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Peach, B., Petkovski, M. orcid.org/0000-0002-3788-0772, Blackburn, J. et al. (1 more author) (2018) The effect of ageing and drying on laser scabbling of concrete. Construction and Building Materials, 188. pp. 1035-1044. ISSN 0950-0618

https://doi.org/10.1016/j.conbuildmat.2018.08.131

The effect of ageing and drying on laser scabbling of concrete

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Abstract

Laser scabbling of concrete is a process by which the surface layer of concrete is removed through the use of a high power (low power density) laser beam. In order to understand how the age and treatment of structures may affect the laser scabbling process, the aim of the research presented in this paper was to establish a relationship between laser interaction time, surface temperature and volume removal for cementitious materials of different ages and different degrees of saturation. The investigation focussed on (i) the effect of age on saturated specimens and (ii) the effect of prolonged drying. The results show that drying of specimens had the largest effect on scabbling. The effect of age on saturated specimens was small for PFA+OPC pastes, mortars and concretes, but significant for OPC pastes, where the volume of scabbling dramatically reduced with age.

Keywords:
Scabbling, Ageing, Concrete, Cement, Spalling, Moisture content, w/b ratio

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1. Introduction

Laser scabbling of concrete is a technique which can be used for removal of the contaminated surface layers in decommissioning of nuclear structures. Significant advantages over alternative methods are that it does not create large reactive forces (typical for mechanical removal) and does not produce additional waste material (water jetting) [1]. Presented here is the fourth part of a study [1, 2, 4] of the key factors and mechanisms that control the efficiency of laser scabbling.

The design life of a nuclear power plant is generally 60 years, which is often extended to improve the economic rewards of the station. Furthermore, the first stage of decommissioning is usually to remove the fuel and leave the structure in a state of passive safety for around 20 years to allow the majority of the short lived radionuclides to decay. As a result, structures undergoing decommissioning will be of the age of around 80-100 years.

Concrete age is an important factor affecting its prop-

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erties, from cement hydration in the early stages to environmental effects, such as drying and weathering, in the later stages.

Extra specimens were saved from the first two test series [1, 2] to be tested at a later date, in order to determine the effects of ageing and drying on laser scabbling. These specimens continued to be exposed to the same conditions as those that were originally tested (i.e. air dried or saturated). The results of this study are important to validate the results and conclusions made in the earlier stages of this investigation [1, 2].

2. Scope and Aim of the Research

This investigation focuses on understanding the effects of ageing and drying of concrete on the effectiveness of laser scabbling. The aim of the research was to determine the relationship between laser interaction time, average surface temperature and volume removal for material compositions of different ages and drying exposure times in order to analyse the effects of concrete age and degree of saturation on laser scabbling behaviour, characterised by temperature at the onset of scabbling, surface temperature changes during scabbling, rates of volume removal, fragment ejection frequency and fragment sizes. The compositions reported in this study (presented in Table 1) were selected for the earlier test series [1, 2] to isolate factors that have a significant effect on the process. The notation in Table 1 is the same as that in the second study [2], but different from the notation used in the first study [1], where PFA+OPC binder was used for all limestone concrete (LC), basalt concrete (BC) and mortar (M) specimens. In this study (as well as in [2]) the investigation was extended to concrete and mortar specimens with OPC binder (Lo, Bo and Mo), in addition to those cast with OPC+PFA binder (now denoted as Lp, Bp and Mp). The results reported here are grouped into two investigations looking at (i) the effect of age on saturated specimens and (ii) the effect of prolonged drying.

3. Materials and Test Methodology

The material compositions of the specimens tested in this investigation are detailed in Table 1. The experimental methodology was the same as the one used in the first two test series ([1] and [2]). The scabbling was induced by using an IPG Photonics YLS-5000 (5 kW) Yb-fibre laser to fire a static, continuous, diverging laser beam with a stand off distance of 340 mm from the focal point (giving a nominal beam diameter of 60 mm) on 100x100mm surface[3] of rectangular specimens (49mm thickness), for exposure (interaction) periods of 10s, 20s, 30s, 40s (for all specimens), and 70s (for selected specimens).

The results are presented as time histories of:

1. Volume Removal: The volume removal histories were constructed by connecting discrete values of volume loss calculated at the end of the interaction periods for each specimen (at 10s, 20s ... etc.), from measurements of mass loss of the specimens before and after scabbling, and converting to vol-

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[3] horizontal in [1], vertical in [2] and in this study

Table 1: Mix compositions of specimens tested in the age comparison study. The labels are different from those used in the report on the early-age study [1]: LC (now Lp), BC (now Bp), M (now Mp), P (now P_{42}) and O (now O_{42}), to account for the extension in the range of tested materials. The new subscripts stand for PFA+OPC paste (p) , OPC paste (o), and water/binder ratios 0.42 and 0.32 (32 and 42). * AGR concrete (a standard mix used in UK's Advanced Gas Reactor vessels) is included for comparison only; not tested in the experimental programme. ** Basalt and Limestone Concrete refer to concrete mixes using basalt and limestone as coarse aggregates.

	*AGR	**Lime. Concrete		**Bas. Concrete		Mortar		PFA+OPC Paste		OPC Paste	
		Lp	Lo	Bp	Bo	Mp	Mo	P_{42}	P_{32}	O_{42}	O_{32}
Water	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.32	0.42	0.32
OPC	0.75	0.75	1	0.75	1	0.75	1	0.75	0.75	1	1
PFA	0.25	0.25	0	0.25	0	0.25	0	0.25	0.25		
Fine agg.	1.84	1.84	1.84	1.84	1.84	1.84	1.84				
Plasticiser	0.0045	0.0045	0.0045	0.0045	0.0045						
10mm agg.	1.05	3.21	3.21	3.21	3.21						
20mm agg.	2.16										

ume by dividing the mass by the density determined in accordance with BS EN123907:2009 [3]. This approach was validated by direct measurements of volume loss using a 3D scanner (see [1]).

2. Average Surface Temperature. The average surface temperature of the heat affected zone (HAZ[4]) was monitored by using an infrared camera (FLIR SC 640) recording thermal images of the surface at time steps of 1/30 s. The average surface temperature changes as a result of scabbling: it rises when there is no scabbling, and drops when material is ejected and cooler surfaces underneath the ejected fragments are exposed. Hence, the temperature histories give a detailed picture of the scabbling process, that complements the discrete volume removal data: continuous rise in temperature indicates that there is no scabbling, small and frequent fluctuations show frequent ejection of small fragments, whereas a monotonic temperature increase followed by a large drop in average temperature indicates a less frequent ejection of larger fragments. The slope of the baseline around which the temperature oscillates is a good measure of scabbling efficiency, with most effective scabbling resulting in zero gradient. The stages of scabbling behaviour are illustrated in Figure 1: (1) initial steep increase in surface temperature until the onset of scabbling, (2) a period of intense scabbling at nearly constant baseline temperature, characterised by either very frequent, small amplitude or larger, but less frequent temperature oscillations (resulting in a high rate of volume removal), followed by (3) a period of reduced scabbling (smaller fragments and/or reduced frequency of ejection), increase in baseline temperature and reduced rate of volume removal) and finally (4) a period of monotonic increase of surface temperature (no further volume removal).

