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The effect of concrete composition on laser scabbling

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HIGHLIGHTS

- Results suggest pore pressures are the main cause of laser scabbling in cement pastes.
- A lower w/b ratio and/or a greater PFA replacement increases volume removal.
- Coarse aggregates do not provide the primary driving force of laser scabbling.
- The low melting point of basalt coarse aggregates reduces volume removal.

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ABSTRACT

Laser concrete scabbling is the process by which the surface layer of concrete may be removed through the use of a low power density laser beam. The main aim of this investigation was to establish relationships between laser interaction time and volume removal for a wide range of material compositions, including different w/b ratios, binder compositions (OPC/PFA), aggregate/binder ratios and coarse aggregate sizes. The results show that 25% replacement of ordinary Portland cement with pulverised fuel ash and/or a reduced water/binder ratio improves the efficiency of scabbling of cement pastes. Mortars and cement pastes were seen to scabble at a constant rate, whereas concretes experienced a peak rate, after which volume removal reduced dramatically. Basalt aggregate concrete was less susceptible to laser scabbling than limestone aggregate concrete. The effects of composition on the mechanisms which drive laser scabbling are discussed. It is suggested that pore pressure spalling governs behaviour in cement pastes, and thermal stress spalling is more dominant in mortar specimens. The driving force responsible for laser scabbling of concretes is developed within the mortar.

1. Introduction

This paper describes the second part of an investigation of the mechanisms responsible for laser scabbling; a technique for removal of the surface layer of concrete which can be used for decontamination in nuclear decommissioning. Radioactive contamination in concrete is generally limited to a depth of around 10 mm [1]. Application of a low power density laser, perpendicular to the concrete surface, causes concrete fragments to be ejected, thus reducing the volume of radioactive waste sent for disposal. This technique is preferable to alternative methods, such as mechanical scabbling or high pressure water jetting, as no reaction forces or secondary wastes are created.

As concrete is exposed to extreme heat rates such as those induced during laser scabbling, there are many interlinked phenomena taking place simultaneously. It is assumed that laser scabbling cannot be attributed to any one mechanism but to a complex combination of coupled hygro-chemo-thermo-mechanical effects. In the first part of this investigation [2], a wide range of materials were investigated with an aim to establish an experimental procedure for quantification of the relationships between laser interaction time, surface temperature, volume removal and size of fragments. Materials tested included hardened cement pastes, aggregate rock, mortars and concretes, as well as two different levels of saturation. The first test series set out the experimental technique and identified parameters to be investigated in further experimental programmes.

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The results of the first series [2] showed that:

1. The use of PFA as a cement replacement material (75% OPC + 25% PFA) enhanced volume removal during laser scabbling of hardened cement paste (this was attributed to reduced permeability of the material);
2. Volume removal of mortars was higher than that of concretes and similar to that of PFA + OPC pastes, but with larger fragment sizes;
3. Results were repeatable, there was no evidence of stochastic tendencies reported in previous studies [3–6];
4. Basalt concrete scabbled more than in any previous study [3,4], but still less than limestone concrete;
5. Reducing the degree of saturation of specimens (saturated vs. air-dried) did not reduce scabbling.

2. Scope and aim of the research

This paper aims to determine the relationship between laser interaction time, volume removal and surface temperatures for different compositions in order to identify the effect of concrete composition on laser scabbling behaviour (rate of volume removal, temperature at the onset of scabbling, surface temperature during scabbling, fragment ejection frequency and fragment sizes, as seen in Fig. 1). These observations were then used to assess the effect of each parameter and form conclusions on the potential mechanisms responsible for laser scabbling.

The compositions selected for investigation in this study were designed to isolate factors of the laser scabbling process identified from the first test series [2], the scopes of the two test series are presented in Table 1.

The compositions tested in this series are as follows:

1. Cement pastes with different *w*/*b* ratios were investigated to determine the effects of permeability and strength on laser scabbling;
2. Concretes, mortars and hardened cement pastes with two different binder compositions (OPC and PFA + OPC) were analysed to determine the effect of PFA replacement in different materials;
3. Limestone and basalt aggregate concretes using OPC and PFA + OPC binders were tested to characterise the effect of different aggregate/binder combinations;
4. Concretes with two coarse aggregate gradings (10 mm and 20 mm) were tested to determine the effect of aggregate size;
5. A wide range of interaction times were applied to each composition to determine the relationship between laser interaction time and volume removal for each composition (10 s and 40 s were used in the first series).

3. Materials, specimens, test set-up and experimental programme

The material compositions used in this study are given in Table 2. The materials used for preparing the test specimens were: Hanson CEM 1 OPC (BS EN 197–1:2000 strength class 52.5 N); CEMEX PFA (LOI-B and fineness-s); fully graded marine dredged quartzitic sand from Hoyle Bank, Morecombe Bay, UK; crushed basalt rock sourced from High Force Quarry, Durham, UK; and crushed limestone rock from Longcliffe Quarry, Derbyshire, UK. Limestone and basalt rock, sourced from the same quarries as the crushed aggregates, was machined to form the rock specimens (100 mm × 100 mm × 49 mm ± 1 mm).

