Construction and Building Materials 89 (2015) 76–89

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An experimental investigation of laser scabbling of concrete

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HIGHLIGHTS

- New experimental methodology, using infrared thermography.
- Scabbling behaviour differs between cement pastes, mortars and concretes.
- Air drying of specimens did not produce the expected reduction in scabbling.
- The effect of PFA in cement paste suggests permeability is a key factor.
- Scabbling is caused by processes in cement paste; and influenced by aggregates.

ARTICLE INFO

Article history:
Received 5 December 2014
Received in revised form 12 March 2015
Accepted 22 April 2015

Keywords:
Concrete
Cement
Scabbling
Spalling
Thermal analysis

ABSTRACT

Laser scabbling of concrete is the process of removal of surface material using a high power laser beam. The main aim of this investigation was to establish an experimental procedure for assessing the effects of various parameters that may be critical for the effectiveness of the process, such as material composition and initial moisture content. The study shows that the key characteristics of the process can be detected by monitoring surface temperature variations. This experimental procedure is used to provide data on the effects of each parameter to explain the mechanisms that drive the process. The results suggest that scabbling is mainly driven by pore pressures in the cement paste, but strongly affected by other factors. Reducing permeability by adding PFA to the cement paste resulted in significant increase in volume removal; but reducing moisture content by air-drying of the material did not result in the expected reduction in volume removal.

1. Introduction

Concrete is widely used in the nuclear industry, often in direct contact with radioactive materials. Concrete contamination tends to extend 8–12 mm from the surface [1]. Removal of the contaminated surface region can reduce the volume of waste requiring controlled disposal. Mechanical scabbling and high pressure water jetting have been used for surface removal in nuclear decommissioning. Water jetting produces large volumes of secondary waste, whereas mechanical scabbling involves large reaction forces, requiring extensive deployment systems unsuitable for remote handling. Application of a high power laser on a concrete surface causes concrete fragments to explosively spall from the surface. Lasers of wavelengths around 1 μm can be transmitted down optical delivery fibres several hundred metres in length, allowing expensive laser generation equipment to be stationed away from contaminated areas. As no reaction forces are developed during laser scabbling, relatively lightweight deployment systems can be used, making remote handling a real possibility. Laser scabbling and surface glazing, with subsequent surface removal, was used successfully in the decommissioning of the Japan Atomic Energy Research Reprocessing Test Facility [2].

Laser scabbling is comparable to explosive spalling exhibited in concrete exposed to fire conditions, but the large difference in heating rates would be expected to produce different mechanisms driving the two processes.

1.1. Laser scabbling

Laser scabbling was discovered in the early 1990's during concrete glazing investigations [3]. The phenomenon was attributed to the rapid expansion of water from cement paste dehydration.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.04.037
0950-0618/

Blair [4], however, found scabbling to take place only in locations where limestone aggregate was close to the surface. A thicker mortar cover created a glazed layer preventing scabbling. Blair concluded that the scabbling was driven by the pressure of gas produced by decarbonation of calcite.

MacCallum and Norris [5] suggested that the mechanism responsible for laser scabbling was the build up of strain in the interfacial transition zone between the aggregate and hardened cement paste. Multiple passes were ineffective suggesting a critical strain may be reached on the initial pass. The authors concluded that scabbling was caused by expansion of aggregates, and hence the beam diameter had to be sufficiently large to heat whole aggregate pieces.

Dowden et al. [6] investigated, through modelling, a mechanism of laser scabbling based on the hypothesis that the laser beam causes expansion of a thin surface layer of concrete which induces internal stresses. Tensile stresses are formed beneath this layer, which are relieved through fracture and buckling of the surface, resulting in ejection.

The effect of type of coarse aggregate on scabbling has been highlighted in several studies. Nguyen [7] found that granite concrete consistently scabbled to a depth of 1.5 mm, whereas whinstone (basalt) concrete, cored from a nuclear facility currently being decommissioned, failed to scabble for any set of laser parameters. A vitrification threshold power density was identified for basalt concrete at 103 W/cm^2, at higher power densities the basalt melted, creating a glazed layer that prevented scabbling. It is not clear, however, why lower power densities were insufficient to initiate scabbling. A number of factors could be responsible, such as damage caused during coring (leading to increased permeability and reduction of pore pressures) or the laser being applied to a cut rather than a cast face (different surface conditions). Hilton [8] reported similar results for basalt concretes, however limestone concrete was seen to scabble successfully for a large range of laser parameters (120–960 W/cm^3).