4. The effect of age on saturated specimens

4.1. Test programme for saturated specimens

In order to test the effect of age on laser scabbling, extra specimens were made during casting for the inves-

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[4] HAZ was defined as the surface area that exceeded 100^{o}C after 1s of interaction time

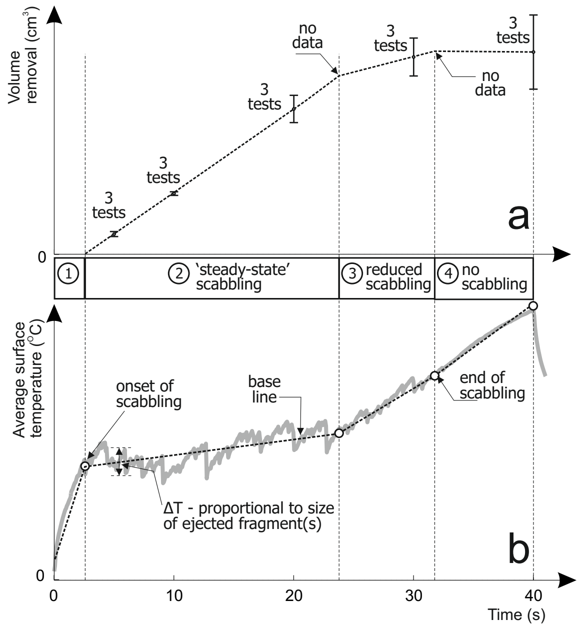

Figure 1: Example of test results, showing different stages of scabbling behaviour; (a) volume removal data from 15 tests (3 repeats at 5 interaction periods), and (b) time history of average surface temperature recorded in one 40s test.

tigation into the effect of concrete composition on laser scabbling [2]. The first series of tests were performed at the ages of 3 months for the cement paste specimens and 8 months for the concrete specimens. The remaining specimens were then stored in a saturated state in a mist room (≈20 °C, ≈95% relative humidity) until they were tested 14 months later.

The experimental programme of this study is presented in Table 2, showing the material composition of the specimens, laser interaction times (duration of exposure), ages of specimens at the time of testing and number of repeats of each test. The test results, presented as time histories of volume removal and average surface temperature (e.g. Figure 4.3), were obtained by using an experimental procedure described in detail in the first report of this investigation [1].

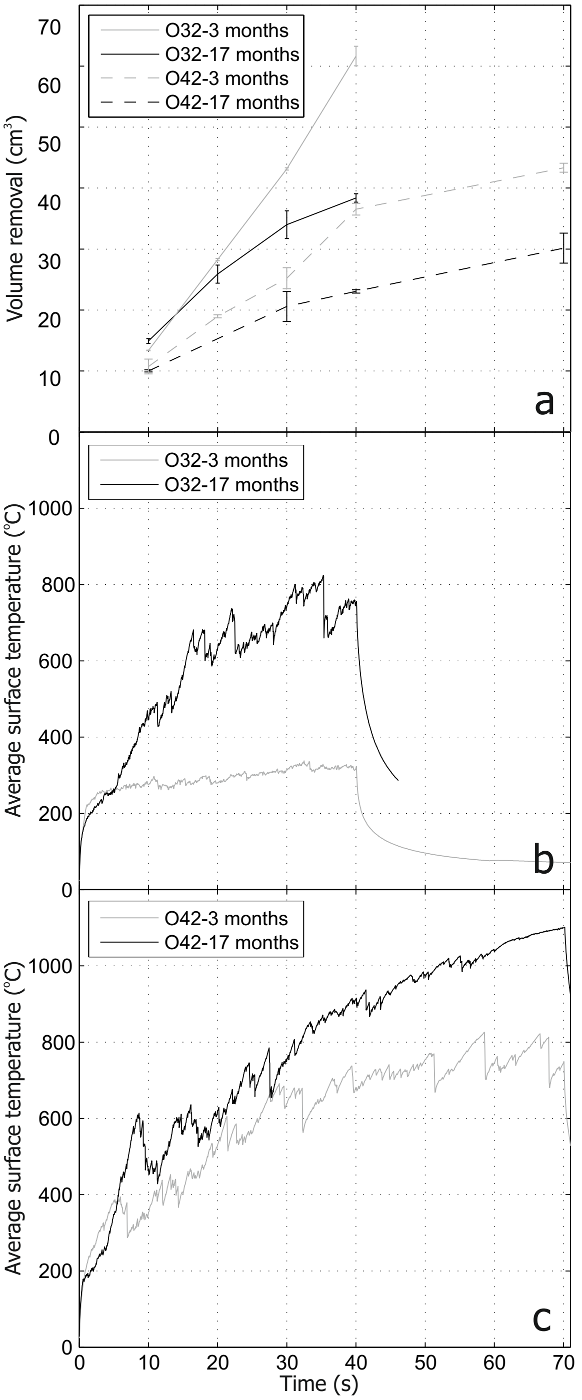

Figure 2: Saturated OPC paste results: (a) volume removal, (b) average surface temperature histories for OPC$_{32}$ pastes and (c) average surface temperature histories for OPC$_{42}$ pastes.

Table 2: Effect of age on saturated specimens: experimental programme and test specimens

Test/ Spec.	Material Composition	Interaction time (s)	Age (days)	No. of Repeats	Age (days)	No. of Repeats
Cement pastes			3 months		17 months	
P_{42}10	PFA+OPC	10	77	2	479	2
P_{42}30	paste	30	77	2	479	2
P_{42}40	(w/b=0.42)	40	72	2	479	2
P_{42}70		70	77	2	479	2
P_{32}10	PFA+OPC	10	77	2	479	2
P_{32}20	paste	20	77	2	479	2
P_{32}30	(w/b=0.32)	30	77	2	479	2
P_{32}40		40	71-73	2	479	2
O_{42}10	OPC paste	10	77	2	479	2
O_{42}30	(w/b=0.42)	30	77	2	479	2
O_{42}40		40	71-72	2	479	2
O_{42}70		70	77	2	479	2
O_{32}10	OPC paste	10	77	2	479	2
O_{32}20	(w/b=0.32)	20	77	2	479	2
O_{32}30		30	77	2	479	2
O_{32}40		40	71-72	2	479	2
Mortars and concretes			8 months		22 months	
Mp10	Mortar	10	232	3	640	3
Mp30	(PFA+OPC	30	234	3	640	3
Mp50	binder)	50	238	2	640	3
Mp70		70	238	1	640	3
Mo10	Mortar	10	232	3	641	3
Mo30	(OPC binder)	30	234	3	641	3
Mo50		50	238	2	641	3
Mo70		70	238	1	641	3
Lp_{10}10	Limestone	10	207	3	612	3
Lp_{10}20	Concrete	20	207	3	612	3
Lp_{10}30	(PFA+OPC	30	207	3	612	3
Lp_{10}40	binder)	40	204-210	3	612	3
Lo_{10}10	Limestone	10	207	3	612	4
Lo_{10}20	Concrete	20	207	3	612	2
Lo_{10}30	(OPC binder)	30	207	3	612	3
Lo_{10}40		40	204-211	5	612	3
Bp_{10}10	Basalt	10	220	3	627	2
Bp_{10}20	Concrete	20	220	3	627	3
Bp_{10}30	(PFA+OPC	30	220	3	627	3
Bp_{10}40	binder)	40	218-220	3	627	2
Bo_{10}10	Basalt	10	220	3	626	3
Bo_{10}20	Concrete	20	220	3	626	3
Bo_{10}30	(OPC binder)	30	220	3	626	3
Bo_{10}40		40	219-220	3	626	3

