of properties and performance data for construction and design [Foldyna 2016]. The tensile strength of plain concrete is in range of 2 MPa to 8 MPa [Neville & Brooks 1987]. The main weaknesses of traditional cement-based materials are low tensile strength and also that it can be easily cracked, which affect safety, strength, and durability of concrete structures [Lim 1987]. Concrete was reinforced with different materials to increase its properties, from ancient age using straw in sun-dried mud bricks [Hassan 2017]. These reinforcing materials provide good crack resistance that can increase the life of the concrete and its strength, the cracks are reduced in the micrometer and also in the nanometric size (under 100 nm) [Conrinaldesi 2012, Metaxa 2012].

Nanoparticles gained significant attention because they can be potentially used in the preparation of concrete to reduce nanocracks [Liew 2016]. Composite materials with nanomaterials increase strength and durability of concrete [Peyvandi 2013, Pacheco-Torgal 2011].

Nanomaterials can have following beneficial effects on properties of cement-based composites and their microstructure:

- speeding up hydration process of cement
- forming crystallic centers
- uniform agglomeration of C-S-H products
- supporting the creation of small crystals (such as $Ca(OH)_2$)
- speeding up pozzolanic reactions, which consume $Ca(OH)_2$
- produce an additional C-S-H gel
- filling in free space between cement grains
- preventing the flow of water
- enhancing contact area, which increases the bonding strength between aggregates and cement compound

One of the most promising fillers are CNTs to improve properties of the concrete nanocomposite. CNTs can be described as hexagonal nets formed from rolled up graphene into cylindrical nanostructured tubes. They are opened or ended with fullerene hemispheres. Carbon nanotubes can be divided into two main groups: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs are single rolled up graphene sheet and MWCNTs consist of two or more layers of graphene [Kang 2015]. MWCNTs are cheaper to prepare so SWCNTs are rarely used. MWCNTs also offer better reinforcement in cement composites. MWCNTs have many applications in industry (such as electronic materials, medicine, and chemistry) due to their exceptional chemical and physical properties (thermal conductivity, electrical conductivity, low specific weight, and high resistance to corrosion) [Popov 2004]. One of the main difficulty is a proper dispersion of the nanomaterials such as carbon nanotubes (CNTs). Nanomaterials tend to agglomerate due to the high length to diameter ratio and the large surface area high attractive forces between them [Cao 2013].

The possible improvement in both mechanical and physical properties of cement-based nanocomposites could lead to the new generation of ultra-high performance concretes. That would allow reduction of the dimensions of structural elements, which would lead to further environmental and economic benefits. Therefore, the joint research program was started at the Institute of Geonics and Brno University of Technology to investigate the influence of nanoscale materials on properties of cement-based composites.

High-speed water jet technology is commonly used in the repair of concrete structures due to its selectivity. It removes only a corroded or degraded layer of concrete (if properly adjusted) and saves any compacted material. The selective properties of water jets can also be used in the determination of concrete quality. The measure of concrete quality can be evaluated as resistance to effects of high-speed water jets. This property is common to both pulsating and continuous water jets. However, a higher volume of concrete can be removed by pulsating jet under the same working conditions [Sitek 2011].

2 METHODS

2.1 *Preparation of Testing Samples*

These methods and the experimental part can be also found in the paper [Foldyna 2017] (research of composite hydrated 7 days), but it is also described in this paper for clarity of the text. Multi-walled carbon nanotubes from Yurui (Shanghai) Chemical Co., Ltd. were used for the preparation of CNT/concrete composite in this work. CNTs were prepared by chemical vapor deposition with purity more than 95 %. Their properties are given in Tab. 1.

Properties	
Internal diameter	approx. 5 nm to 12 nm
Outer diameter	approx. 30 nm to 50 nm
Length	10 µm to 20 µm
Bulk density	$0.22\ g \cdot cm^{-3}$
True density	$2.1\ g \cdot cm^{-3}$

Table 1. Properties of MWCNTs from Yurui

Defined volume (0.564 g) of naphthalene-based superplasticizer with polymeric chain (surfactant) was mixed with 0.1 liters of water and 0.141 g of CNTs (0.003 wt. % of cement weight) in rosette vessel. Then the suspension was ultrasonified for 10 min. After homogenization, the solution was added to 2.3 liters of water. The mixture of small quarry stone sand 0/4 mm (locality Zabcice), rough-crushed stone 4/8 mm (locality Olbramovice), rough-crushed stone 8/16 mm (locality Olbramovice) and Portland cement CEM I 42.5 R from cement plant Mokra (Heidelberg Cement Czech Republic) was added into mixer and mixed for 1 min without addition of water.

