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Effects of Water Jet on Heat-Affected Concretes

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Abstract

The paper is dealing with the effects of flat high-speed water jet on concretes affected by high temperature. Research should help to correct use of water jet technology in repair works on concrete structures especially after wildfires in tunnels, underground garages, etc., which are exposed to enormous thermal stress. Four concrete mixtures were prepared for tests of interaction of water jet with concrete. The samples were exposed to 200 °C and 600 °C and for comparison one third of samples were left unaffected. It was found, that both lower traversing velocity (cutting speed) and higher water pressure led to removal of higher amount of concrete. Higher temperature loading caused decrease of concrete strength and thus easier removal of surface layers by water jet. Concrete mixtures with basalt aggregate demonstrate higher resistance against water jet penetration regardless thermal loading compared to mixture with standard granodiorite aggregate. Presence of polypropylene fibres has substantial influence on concrete strength properties, however only marginal impact on resistance against water jet penetration.

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Keywords: concrete; heating; fire; fireproof concretes; repair of structures; surface layers; water jet.

1. Introduction

Using of high-speed water jets for removal of eroded or degraded concrete (so-called hydrodemolition or water-jet blasting) in repair works on concrete structures is already quite widespread. This technology is recommended for operations of the removal of surface layers and concrete surface treatment before the repair action in many countries. For example, Technical Regulations of the Ministry of Transport of the Czech Republic for construction of roads (TP 120), recommend high-speed water jet as a suitable method for removal of damaged layers of concrete. It is expected that the use of technology will continue to expand, especially for its unique features.

Our research team is dealing with the effects of water jets on the concrete for several decades. During tests oriented at removal of surface concrete layers, we examined not only different types of jets, such as round jets with a circular diameter [1], rotating jets with multiple nozzles [2], fan (flat) jets [3-4] and oscillating jets [5], but also different methods of jet generation: continuous jets with a constant flow of water through the nozzle [6] and pulsating ones with the changing flow caused by pressure pulsations in a high pressure system [7-8]. In our research, we tested the removal of surface layers of undamaged (healthy) concrete [8], the concrete damaged by technological lack of discipline (high amount of mixing water,

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higher amount of sand, insufficiently compacted concrete, low strength concrete etc. [2] and the concrete damaged by various degradation environmental effects (frost, chemical de-icers, chlorides, sulphates and nitrates [4]). Our current activity is focused on removal of layers of concrete damaged by high temperature and/or fire. Research being on progress will help the correct use of water jet technology in repair works on concrete structures especially after wildfires in tunnels, underground garages, etc., which are exposed to enormous thermal stress.

2. Utilization of water jets during repair of concrete structures

In repair works, high-speed water jets are usually used for removal of defected concrete and preparation of surface for subsequent application of repair coatings and/or mortars, e.g. [9]. The growing popularity of the water jet technology in civil engineering is based on its unique properties, which other technologies lack. Water jet is able to disintegrate even the hardest materials due to high energy transmitted to extremely small area. There is no mechanical tool-material interaction in the process of disintegration. The jet can selectively remove damaged concrete; furthermore, reinforcing bars occurring inside the concrete are not cut or damaged. Disintegrated material is not exposed to any thermal impact. The method is dust-free and vibration-free; no cracks or fractures are introduced to construction unlike mechanical methods. Equipments are lightweight (except the high-pressure pump) and the whole blasting process can be easily automated. The main working media – water – is easily available; products after blasting minimally load the environment, see e.g. [10-11]. Due to operational advantages, the water jet replaces conventional mechanical techniques, such as sawing, grit-blasting, jack hammering and milling [12].

Unlike single water jet suitable primarily for cutting, heads with multiple nozzles generating multiple jets are mostly used in practice for the removal of defective concrete layers. The main goal is to spread jet(s) energy to larger area. Heads perform ordinarily rotary, oscillating or vibrating movements; jet marks on the surface are then result of a movement mostly composed of a few simple movements [13]. Abrasive material is not usually utilized in these cases; increased effect of the jet on the material is achieved by increasing the water pressure or decreasing the speed of movement of the head over the material and thus a longer exposure time of the jet on the surface element. There are plenty of studies that attempt to optimize the location and movements of the nozzles so that the disintegrating jets ideally "cover" area to be removed. Momber [14] pointed out that the energy distribution can be smooth down if a high overlap ratio between the individual cleaning steps is realised using rotating hydrodemolition tools. Several models of estimation of power distributions of rotating tools were published by Blades [15]. Wright *et al.* [16] as well as Wolgamott *et al.* [17] presented various designs of water blasting tools, while Yan *et al.* [18] focused on design and analysis of rotating tool generating pulsed water jet. Practical aspects of layers removal by water jets were published for instance by Schmid [19].