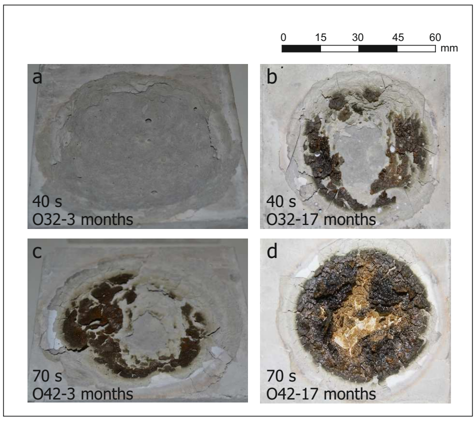

Figure 3: Photographs illustrating different extents of vitrification in OPC paste specimens: OPC_{32} paste after 40 s at (a) 3 months and (b) 17 months, OPC_{42} paste after 70 s at (c) 3 months and (d) 17 months.

4.2. Test results for saturated specimens

The time histories of volume removal and average surface temperature of saturated hardened OPC paste specimens, tested at the age of 3 months (71–77 days) and 17 months (479 days) are presented in Figure 4.3.

Figure 4.3a shows that both OPC pastes (with w/b ratios of 0.32 and 0.42) experienced reduced volume removals when tested at 17 months compared to those tested at 3 months (up to around 40% drop for O_{32}, and 30% for O_{42}). At interaction times below 40 s, the younger O_{42} paste experienced a higher rate of volume removal (around 0.9 cm^3/s) than the older O_{42} paste (around 0.4 cm^3/s), but between 40 s and 70 s both ages showed similar rates of volume removal (around 0.2 cm^3/s). The younger O_{32} paste shows a much higher rate of volume removal throughout the interaction times tested (1.6 cm^3/s), compared to the older O_{32} paste (1.1 cm^3/s initially, reducing to 0.4 cm^3/s). OPC pastes with lower volume removals exhibit higher average surface temperatures (Figure 4.3, b and c); as material is re-

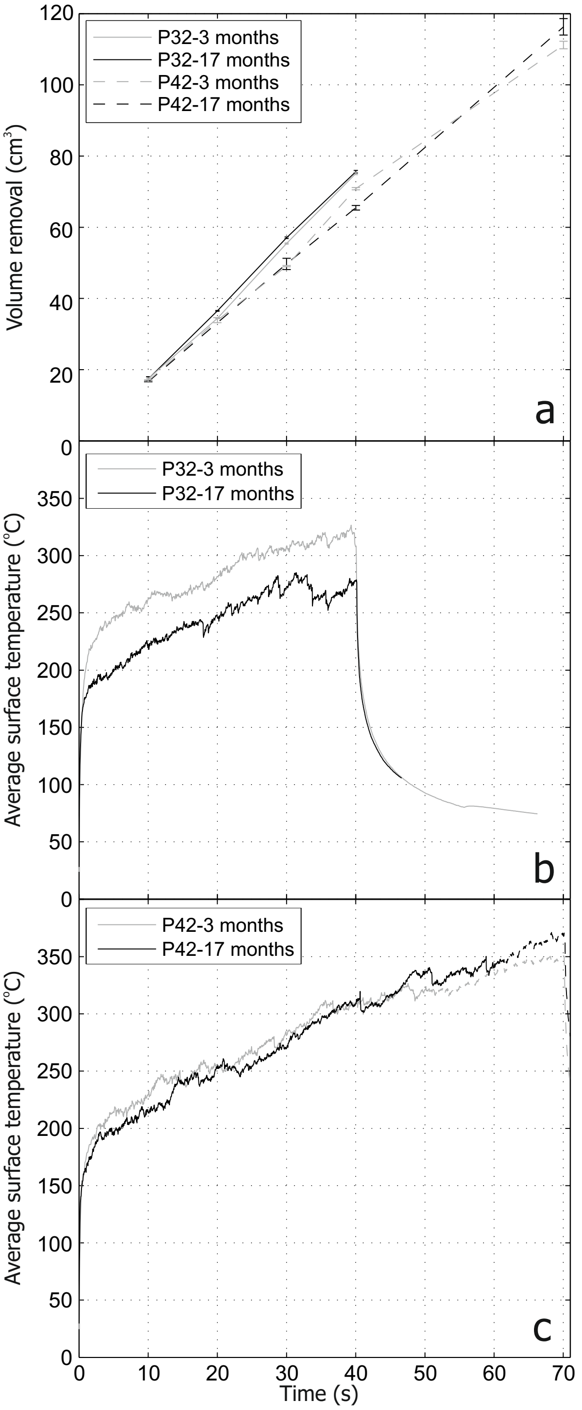

Figure 4: Saturated PFA+OPC pastes results: (a) volume removal, (b) average surface temperature histories for $(PFA+OPC)_{32}$ pastes and (c) average surface temperature histories for $(PFA+OPC)_{42}$ pastes.