Then a prepared solution of water, superplasticizer, and CNTs were added to the mixture and mixed for another 2 minutes. The total volume of prepared concrete with CNTs was 15 dm^3 in Tab. 2. Reference material was prepared same way only without CNTs. The composition of CNTs concrete and reference is summarized in Tab. 2.

Material	Reference	CNT/concrete
CNTs	-	0.141 g
Superplasticizer	0.564 g	0.564 g
Cement	4.7 kg	4.7 kg
Small quarry stone sand 0/4 mm	10.6 kg	10.6 kg
Rough-crushed stone 4/8 mm	4.7 kg	4.7 kg
Rough-crushed stone 8/16 mm	12.5 kg	12.5 kg
Water	2.4 kg	2.4 kg

Table 2. Composition of reference and CNT/concrete

2.2 Physical and Mechanical Properties

Tests of consistency of concrete and compressive strength and flexural strength of fully hydrated concrete after 28 days were carried out. The test of consistency was performed in accordance with the standard EN 12350-2 Testing of fresh concrete - Part 2: Slump-test. The compressive strength of hardened concrete was measured in accordance with EN 12390-3 Testing hardened concrete – Part 3: Compressive strength of test specimens, and flexural strength in accordance with EN 12390-5 Testing hardened concrete - Part 5: Flexural strength of test specimens. Measured physical-mechanical properties of reference and CNT/concrete test specimens are given in Table 3, both for samples hydrated 7 and 28 days.

Properties	Reference		CNTs/concrete	
	after 7 days	after 28 days	after 7 days	after 28 days
Consistency [mm] - degree	20 – S1	20 – S1	10 – S1	10 – S1
Flexural strength [MPa]	8.98	9.50	8.38	10.29
Compressive strength [MPa]	42.29	50.42	43.75	50.63

Table 3. Physical-mechanical properties of reference and CNTs/concrete samples after 7 and 28 days of hydration

3 EXPERIMENTS

The experiments were focused on the determination of erosion effects of pulsating (PWJ) and continuous (CWJ) water jet impinging the surface of CNTs/concrete composite and reference (concrete) samples. High-speed water jets disintegration effects were evaluated to compare their effects on CNT/concrete composite and reference samples. Tests were performed in the Waterjet laboratory of the Institute of Geonics.

3.1 Laboratory equipment and testing conditions

The experimental assembly for evaluation of water jet effects consisted of a pulsating water jet head (with a 20 kHz ultrasonic generator) installed on the arm of the ABB IRB 6640 robot and the high-pressure plunger pump Hammelmann HDP 253 (delivering up to 67 $l \cdot min^{-1}$ at the maximum operating pressure of 160 MPa). Two values of operating pressure p 20 and 40 MPa were used in experiments. Standoff distances SOD of 25 mm for pressure 20 MPa and 35 mm for pressure 40 MPa were determined in previous experiments to be optimal for given testing conditions. The commercially available nozzle StoneAge Attack (nozzle diameter d = 1.9 mm) was used in the experiment to generate both PWJ and CWJ. The nozzle was moved over the tested sample by the robot using various traversing velocities v_{TR}. Traversing velocity was set from 10 $mm \cdot s^{-1}$ to 80 $mm \cdot s^{-1}$ during tests at 20 MPa and from 50 $mm \cdot s^{-1}$ to 160 $mm \cdot s^{-1}$ during tests at 40 MPa. A proprietary method of the generation of the pulsating liquid jet 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 (so-called acoustic generator of pressure pulsations) was used to generate PWJ. The acoustic generator of pressure pulsations used in experiments generated pressure pulsations at the frequency of about 20 kHz (exact frequency depends on the actual geometrical configuration of the generator), the amplitude of vibrations of the acoustic transducer was set to 7 µm. More details on the method of pulsating water jet generation can be found elsewhere, see e.g. [Foldyna 2011] and [Foldyna 2009]. Schematic drawing of the experimental assembly is given in Fig. 1.