Another way how to spread jet energy to greater width represents so-called flat water jet (based on its shape, it is also mentioned fan jet in some literature). Such jet is generated by specially shaped single nozzle, see Fig. 1. It was developed originally for some special applications like cleaning thin layers of dirt or contamination from surfaces, removal of hot iron scales etc. Xu and Summers [20] reported that using relatively low water pressures (up to 100 MPa) the removed material thickness is in the order of 1 mm or less. On the other hand, Shimizu [21] demonstrated, that water jet issuing from a fan jet nozzle can remove thermal spray coatings in a more effective and environmentally clean manner than the conventional shot blast and chemical stripping methods when using high water pressures (up to 300 MPa). Flat jet is unable to disintegrate the concrete quickly and in sufficient amount and quality using usual jet operating parameters and disintegration speeds. However, it is suitable testing method for concrete disintegration in laboratory conditions due to its regular energy distribution along the line and thus its ability of areal concrete treatment. This water jet type as well as jet parameters were selected intentionally for testing in progress according to our previous experiments on water jet interaction with concrete [4]. Therefore obtained results can be directly compared with results from our previous research.

Mechanism of concrete failure by action of high-speed water jets is rather complicated. Momber [12] stated that the removal of a brittle, tension-softening material by a high-speed water jet is predominantly a fracture mechanical process. He noted that this is verified for cement-based composites and rocks. Momber [14] in his book summarized his own findings and findings of other authors as follows. If the jet hits a solid surface, a stagnation pressure profile forms at a surface. The difference between the stagnation pressure at the surface and pressure inside the target material forces a certain volume of water to penetrate the structure. Let us assume that some water penetrates into the material, then following three cases can be distinguished [14]: (i) the water flows into a crack and creates a corresponding stress at the crack tip. Fracture started in the interfacial zone between cement matrix and aggregate which is known to be weakest link in conventional concrete. Fracture propagation is mainly affected by aggregate size and distribution, (ii) the water flows into a capillary which results in pressure amplification. A liquid jet that strikes a pore opening, transports liquid into this capillary and displaces the air, (iii) the water flows through an open pore system and creates frictional forces to the structural elements (e.g. grains). If the frictional force exceeds the cohesion force to neighbouring grains, the grain in question will be removed.

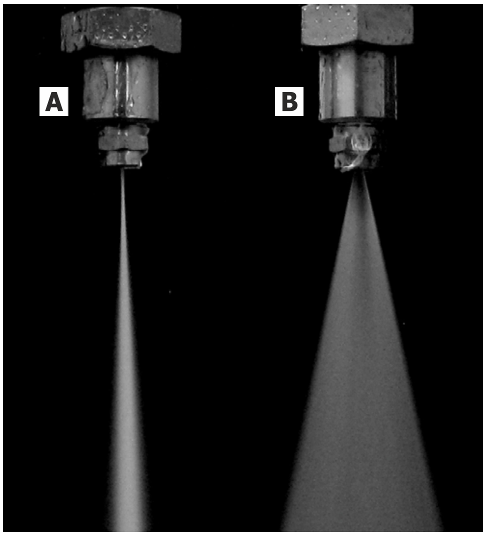

Fig. 1. Flat water jet used during experiments (A – side view; B – front view; equivalent nozzle diameter: 2.05 mm, spraying angle: 15°)