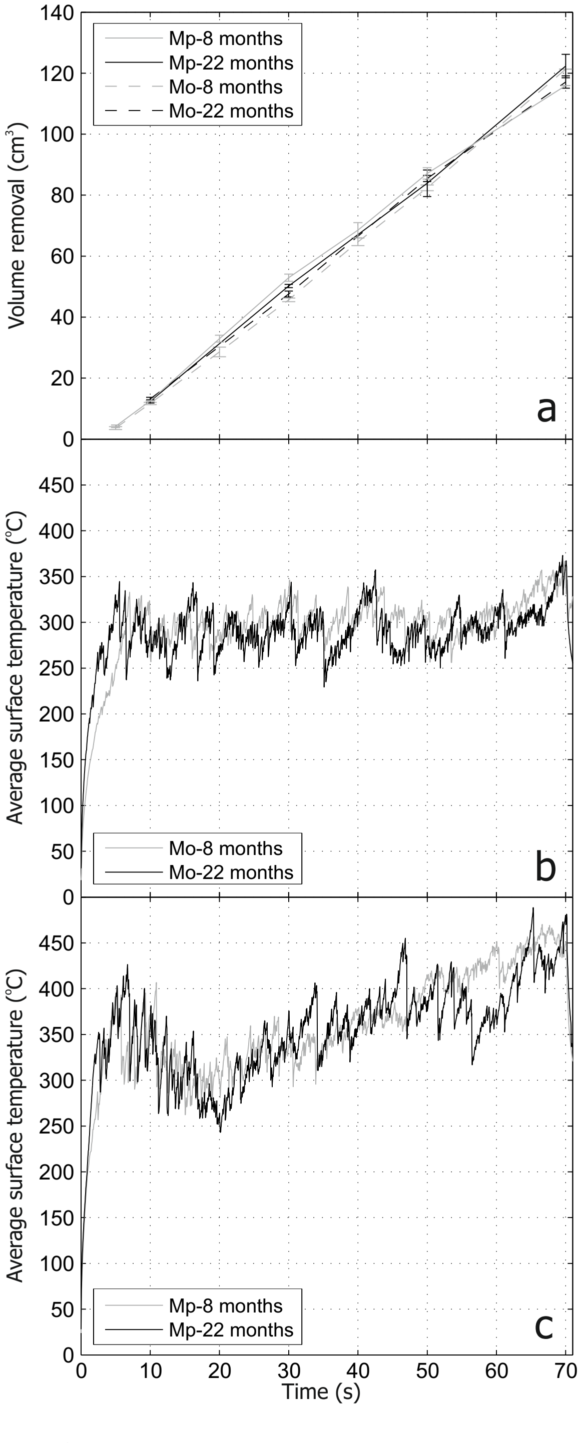

Figure 5: Saturated mortar results: (a) volume removal, (b) average surface temperature histories for OPC mortars (Mo) and (c) average surface temperature histories for PFA+OPC mortars (Mp).

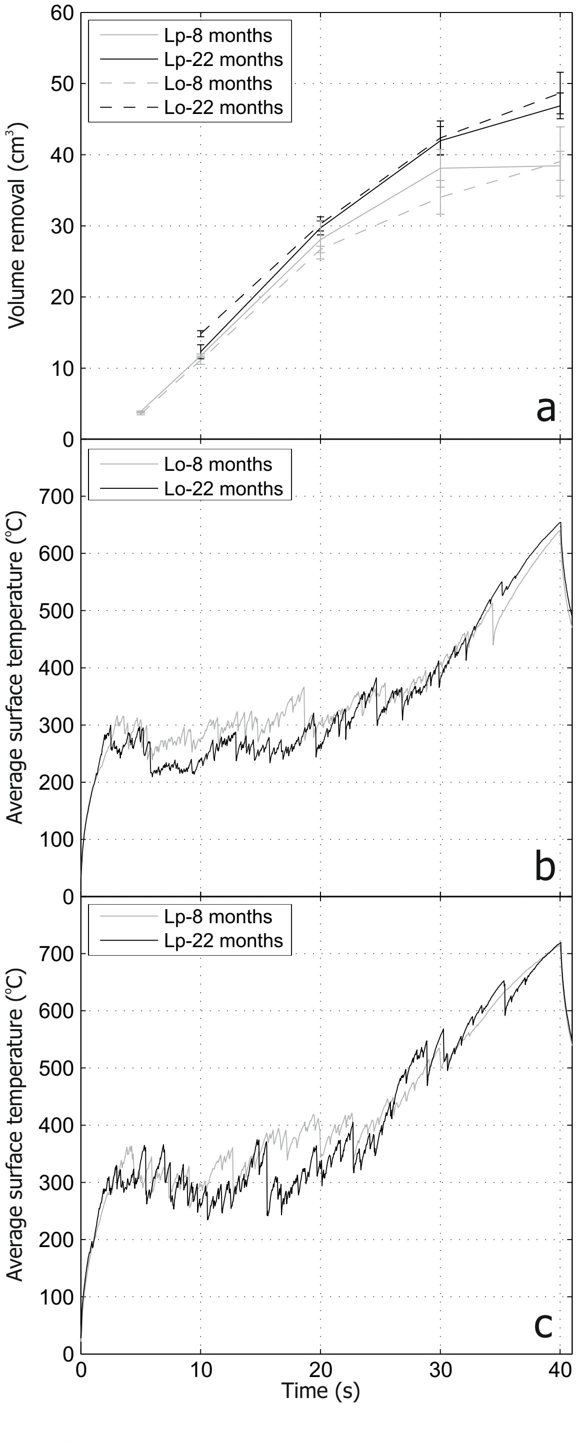

Figure 6: Saturated limestone concrete results: (a) volume removal, (b) average surface temperature histories for OPC limestone concretes (Lo) and (c) average surface temperature histories for PFA+OPC limestone concretes (Lp).

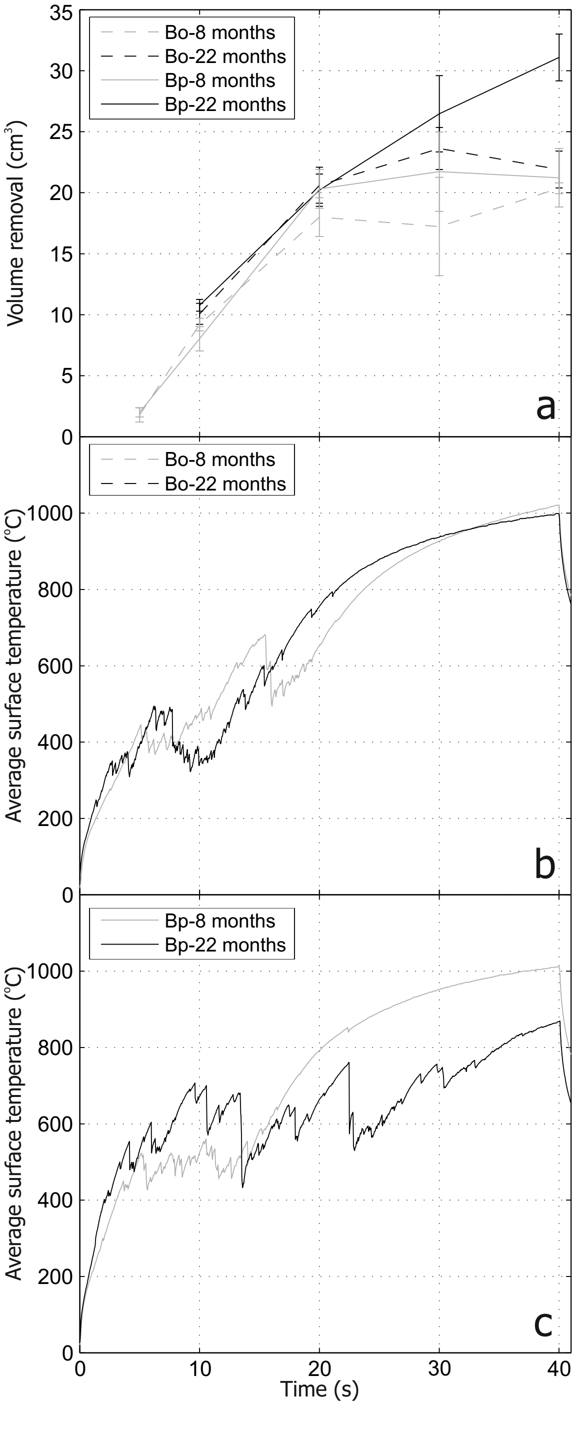

Figure 7: Saturated basalt concrete results: (a) volume removal, (b) average surface temperature histories for OPC basalt concretes (Bo) and (c) average surface temperature histories for PFA+OPC basalt concretes (Bp).

moved less frequently, the surface is exposed to prolonged laser interaction and heated to a greater extent, inducing more extensive vitrification (Figure 4.3).