3.2 Experimental Procedure

Erosion effects of CWJ and PWJ on reference (concrete) and CNTs/concrete composite samples were determined by their exposure to the jet action under various operating parameters. Grooves created by the action of the jets were evaluated in terms of material removal rate. The grooves were scanned and measured using digital microscope Keyence VHX 5000: the microscope created 2D and 3D images of grooves and obtained data were processed by the SPIP software to determine the volume of removed material V. In total, 56 grooves were processed. Evaluated length of the groove l was 20 mm. Material removal rate ΔV (see in Eq. (1)) was determined using following formula:

$$\Delta V = \frac{V \cdot v_{TR}}{l} \left[\mathrm{mm}^3 \cdot s^{-1} \right] \tag{1}$$

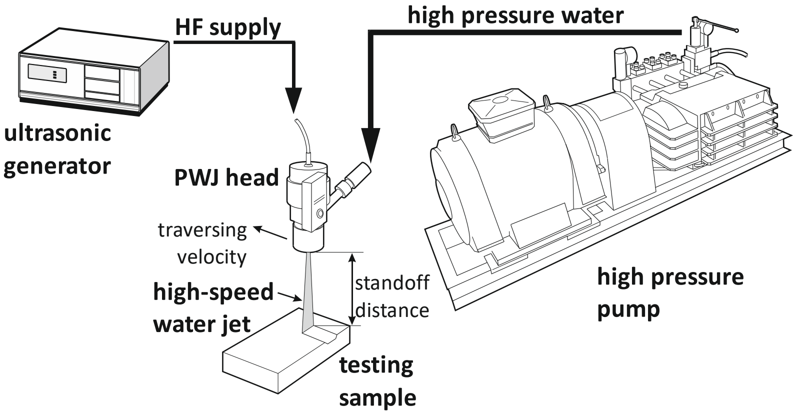

Figure 1. Schematic drawing of the experimental assembly

The resistance of the samples to the action of PWJs and CWJs was evaluated by the material removal rate ΔV.

4 RESULTS

Results of the evaluation of erosion effects of PWJ and CWJ on CNT/concrete composite and reference samples (both fully hydrated after 28 days) are presented in form of graphs in Figs. 2 and 3.

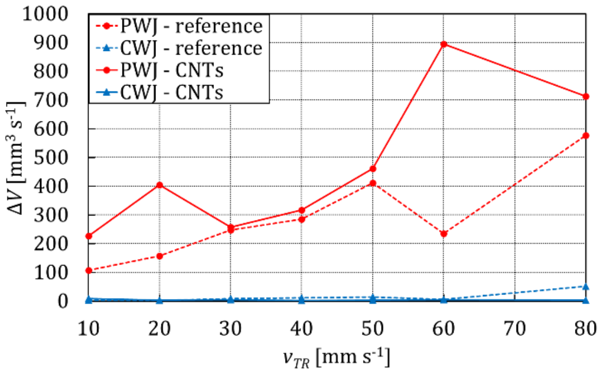

Figure 2. Influence of traversing velocity v_{TR} on the material removal rate ΔV in CNT/concrete composite and reference concrete (both fully hydrated after 28 days) exposed to PWJ and CWJ generated at 20 MPa

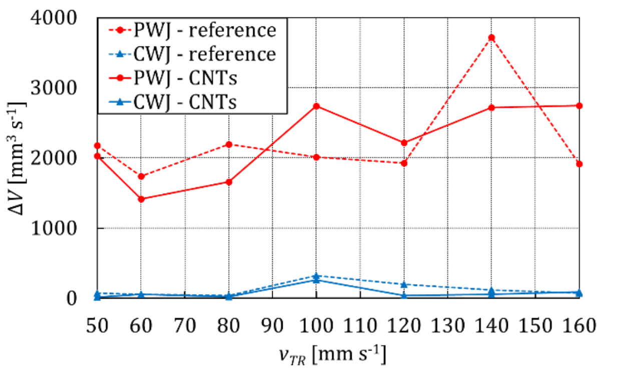

Figure 3. Influence of traversing velocity v_{TR} on the material removal rate ΔV in CNT/concrete composite and reference (both fully hydrated after 28 days) concrete exposed to PWJ and CWJ generated at 40 MPa

The material removal rate is influenced by the type of water jet. The material removal rate of continuous water jet remains almost constant with increasing traversing velocity in given range. The material removal rate of pulsating water jet increases at higher traversing velocities in given range, as can be seen in Figs. 2 and 3. One can see that the resistance of both fully hydrated (after 28 days) CNTs composite and reference samples to the impact of both types of jets is higher than of those after 7 days of hydration (see Figs. 4 and 5).