3. Damage of concrete structures by high temperatures

It is known that loading of concrete structures by high temperature causes loss of its capacity particularly at the most strained surface layers. Damage can be so large that even the whole structure can be destroyed. Temperature during fire which destroys concrete structure e.g. in road tunnel can be as high as 1200°C. At this temperature, the whole structure of cement paste degrades and the bearing capacity decreases rapidly. The rate and mode of concrete degradation and destruction of whole structure depends on the type of fire, the rate of rise in temperature and duration of the fire. Several tragic accidents of fires in road and rail tunnels worldwide (e.g. the Channel Tunnel in 1996, 2006 and 2008, the Summit Tunnel in the UK in 1984, the Great Belt Tunnel in Denmark in 1994, the Daegu Metro Tunnel in the South Korea in 2003, the Funicular Railway Tunnel in Kaprun, Austria in 2000, the Mont Blanc Tunnel in 1999, the Tauern Road Tunnel in 1999, the Gotthard Tunnel in 2001 etc.) remind that it is necessary to address this issue.

Particular solution represents the use of appropriate concrete components (cement matrix, aggregate, fibers etc.) which should be in reciprocal co-action able to eliminate adverse effects of heat stress and/or fire. Such research was carried out or is still in progress at many workplaces with various results, see for instance [22–28]. Our research is based on results by other researchers and is oriented at finding a solution that would largely utilize basic raw materials commonly available in the Czech Republic. It should not only help to support the respective branch of industry in crisis period, but should also reduce costs of manufacturing of concrete resistant to high temperatures.

4. Experimental procedure and setup

The main objective of the experiments described in this article was to assess behaviour of concretes after thermal loading when applying water jets if this technology will be used for removal of damaged heat-affected layers during repair works in the future.

For the first test on resistance of various concretes (exposed to thermal stress) against the penetration by high-speed water jet, four series of cubic concrete samples of approximate dimension of 100×100×100 mm were prepared. The same cement was used for fabrication of all samples; concrete mixtures differed by various types of aggregates and the presence of polypropylene fibres. Two types of polypropylene fibres were used for preparation of some mixtures. Type I fibres (diameter of 15 μm and length of 3 mm) were applied in mixture III, while fibres of type II (diameter of 28 μm and length of 12 mm) in mixture IV. Detailed composition of each concrete mixture tested and their properties after 28 days of ageing are given in Table 1. All mentioned parameters of the tested concrete were always verified on 3 specimens. Afterwards, all samples were stored in the same normalised environment.

Subsequently, part of the samples were heated to temperature of 200 °C, another part to 600 °C and the last part was left without any thermal loading as a reference samples for comparison of property changes. The growth of the temperature was set to 10°C.min^{-1}, the samples were left at the relevant temperature for 24 hours (samples heated to 200 °C) or 60 minutes (samples heated to 600 °C). Then, the samples were slowly cooled down to room temperature.

Table 1. Composition of concrete mixtures

Composition (per 1 m^3 of fresh concrete)	Quantity [kg]
MIX I	
Cement CEM II/B-M 32.5 (S-LL) 32.5 R	320
Aggregate 0-4 mm sandstone (psammite) Náklo	953
Aggregate 4-8 mm granodiorite Olbramovice	363
Aggregate 8-16 mm granodiorite Olbramovice	531
Water	174
MIX II	
Cement CEM II/B-M 32.5 (S-LL) 32.5 R	300
Aggregate 0-4 mm basalt Bílčice	1162
Aggregate 4-8 mm basalt Bílčice	340
Aggregate 8-16 mm basalt Bílčice	497
Water	163
MIX III	
Cement CEM II/B-M 32.5 (S-LL) 32.5 R	300
Aggregate 0-4 mm basalt Bílčice	1162
Aggregate 4-8 mm basalt Bílčice	340
Aggregate 8-16 mm basalt Bílčice	497
Water	163
Plasticizer Chrysofluid Optima 208 1.8 % m_c	5.4
MIX IV	
Cement CEM II/B-M 32.5 (S-LL) 32.5 R	300
Aggregate 0-4 mm basalt Bílčice	1162
Aggregate 4-8 mm basalt Bílčice	340
Aggregate 8-16 mm basalt Bílčice	497
Water	163
Plasticizer Chrysofluid Optima 208 1.8 % m_c	5.4
Polypropylene fibres – TYPE II	0.6