The results for the saturated PFA+OPC pastes (Figure 4.3) show that the age difference of the specimens had little effect on their scabbling behaviour. The rate of volume removal of the two P_{32} pastes is practically identical (Figure 4.3a). The temperature at the onset of scabbling is higher for the aged P32 specimen (Figure 4.3b), but once the process started the rates of temperature increase were the same. The surface temperature histories of the two P_{42} specimens (Figure 4.3c) are very close, resulting in very similar volume removal rates (Figure 4.3a).

The volume removal and average surface temperature results recorded for the saturated mortars and concretes tested at 8 months (207–238 days) and 22 months (612–640 days) are presented in Figures 4.3, 4.3 and 4.3.

The results for the two tested mortars (Figure 4.3) show that age had practically no effect on their scabbling behaviour. The rates of volume removal for all specimens are the same, and remain constant over 70 s of laser beam interaction (Figure 4.3a), regardless of the type of binder (OPC in Mo, and PFA+OPC in Mp) or age (8 or 22 months). However, the temperature time histories of the two compositions are different. The two Mo specimens show bi-liner behaviour, with lower temperatures at the onset of scabbling (~250^{o}C), followed by fluctuations around a constant temperature of ~280^{o}C (Figure 4.3b). Mp specimens experienced higher temperatures at the onset (~320^{o}C), an increase in the first 10 s, followed by a drop between 10s and 20s and a steady increase from 20 s to 70 s (Figure 4.3c). The surface temperature histories of the two mortars were not affected by the age of specimens.

The tests on saturated concretes show that the volume removal (Figures 4.3a and 4.3a) increased with the age of the specimens for all four tested materials (limestone and basalt concretes with OPC and PFA+OPC binders). In the first 20s of exposure there is very little effect of age or type of binder on the volume removal, with all limestone concretes scabbling more (~$30cm^3$) than basalt concretes (~$20cm^3$). In the later stages of the process the rates of volume removal gradually reduce for all specimens, but remain higher for the aged specimens, except for the Bo (basalt, OPC+PFA) concrete. At the end of the exposure interval of 40 s, the volume removal of aged concretes is 20-30% higher than the corresponding early age materials, with the exception of Bo concrete, where the difference is below 10%.

The two limestone concretes (Lo and Lp), with different ages (Figures 4.3 b and c) show similar tri-linear curves: onset of scabbling at 300^{o}C after 2.5s, steady-state temperature oscillations about 300^{o}C in the period 2.5-20 s, and linear increase to 650-700^{o}C after 20 s. The age affected the amplitudes of temperature fluctuations, which are larger for the aged concretes, indicating ejection of larger fragments, resulting in larger volume removal.

The age effect is most pronounced for the basalt concrete with PFA+OPC binder (Bp), where the process continues at a nearly constant rate throughout the exposure period of 40 s (Figure 4.3a), and the the surface temperature at 25 s is below 650-700^{o}C (Figure 4.3c), close to the onset temperature. The temperature time histories of the early age basalt concretes and the aged Bo concrete (Figures 4.3 b and c) show that the scabbling stops after 15-20 s, and the temperature rises continuously to 1000^{o}C, indicating vitrification of the surface.

4.3. Discussion of results for saturated specimens

Volume removal of the saturated OPC pastes reduces with age (Figure a). Assuming that the scabbling is caused by a build up of pore pressures and the tensile strength increases with age (from 3 to 17 months), larger pore pressures would be required to break the material and eject fragments. This build up of pore pressure results in longer intervals without scabbling, which causes longer exposure of the surface, leading to rapid increase of surface temperature (Figure a,b) and vitrification of the surface (Figure). This behaviour was observed for the aged O_{32}, and the two O_{42} pastes. The very different behaviour of the early age O_{32} (Figure b) could be a result of a balance between higher pore pressures (being less permeable than the early age O_{42}, due to its lower w/b ratio), and relatively low tensile strength (weaker than the aged OPC pastes). The scabbling behaviour of the early age O_{32} is characterised by steady state for the entire duration of the test: frequent ejection of small fragments, maintaining nearly constant, low surface temperature, no vitrification (Figure) and high volume removal. This behaviour would almost certainly continue beyond the 40s exposure used in the tests.

The results of the age investigation suggest that age had little effect on scabbling of saturated PFA+OPC pastes and mortars , but perhaps for different reasons. One possible explanation can be based on the same assumption of a balance between pore pressure and tensile strength.

It is generally accepted that replacing part of the OPC with PFA reduces the permeability of the cement pastes. The permeability of the more permeable of the two OPC+PFA pastes (P_{42}) could be low enough to produce sufficient pore pressures, at relatively low temperatures (200-300^{o}C), to overcome even the higher tensile strength of the aged material. This would result in steady-state scabbling (frequent scabbling of very small fragments and very low rate of increase of the surface temperature, Figure b,c) and a nearly constant (high) rate of volume removal (a). Presumably there is a limit to the minimum size of fragments, so that a further reduction in permeability (and increase of pore pressures) caused by a lower w/b ratio (for P_{32}) or tensile strength (for the early age pastes) would not result in an even more frequent ejection of smaller fragments.

The scabbling of mortars would be expected to be governed by the behaviour of the aggregate-paste matrix, in which, at the highest level of simplification, pore pressures are generated in the paste and the tensile resistance is provided by the aggregate, acting as reinforcement. The full model would be far more complex, with different thermal expansion and thermal conductivity of the two phases generating complex stress fields and thermal gradients, and further complications associated with the behaviour of the aggregate-paste interface. The surface temperature histories (Figure b,c) show that the onset of scabbling (at about 300^{o}C; higher than in the OPC+PFA pastes) is followed by a long steady state phase of oscillations around a nearly constant temperature, characterised by two periodic functions: one with low frequency (2-3 cycles/s) and larger amplitudes (50-100^{o}C), and one with much higher frequency (30-40 cycles/s) and low amplitudes (10-20^{o}C). The first is a result of ejection of larger fragments, normally containing pieces of aggregate surrounded by paste, the second of frequent ejection of smaller fragments, containing pieces of paste and smaller aggregates. The continuous, frequent ejection of small aggregates in OPC mortar (Mo), not seen in O_{42} paste, shows that the presence of fine aggregates governs the scabbling process. This could be caused by changes in temperature distribution (different thermal conductivity), reduced permeability (impermeable sand particles reducing the overall porosity of the material), fractures due to differential thermal expansion or a combination of these factors.