All mixes underwent 30–60 s dry mixing followed by 3–5 min wet mixing. The slurry was transferred to 100 mm cube moulds which were 3/4 filled and vibrated for approximately 10 s before being filled and vibrated again for approximately 10 s, and the cast face trowelled smooth. All specimens underwent a ten day temperature matched curing regime reaching a peak temperature of 65 °C after 36 h, gradually returning to 20 °C after 240 h. After curing, the 100 mm cubes were cut in half using a diamond saw, creating 100 mm × 100 mm × 49 mm (±1 mm) cuboid specimens, which were stored in a mist room at 100% relative humidity until testing. Concretes using different aggregate sizes had the same mass ratio of coarse aggregates; only the aggregate size used was different. All '10 mm' aggregates passed a 10 mm sieve and were retained on a 6 mm sieve. The 20 mm aggregates had the particle size distribution as follows: all aggregates passed a 24 mm sieve, 23% was retained on a 20 mm sieve, 66% on a 14 mm sieve, 10% on a 10 mm sieve and 1% on a 5 mm sieve.

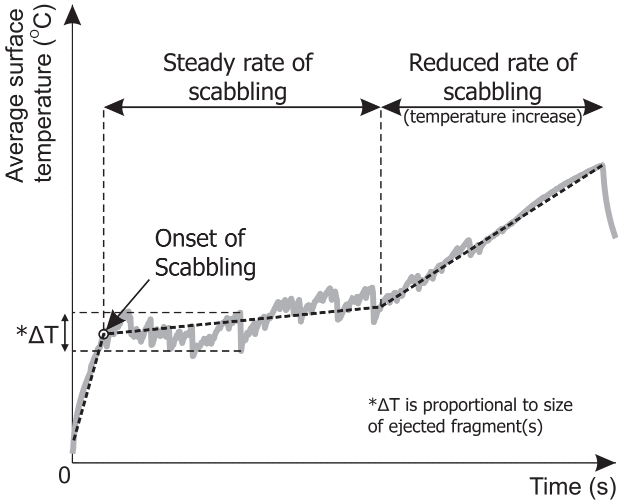

Fig. 1. Example average surface temperature graph, showing trilinear behaviour with different stages of scabbling behaviour highlighted.

Table 1
The scopes of the 1st series [2] and the 2nd series (presented in this paper).

	1st series [2]	2nd series
w/*b* ratio of cement pastes	0.42	0.32 & 0.42
Binder of concretes and mortars (*OPC%*/*PFA%*)	75/25	75/25 & 100/0
Coarse aggregate size	10 mm	10 mm & 20 mm
Laser interaction time intervals	10 s, 40 s	5 s, 10 s, 20 s, 30 s, 40 s, 50 s, 70 s

The laser interaction times, number of repeats and age of specimens at the time of testing are given in Table 3 for the concretes and Table 4 for the pastes and mortars. Hardened cement paste samples were cast 3 months after the mortar and concrete specimens and as a result underwent less ageing/curing. All scabbling tests were carried out using an IPG Photonics YLS-5000 (5 kW) Yb-fibre laser. The specimens were subjected to a static, continuous, diverging laser beam with a stand off distance of 340 mm from the focal point which gave a nominal beam diameter of 60 mm. Tests were conducted with the laser beam applied to a vertical concrete surface to avoid debris falling back onto the specimen during testing (in situ the vacuum used to remove the debris would eliminate this problem).

The change in mass due to laser application was determined as the difference in mass of the specimen measured before and after testing. The mass change was converted to volume by dividing the mass by the density determined in accordance with BS EN12390–7:2009 [7]. The volume removal graphs show the mean of the repeats with maximum/minimum error bars. Porosity, moisture content and degree of saturation were subsequently determined using values found in the density tests.

$$\text{Porosity} = 100 * ((m_{sat} - m_{od})/(m_{sat} - m_{sub})),$$
$$\text{Moisture content} = 100 * ((m_t - m_{od})/m_t),$$
$$\text{Degree of saturation} = 100 * ((m_t - m_{od})/(m_{sat} - m_{od}));$$

where m_{sat}, m_{od}, m_{sub} and m_t are saturated, oven-dried, submerged and as received masses respectively.

An infrared camera (FLIR SC 640) was used to monitor the surface temperatures; and a high-speed camera (Phantom V5.1) to record the ejection of fragments. The average surface temperature was taken over the surface area that exceeded 100 °C after 1.0 s of interaction time. The time histories of average surface temperature, showing the temperature fluctuations due to ejection of fragments (their amplitudes corresponding to size of fragments), were used as key data in characterisation of the scabbling behaviour of each material.

The infrared camera can operate within temperature ranges of 0–550 °C or 200–2000 °C. If the average surface temperature of a specimen exceeded the lower temperature range of the infrared camera the test was repeated using the higher temperature range. The two data sets were then merged to give data for the whole temperature range over the whole interaction time. Volume removal data is presented with the average surface temperature data on the same timescale. It should