Table 2. Properties of concrete mixtures before and after thermal loading

Mixture	After 28 days	200°C	600°C
Density [kg.m^{-3}]			
MIX I	2350	2260	2210
MIX II	2470	2410	2320
MIX III	2510	2450	2380
Compressive strength [N.mm^{-2}]			
MIX I	41.8	40.2	35.6
MIX II	34.3	33.4	24.4
MIX III	38.0	35.4	31.7
Flexural strength [N.mm^{-2}]			
MIX I	5.5	5.3	N/A
MIX II	5.5	5.2	
MIX III	5.9	5.6	
Tensile strength of surface layers [N.mm^{-2}]			
MIX I	2.7	1.8	0.9
MIX II	3.6	3.2	2.7
MIX III	3.2	3.1	2.5

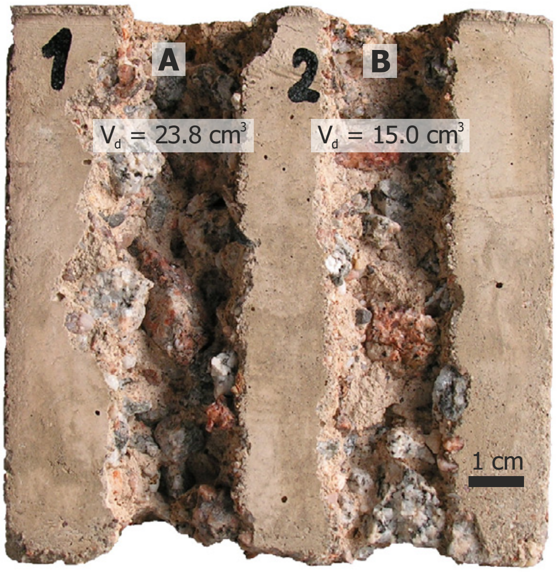

Fig. 2. Example of kerfs created by flat jet in concrete prepared according to mixture I after heat loading to 600°C (V_d – disintegrated volume, equivalent nozzle diameter: 2.05 mm, standoff distance: 40 mm, water pressure: 30MPa, traversing velocity: 0.2 m.min^{-1} – A, 1 m.min^{-1} – B)

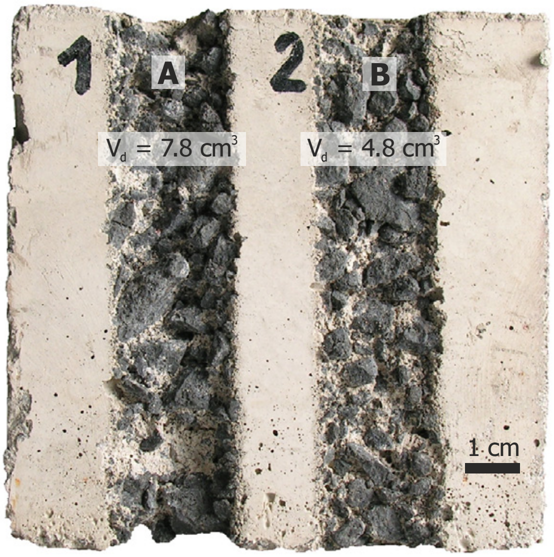

Fig. 3. Example of kerfs created by flat jet in concrete prepared according to mixture IV after heat loading to 600°C (V_d – disintegrated volume, equivalent nozzle diameter: 2.05 mm, standoff distance: 40 mm, water pressure: 30MPa, traversing velocity: 0.2 m.min^{-1} – A, 1 m.min^{-1} – B)

Straight kerfs were cut in every concrete sample by flat continuous high-speed water jet. Cuts were performed at pressures of 30 MPa and 70 MPa. The standoff distance from the nozzle exit was 40 mm that is optimal distance for given conditions of flat jet determined by erosive tests on aluminum [29]. Traversing velocity was set to 0.2 m.min^{-1} and 1 m.min^{-1}, respectively. Disintegrated volume of every kerf was determined as a measure of performance of the jet.

5. Experimental facility

The laboratory experimental facility consisted of a high-pressure water supply system and a robot for traversing of the water nozzle over testing samples.