The effect of degree of saturation on laser scabbling has been investigated in several experiments. Blair [4] found that specimens of limestone concrete soaked overnight experienced a greater extent of scabbling. Hilton [8] also found that a wet surface increased volume removal of limestone concrete specimens but had no noticeable effect on basalt or granite concretes. Johnston found that laser scabbling was ineffective on specimens that had free water removed by heating prior to testing (reported in [6]). Rather than claiming that this was due to a reduction in pore pressure spalling, Dowden suggested that the ineffectiveness was due to a reduction in the coefficient of expansion, a reduction in the Youngs modulus, an increase in density, an increase in specific heat capacity or a reduction in strength, as a result of drying.

Stochastic scabbling behaviour has been identified in several studies [7–9,5]. Trials conducted using identical laser parameters on concretes of identical composition yielded vastly different outcomes, ranging between scabbling, vitrification and faint heat marks.

Laser beam parameters are critical for laser scabbling of concrete. A number of authors have identified threshold power densities at constant scan speeds, defined as laser power per unit area, below which concrete scabbles and above which the surface vitrifies [4,5,10,11,2]. Vitrification relieves strains preventing scabbling [5]. Blair [4] suggested that beam diameter had to be large enough to heat entire pieces of aggregate. MacCallum and Norris [5] went further, suggesting that laser scabbling was not a scalable function with power density and heat input, but also depended on the ratio between beam diameter and aggregate size. Blair [4] also found that trials with high power density and high scan speed resulted in the same concrete behaviour as low power density and low scan speed trials; suggesting that the rate of energy emitted by the laser, to a unit area of concrete, was the key factor determining the scabbling of concrete. Experiments carried out by MacCallum and Norris [5] using laser powers in the range 200–1000 W and beam diameters of 0.05 mm and 26 mm also showed that the process was dependant on heat input and diameter size. For a single pass on limestone concrete (with laser beam diameter of 60 mm, power 5 kW, scan speed 200 mm/min, and power density 177 W/cm^2) Hilton [9] achieved removal rates of up to 217 cm^3/min. Johnston and Spencer [12] compared the scabbling performance of a CO_2 laser and a Nd:YAG laser, with wavelengths of 10.6 μm and 1.06 μm respectively, and found very little difference: identical laser parameters yielded similar removal rates with slight variations in trough profiles.

1.2. Explosive spalling

Explosive spalling is a phenomenon observed in concrete structures exposed to fire conditions, where the heating rates are much lower than those in laser scabbling. Connolly [13] found the temperature at the onset of spalling to be higher for a lower heat rate (varying from 130 °C for 75 °C/min to 340 °C for 25 °C/min), whereas other authors reported that surface temperatures at the onset of spalling are between 300 and 425 °C [14] dependant upon material composition rather than heat rate. For laser scabbling heat rates are typically around 200 °C/s. The fragment sizes in the two processes are also very different: 10 mm depth and 30 mm width [8] for scabbling, and 100 mm depth and 200–300 mm width [14] for spalling.

It is generally accepted that high strength concrete (water/cement < 0.4) has a tendency to spall more than normal strength concrete (water/cement > 0.4) [15–18]. This is attributed to the higher permeability in normal strength concrete, which allows dissipation of water pressures within the pore network. Many authors have highlighted the relationship between moisture content (degree of saturation) and spalling, with a higher moisture content leading to a greater degree of spalling [19–23]. It has also been reported that the higher the concrete strength the lower the moisture content required for spalling [21]. The general assumption is that this is most likely due to concrete properties affected by concrete strength, such as porosity and permeability, rather than a direct consequence of concrete strength. Hertz [20] found that dry specimens experienced spalling too, concluding that chemically bound water must have contributed towards pore pressure spalling as the source of moisture in these specimens. Copier [23] found that concrete with a moisture content below 5% will not spall, although in reality concrete will always have a moisture content of 7–10% (by volume).

Connolly [13] investigated the effects of aggregate type on spalling in experiments on concretes using limestone, gravel and Lytag (a lightweight aggregate). He found that limestone and Lytag concretes behaved similarly, with gravel concrete being the most susceptible to spalling. Lightweight aggregates are used to mitigate spalling by increasing the permeability of concrete. The lightweight aggregate, however, experienced the most violent spalling with fracture taking place within the aggregate itself, whereas in gravel and limestone concrete fractures occurred exclusively in the cement paste. Connolly suggested that the greater porosity of lightweight aggregates allowed pore pressures to build within the aggregates causing them to explode. Connolly and Khoury [13,14] suggested that if the moisture content was high enough for saturation in the aggregate to exceed that of the cement paste, the use of lightweight aggregate would encourage spalling rather than mitigate against it.