Saturated concretes show similar behaviour after ageing (Figures and), with a small increase in volume removal with age. The only substantial difference is observed in B_p concrete (Figure ,c), where larger fragments are ejected in the later stages. This could be a result of larger moisture content below the surface leading to either a development of larger pore pressures, or cooling of the surface and postponing vitrification.

In conclusion, the results of the investigation into the effect of age on saturated specimens suggests saturated

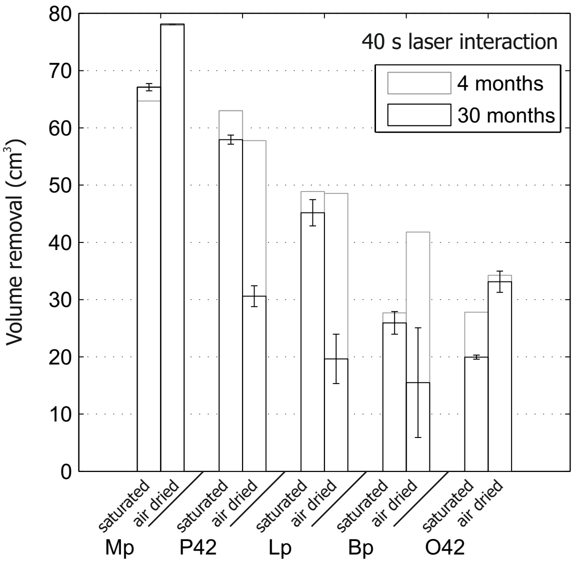

Figure 8: Volume removal results for specimens tested in the investigation of the effects of prolonged drying.

OPC pastes scabble more successfully at an earlier age, saturated PFA+OPC pastes and mortars are unaffected by age, and saturated concretes show a minor increase in scabbling with age.

5. The effect of prolonged drying

5.1. Test programme of the effects of prolonged drying

All specimens used for this study were cast at the same time and stored in a mist room (≈20 °C, ≈95% relative humidity) for 50 days. After that the air dried specimens (xxA) were moved to the laboratory and kept at ambient conditions (≈20 °C and ≈95% relative humidity); whereas the saturated specimens (xxS) remained in the mist room until testing. The specimens were tested at two ages: 4 months (after 49-64 days of drying) and 30 months (after ≈800 days of drying).

The specimens and the experimental programme (laser interaction times, specimen ages and number of repeats) used for this study are shown in Table 3.

5.2. Test results of the prolonged drying investigation

The degrees of saturation (SR) and moisture contents (MC) of the test specimens at two different ages (Table 3) show that after the first 50-60 days of drying their values decreased by 30-35% for the two concretes, 25% for the OPC paste, and 17-21% for the mortar and PFA+OPC paste. After the additional 26 months of air drying SR and MC decreased further by 20-25% for the concretes, 35% for the mortar, 45% for the OPC paste and 55% for the PFA+OPC paste.

Figure 8 shows the volume removals for air dried and saturated specimens exposed to 40 s laser interaction time and tested at the ages of 4 and 30 months. The tests on saturated specimens were repeated in this test series in order to provide a comparison with the air dried specimens tested at the same ages. The results for the saturated specimens can be also compared with those of the first test series, where the ageing effect were investigated on specimens at the ages of 3 and 17 months, for cement pastes, and 8 and 22 months, for mortar and concretes.

The reductions in volume removal for the saturated concrete specimens (Lp and Bp, Figure 8) are small (7-8%), yet showing a reversal of the trend observed for the same saturated materials of the first series (compared at the ages of 8 and 22 months), when the aging resulted in a 20-30% increase in volume removal (Figures 4.3a and Figures 4.3a). The aging of the saturated P_{42}S specimens resulted in small reduction (7%) of volume removal, whereas no effect of aging was noticed in the

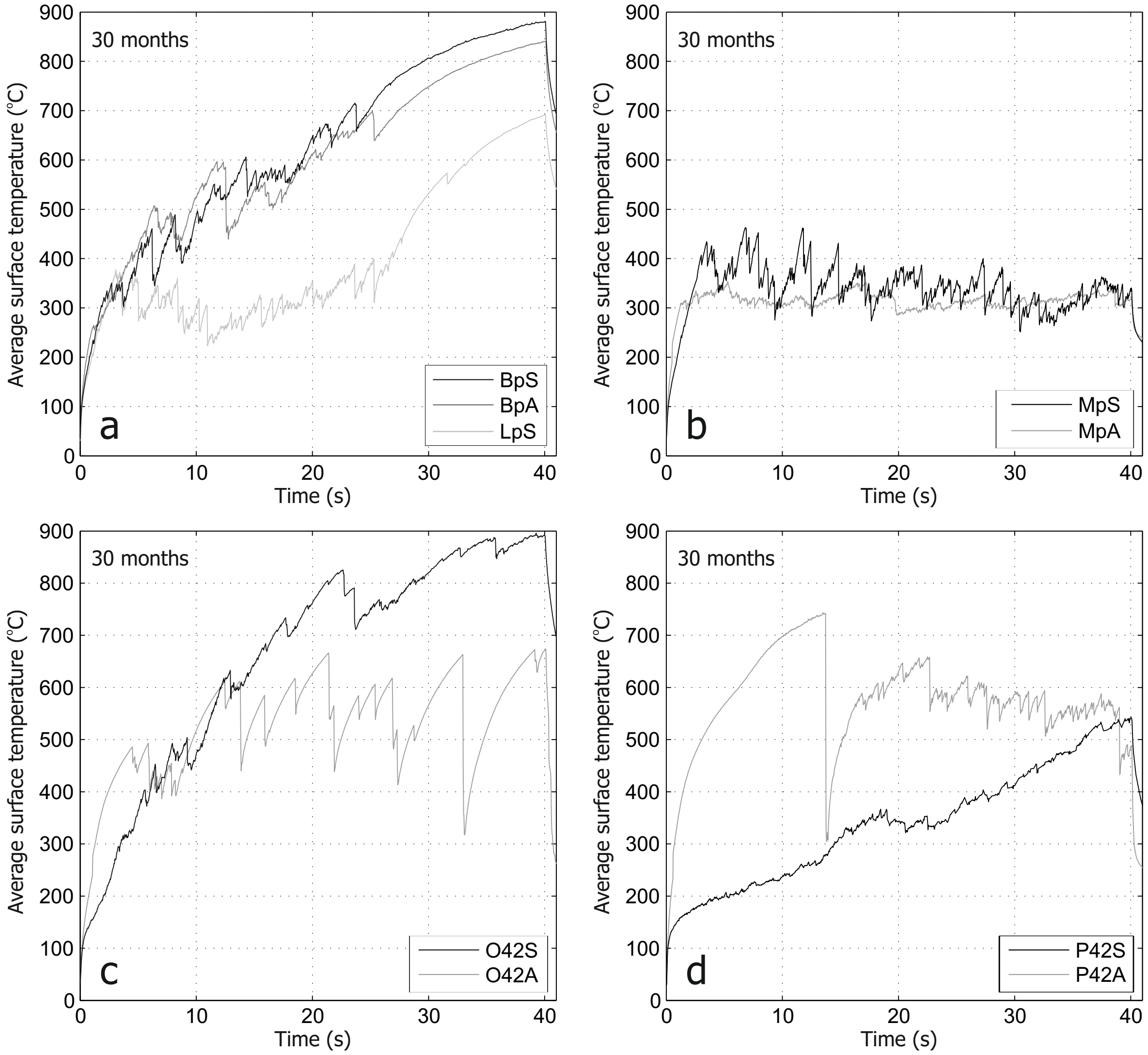

Figure 9: Average surface temperatures recorded in the investigation of effects of prolonged drying: (a) basalt and limestone concretes, (b) mortars, (c) OPC pastes and (d) PFA+OPC pastes.