High-pressure water was supplied to the flat nozzle by a plunger pump capable of delivering up to 67 litres of water per minute at pressure up to 160 MPa. Flat nozzle with equivalent diameter of 2.05 mm and spraying angle of 15° was used to generate flat jet.

6. Result and discussion

Selected properties of concrete samples prepared according to particular formulae before and after thermal loading are specified in Table 2. Example of typical samples with formed kerfs as well as values of disintegrated volume V_d of particular kerfs are shown in Figures 2 and 3. Examples of comparison of efficiency of flat jets on concrete samples exposed to high temperature and reference samples cut at various traversing velocities and water pressures are illustrated in Figures 4 and 5.

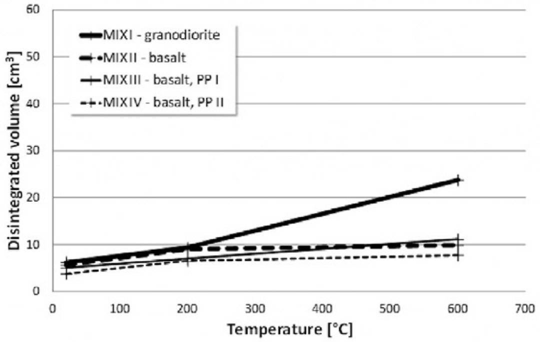

Fig. 4. Efficiency of flat water jet depending on temperature and concrete mixture (traverse velocity: 0.2 m.min^{-1}, water pressure: 30 MPa)

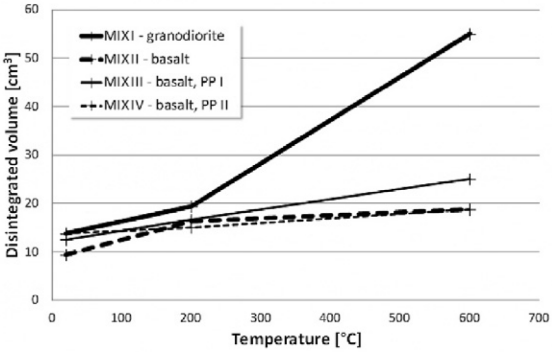

Fig. 5. Efficiency of flat water jet depending on temperature and concrete mixture (traverse velocity: 1 m.min^{-1}, water pressure: 70 MPa)

The results of all the tests obtained for the given operating parameters of high-speed water jet suggest that the water pressure and traversing velocity (i.e. cutting speed) have a significant influence on the amount of the concrete removed during its interaction with the jet. The amount of removed concrete is reduced at higher velocity (1 m.min^{-1}) up to 2.3 times for MIX II concrete unaffected by heating and up to 2.5 times for the concrete prepared from MIX III after heating to 600 °C compared to lower velocity (0.2 m.min^{-1}). Similarly, one can observe increasing amount of concrete removed at higher water pressures (70 MPa): up to 6.1 times for MIX IV concrete unaffected by heating and up to 5.7 times for MIX III concrete heated to 600 °C in comparison with a water pressure of 30 MPa.

The results also imply that the concrete prepared according to mixture I (concrete with standard granodiorite aggregate) is the least resistant to water jet action of all tested concretes. This difference increases markedly after heating the samples to 600 °C, see Fig. 6. At this temperature, the destruction of the cement matrix occurs in the concrete due to the different thermal expansion of cement and aggregate. Aggregate expands due to transformation of α-quartz to β-quartz accompanied by the development of cleavage in feldspars; as a result, secondary cracks are developed inside concrete structure. Thus, water jet easily penetrates into these cracks and causes destruction of the concrete in surface layers. This is supported also by decreasing strength of the concrete after heating (higher temperatures leads to mineral transformations and change of pore space in the concrete). The difference in resistance against jet penetration in the concrete unaffected by higher temperature and concrete after heating to 600 °C is more noticeable at lower traversing velocity (0.2 $\mathrm{m.min^{-1}}$), when the jet acts on the surface area for a longer time, or on the contrary, at higher water pressure (70 MPa), when the jet has greater penetrating effect.