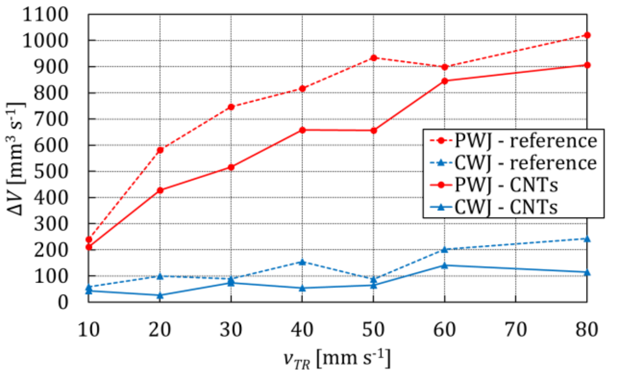

Figure 4. Influence of traversing velocity v_{TR} on the material removal rate ΔV in CNT/concrete composite and reference (both after 7 days of hydration) concrete exposed to PWJ and CWJ generated at 40 MPa [Foldyna 2017]

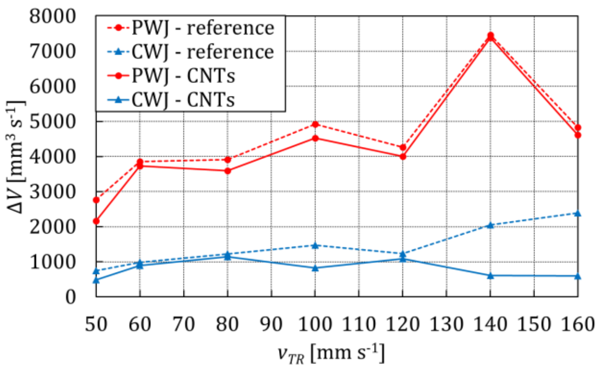

Figure 5. Influence of traversing velocity v_{TR} on the material removal rate ΔV in CNT/concrete composite and reference (both after 7 days of hydration) concrete exposed to PWJ and CWJ generated at 40 MPa [Foldyna 2017]

Photographs and 3D images of selected examples of grooves created by the CWJ and PWJ in fully hydrated reference and CNTs/concrete composite samples can be seen in Fig. 6 to 9.

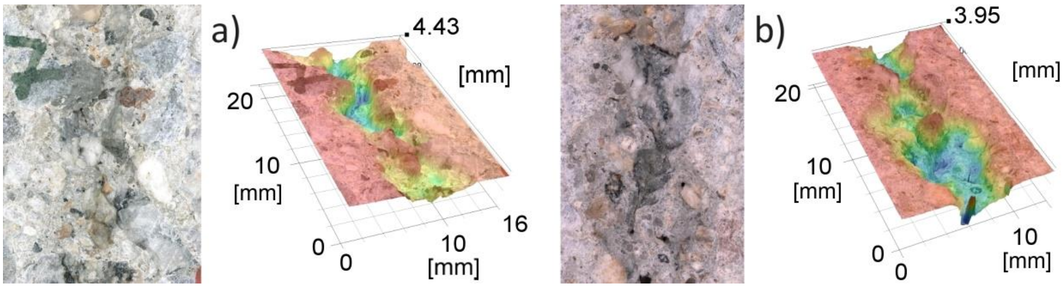

Figure 6. Photograph and 3D view of the groove created by the PWJ a) in reference and b) CNTs/concrete composite sample (operating pressure p = 20 MPa, traversing velocity v_{TR} = 40 mm·s^{-1})

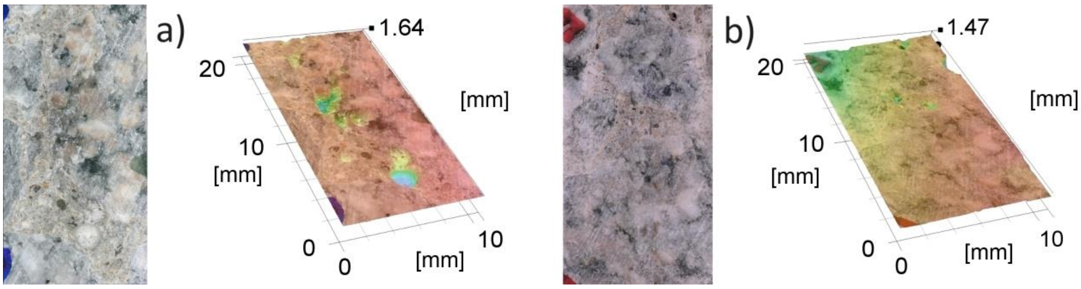

Figure 7. Photograph and 3D view of the groove created by the CWJ a) in reference and b) CNTs/concrete composite sample (operating pressure p = 20 MPa, traversing velocity v_{TR} = 40 mm·s^{-1})