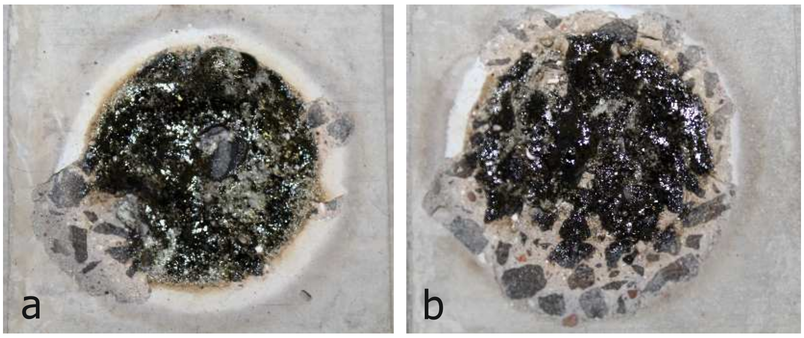

Figure 10: The two air dried basalt concrete (BpA) specimens from Series 1 exposed to 40 s laser interaction; (a) stopped scabbling after 5 s, whereas (b) stopped scabbling after 25 s.

Table 3: Effect of drying with age: Experimental programme and test specimens. (Las. Int. = laser interaction time, MC = moisture content, SR = degree of saturation)

				4 months				30 months			
Test/ Spec.	Material Composition	Precon- ditioning	Las. Int. (s)	Age (days)	Repeats	MC (%)	SR (%)	Age (days)	Repeats	MC (%)	SR (%)
LpS	Limestone	Saturated	40	114	1	4.6	98.7	851	2		
LpA	concrete	Air dried	40	113	1	3.0	67.3	851	2	2.3	50.6
BpS	Basalt	Saturated	40	114	1	4.5	98.5	851	2		
BpA	Concrete	Air dried	40	113	1	3.2	71.2	851	2	2.6	57.4
MpS	Mortar	Saturated	40	100	1	9.7	97.7	837	2		
MpA		Air dried	40	99	1	8.0	77.9	837	2	5.0	51.2
P_{42}S	PFA+OPC	Saturated	40	100	1	21.9	96	837	2		
P_{42}A	Paste	Air dried	40	99	1	18.2	79.0	837	2	8.2	37.5
O_{42}S	OPC	Saturated	40	100	1	19.8	102.8	837	2		
O_{42}A	Paste	Air dried	40	99	1	14.9	70.4	837	2	7.9	39.9

comparison between 3 and 17 months old specimens of the same material. The saturated OPC paste (O_{42}S) saw a larger 28% reduction in volume removal in the aged specimens, similar to that recorded earlier for the ageing period between 3 and 17 months (30%, Figure 4.3a). These results suggest that ageing has different effects on the effectiveness of laser scabbling of different saturated materials: (a) it reduces the volume removal of OPC pastes, but the reduction occurs in the first 20 months (or earlier) and further ageing has no effect; (b) has very little effect (small reduction) on PFA+OPC pastes and mortars; and (c) it may have a positive effect on concretes initially (e.g. the first 20 months), but the effect diminishes with time.

The volume removal, recorded after 40 s of laser beam exposure of air dried specimens at the ages of 4 and 30 months is shown in Figure 8. The prolonged drying had different effects on volume removal, ranging from (a) no effect on mortar (Mp) and (b) very little reduction (3.4%) in OPC paste (O42) to (c) very significant reductions in PFA+OPC paste (47%) and the two concretes (60% for Lp and 63% in Bp). The comparison with the saturated specimens of the same age (40 months) shows that the drying had positive effect, increasing the volume removal by 15% in mortar (Mp), and by 65% in OPC paste (O42). The effect on the other three materials was negative; with volume reductions of 47% in PFA+OPC paste (P42), 54% on limestone concrete (Lp) and 39% in basalt concrete (Lp).

Average surface temperatures for the concrete and mortar specimens tested at 30 months are presented in Figures 5.3a and b. Unfortunately, due to experimental error, the infrared data for the air dried limestone concrete (LpA) was not recorded. The degree of saturation had little effect on the surface temperature of basalt concrete (BpS and BpA), whereas the saturated mortar (MpS) experienced much larger but less frequent temperature fluctuations compared to the air dried mortar (MpA), while remaining at a similar background temperature, which resulted in similar volume removal rates.

Average surface temperature results for the hardened cement pastes (Figures 5.3c and d) show very different behaviour between the saturated and air dried specimens. The behaviour of saturated OPC paste ($O_{42}S$) is characterised by small temperature fluctuations and a steady increase in background temperature (reaching 900°C at the end of the interval), indicating that the rate of volume removal is low. The air dried paste ($O_{42}S$) shows infrequent but very large temperature fluctuations (of over 300 °C in the latter stages), which is a result of ejection of large fragments. The volume removal rate is sufficient to maintain lower background temperature (about 500°C). The behaviour of the saturated PFA+OPC pastes is the opposite to that of OPC pastes. Here the saturated paste ($P_{42}S$) undergoes small, frequent temperature fluctuations with a nearly linear average surface temperature increase of around 10°C/s throughout the entire period of exposure. The air-dried paste ($P_{42}A$) shows no signs of scabbling at the beginning (hence the large temperature increase to 740°C at 15 s), but then after the ejection of a large fragment, the temperature drops by over 400°C. This is followed by another interval of monotonous temperature increase (no scabbling) to 600°C, after which it continues with steady scabbling at a rate that is sufficient to maintain constant background temperature over the last 25 s. The overall effect is that the removed volume at the end of the test is about half of that in the saturated paste (Figure 8). Generally, air dried cement pastes behave in a more erratic way, their scabbling behaviour characterised by ejection of large fragments.

It can be seen in Figure 8 that the air dried basalt concrete (BpA) exposed to 40 s laser interaction had a much larger error than the other compositions tested. From inspection of the infra red videos it was seen that one of the two air dried basalt concrete specimens tested did not scabble substantially after 5 s resulting in extensive vitrification and a thick white ring around the heat affected zone (Figure 10a). The second specimen scabbled frequently until 25 s, and as a result underwent less vitrification and has only a small part of the white ring (Figure 10b).