On the other hand, basalt aggregate as igneous rock has a very low thermal expansion and therefore concrete structure after heating is slightly disturbed by formation of secondary cracks (MIX II – MIX IV). Although the compressive strength of concretes with basalt aggregate is lower than that with granodiorite aggregate, their resistance to penetration of water jet is higher. Granodiorite aggregate unlike basalt is more porous with higher water absorption capacity, therefore granodiorite binds cement paste very well and this fact contributes to the higher compressive strength. However higher resistance of concrete with basalt aggregate to jet penetration can be explained by its higher tensile strengths (flexural strength and tensile strength of surface layers, see Table 2), because brittle materials are damaged predominantly by tensile stresses when exposed to water jet action. Therefore, it is possible that the concrete demonstrating higher compressive strength after heating to 600 °C (concrete with granodiorite aggregate in this case) breaks easily during interaction with water jet. Similar results were observed in our previous research also for concrete subjected to 100 cycles of freezing. Although the final compressive strength after freezing was almost 85% of its original strength, tested samples were completely broken after interaction with water jet [4].

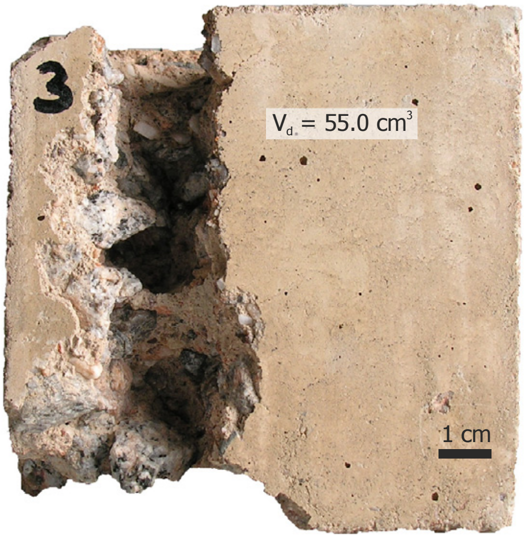

Fig. 6. Kerf created by flat jet in concrete prepared according to mixture I after heat loading to 600 °C (V_d – disintegrated volume, equivalent nozzle diameter: 2.05 mm, standoff distance: 40 mm, water pressure: 70MPa, traversing velocity: 1 $\mathrm{m.min^{-1}}$)

The presence of polypropylene fibres in the concrete matrix has only a small effect on the resistance against water jet penetration, but it seems that the mixture II with basalt aggregate without polypropylene fibres before heating resists to the jet slightly better. Possible explanation is as follows: polypropylene fibres form artificial channels in the concrete matrix. Water jet easily penetrates into these channels and breaks concrete according to the above mentioned mechanism. For concrete without polypropylene fibres, the pressurised water penetrates only into surface layers and disintegrates cement paste mainly. This fact is evident especially at higher traversing velocities. On the other hand, polypropylene fibres have a positive effect on the final concrete strength that does not decrease as much as for mixtures without fibres even after heating to 600 °C.

If one compares concretes with both types of polypropylene fibres, concrete prepared from mixture IV (type II fibres - longer fibre with larger diameter) resists slightly better to the action of water jet than that prepared from mixture III (type I fibres – 4 times shorter fibre with about half the diameter compared to type II) especially at higher water pressures.

Confirmation or explanation of this fact will require performing of more detailed tests of concrete disintegration by water jet and especially detailed macro- and microscopic analysis of samples before and after jet exposure.

Further research in this area should be oriented to the verification of using of so-called pulsating water jet, which is not only more effective in disintegration of materials [5], but its use in hydroblasting is also economically competitive [30-31].

7. Conclusions

It follows from the results on disintegration of thermally affected concretes by high-speed water jet that the higher working water pressure and slower movement of the nozzle over the treated surface cause removal of higher amount of concrete regardless whether the concrete is influenced by high temperature or it is thermally unaffected. The higher the temperature influencing the concrete, the better is disintegration of surface layers by flat water jet and penetration to greater depths because of damaged concrete structure and lower strength. Concrete with basalt aggregate resists better to action of water jet compared to concrete with standard granodiorite aggregate. The presence of polypropylene fibres has a positive effect mainly on the strength of concrete; the difference in the resistance of such concrete to penetration of water jet is more or less negligible. Crucial role in the resistance of concrete against the jet penetration plays especially type of used aggregate.

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