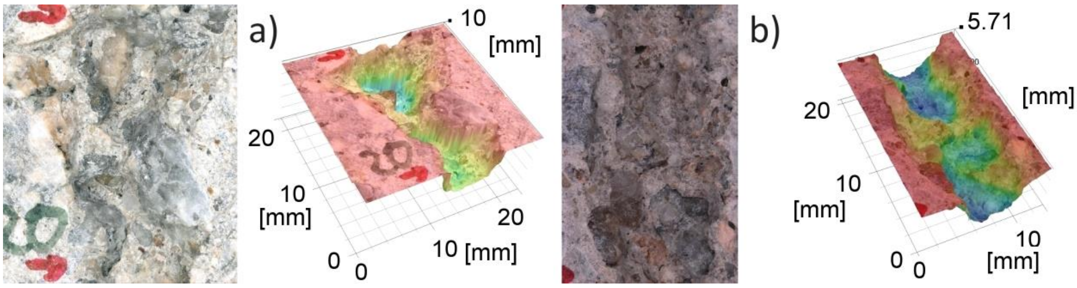

Figure 8. Photograph and 3D view of the groove created by the PWJ a) in reference and b) CNTs/concrete composite sample (operating pressure p = 40 MPa, traversing velocity v_{TR} = 80 mm·s^{-1})

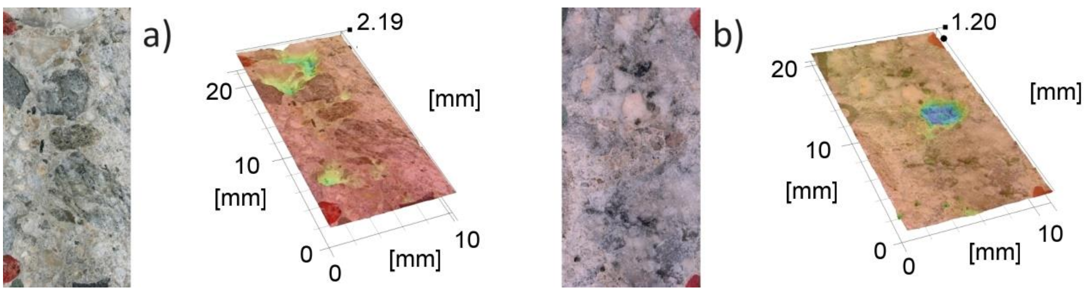

Figure 9. Photograph and 3D view of the groove created by the CWJ a) in reference and b) CNTs/concrete composite sample (operating pressure p = 40 MPa, traversing velocity v_{TR} = 80 mm·s^{-1})

5 DISCUSSIONS

Generally, higher differences in the resistance of tested samples to the action of PWJs and CWJs can be seen at operating pressure of 20 MPa. Whereas PWJs created deeper grooves and were able to remove also larger stone grains from the cement matrix, CWJs were able to remove an only upper layer of cement matrix and only some small stone grains. Fully hydrated samples (after 28 days of hydration) exhibit higher resistance to actions of both jets at operating pressure of 20 MPa compared to samples hydrated 7 days only.

Similar results can be observed at the operating pressure of 40 MPa. PWJs again created deeper grooves and were able to remove also larger stone grains from the cement matrix compared to CWJs. Fully hydrated samples also exhibit higher resistance to actions of both jets at operating pressure of 40 MPa in comparison to samples hydrated 7 days only.

Although the first results published by [Foldyna 2017] seem to indicate that the CNTs/concrete composite samples after 7 days of hydration exhibit higher resistance to the action of both PWJs and CWJs under the given testing conditions than reference concrete (see Figs. 4 and 5), results obtained with fully hydrated samples were not so clear (see Figs. 2 and 3).

6 CONCLUSIONS

Results of the study aimed at the determination of the possible influence of addition of CNTs to the concrete matrix on its resistance to the action of continuous and pulsating water jets presented in the paper lead to following conclusions:

- Physical-mechanical properties of CNTs/concrete show an only slight increase of flexural and compressive strength in comparison to reference.
- The experiments did not prove that fully hydrated CNTs/concrete composite exhibits higher resistance than reference concrete to the action of both PWJs and CWJs under the given testing conditions. Therefore, the upcoming study will be oriented at experiments on samples prepared from cement paste only to better understand the role of CNTs in the process of cement hydration and their influence on the resistance to the water jet action.

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