5.3. *Discussion of the results of prolonged drying investigation*

The results of the investigation into the effect of prolonged drying highlights the effect of pore pressure spalling in PFA+OPC pastes. In the first test series [1], the effect of permeability on scabbling of hardened pastes led the authors to suggest that pore pressure spalling is the dominant mechanism in laser scabbling of cement pastes. PFA is known to reduce the permeability of a cement paste [5], resulting in sufficiently low permeability of the PFA+OPC paste for pore pressure spalling to take place in the saturated specimen, inducing small, frequent fragment ejections. By removing the free water through prolonged air drying, the driving force for pore pressure spalling is reduced. As pore pressure spalling does not remove material from the surface, the temperatures increase causing a development of severe thermal gradients. This in turn causes large fragments to be ejected as a result of thermal stress spalling, with pore pressures acting as a secondary factor.

The situation is different with the OPC pastes, especially the ones with the higher w/b ratio of 0.42 (O_{42}), which are expected to be more porous (and more permeable). In O_{42} the volume removal increases with air drying, suggesting that free water is detrimental to the laser scabbling process. The permeability of O_{42} paste could be too high for pore pressure spalling to be effective in the saturated specimens, while intense evaporation would reduce the thermal gradients under the surface, reducing the potential for thermal stress spalling. If there is no spalling, the surface temperature of the specimen increases dramatically reaching surface vitrification levels. The reduced moisture content in the air dried O_{42} paste specimens at 30 months (Table 3) means less energy is lost from the system due to evaporation, allowing thermal stress spalling to occur more efficiently. This leads to ejection of very large fragments at high temperature (around 500^{o}C, Figure c), not seen in any of the saturated cement paste specimens.

The greater reduction in volume removal due to age in air dried concretes (compared to saturated) suggests that the free water aides the scabbling process in concretes. The moisture content of the air dried specimens (2.3% and 2.6%) at 30 months may be below a threshold value that was not reached when tested at 4 months (3.0% and 3.2%). Eurocode 2 suggests a moisture content of 3% is necessary for spalling to take place [6]. The fact that air dried mortars tested at 30 months (with moisture content of 5.0%) did not experience a reduction in volume removal compared to the 4 month specimens (8.2%), suggests the greater cement paste content of mortars compared to concretes means mortars have more free water to loose, and as a result, both the saturated and the air dried mortars (at 30 months) are above the spalling moisture content threshold. Previous results [4] show that oven drying of PFA+OPC mortar (w/b = 0.42) to a moisture content of 0%, reduces the scabbling to zero.

Results for the mortar show that the drying increases volume removal and reduces fragment sizes. Similar results were reported before [4]. A possible explanation for this lies in the effect of saturation on thermal conductivity: as water is more conductive than air, heat will transfer through a saturated specimen easier [7]. This will cause heat (and consequently pore pressures) to spread out deeper within the specimen and over a larger area, during laser interaction. This means that temperatures (and pressures) necessary for scabbling must occur over a larger depth, causing larger (thicker) fragments to be ejected. The lower thermal conductivity of the air dried specimen, on the other hand, would create high temperature (and pressure) close to the surface, forcing smaller (thinner) fragments to be ejected more frequently. In both cases this results in very effective steady-state scabbling at nearly constant, relatively low surface temperature (about 300^{o}C, Figure b).

Figure 11 displays the volume removal results of the prolonged drying investigation (Figure 8) plotted against the initial degree of saturation. It can be seen that volume removal due to scabbling is sensitive to the degree of saturation. Although there are only three data points for each composition from the prolonged drying

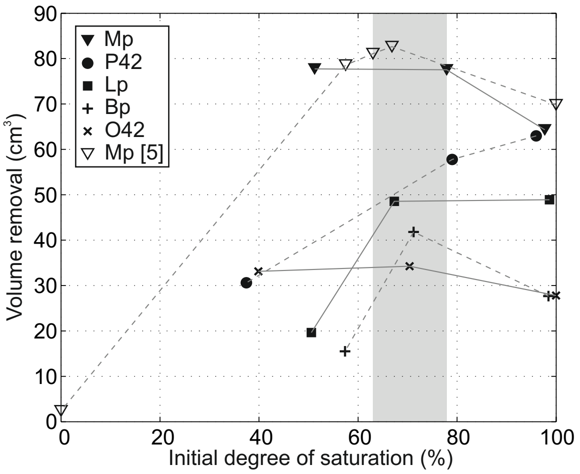

Figure 11: Volume removal results from prolonged drying investigation plotted against degree of saturation. Hollow triangles [4] and solid triangles show results of the same composition (Mp). Shaded area shows the range of optimum moisture content for the PFA+OPC mortar (Mp). All results are after 40 s laser interaction.

investigation, the higher volume removal for lower degrees of saturation in some compositions (basalt concrete Bp, OPC paste O_{42}, and the Mp mortar) suggests that an optimum initial degree of saturation exists below 100%. Along with the results of the investigation into the effect of free water content in mortars [4] (hollow triangles), where there are more data points, an optimum degree of saturation for the PFA+OPC mortar composition (Mp) can be identified between 63% and 78% (shaded area).

6. Stochastic behaviour

This investigation has given an indication that there may be some stochastic behaviour present in the laser scabbling of concretes as reported in previous studies ([8, 9, 10, 11]). All PFA+OPC basalt concretes (Bp) reported here have displayed unpredictable behaviour. The saturated PFA+OPC basalt concrete tested at 22 months (Figure 4.3c) shows quite different behaviour and large margins of error compared to the specimens tested at 8 months, something that is not seen in the OPC basalt concrete or either of the limestone concretes (Figure 4.3). The air dried basalt concrete tested at 30 months (Figure 8) shows a much larger margin of error in volume removal compared to any other composition. The two air dried basalt concrete specimens also displayed different behaviour in the infra red recordings (Figure 5.3a) and different extents of vitrification after 40 s laser interaction (Figure 10). The results suggest that stochastic behaviour may increase with age for PFA+OPC basalt concrete. Alternatively, this could be a combination of the natural variability of the concrete and the high sensitivity of basalt aggregates to laser scabbling [2].

7. Conclusions

1. The largest effect of concrete age on laser scabbling is due to the reduction in the degree of saturation caused by drying. Results suggest that drying reduces laser scabbling in concretes. This is of the utmost importance when considering the use of laser scabbling in situ on structures liable to drying during their operational use.
2. An optimum degree of saturation exists, below 100%, where volume removal due to scabbling will be at a maximum.
3. The effect of ageing on saturated specimens is generally small: saturated OPC pastes scabble more successfully at an earlier age, saturated mortars are

unaffected by age, and saturated concretes scabble more successfully with the increase in age.

4. The effect of saturation on thermal conductivity may cause saturated mortars to experience different scabbling behaviour to that of the air dried.
5. This investigation has given an indication of an increase in stochastic scabbling behaviour with age.

8. Acknowledgements

The authors would like to thank the UK Engineering and Physical Sciences Research Council (EPSRC) for the financial support for this study and the EPSRC Engineering Instrument Pool for lending the equipment (FLIR SC640) used in this study. The authors are also grateful to CEMEX UK and Longcliffe Ltd for providing aggregates for the test specimens.

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