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The effect of ageing and drying on laser scabbling of concrete

B. Peach^{a,2,**}, M. Petkovski^{a,1,*}, J. Blackburn^b, D.L. Engelberg^c

^aDepartment of Civil and Structural Engineering, Sir Frederick Mappin Building, Mappin Street, University of Sheffield, Sheffield, S1 3JD, UK

^bTWI Ltd, Granta park, Great Abington, Cambridge, CB21 6AL, UK

^cResearch Centre for Radwaste & Decommissioning, School of Materials, The University of Manchester, Manchester, M13 9PL, UK

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

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-

*Corresponding author

**Principal corresponding author

Email addresses: bdpeach1@sheffield.ac.uk (B. Peach),
m.petkovski@sheffield.ac.uk (M. Petkovski),
jon.blackburn@twi.co.uk (J. Blackburn),
dirk.engelberg@manchester.ac.uk (D.L. Engelberg)

¹Tel: +44 (0) 114 222 5729

²Tel: +44 (0) 114 222 5759

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 surface³ 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-

³horizontal 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 P₄₂) and O (now O₄₂), 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 (HAZ⁴) 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 in-

dicates 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-

⁴HAZ was defined as the surface area that exceeded 100°C after 1s of interaction time

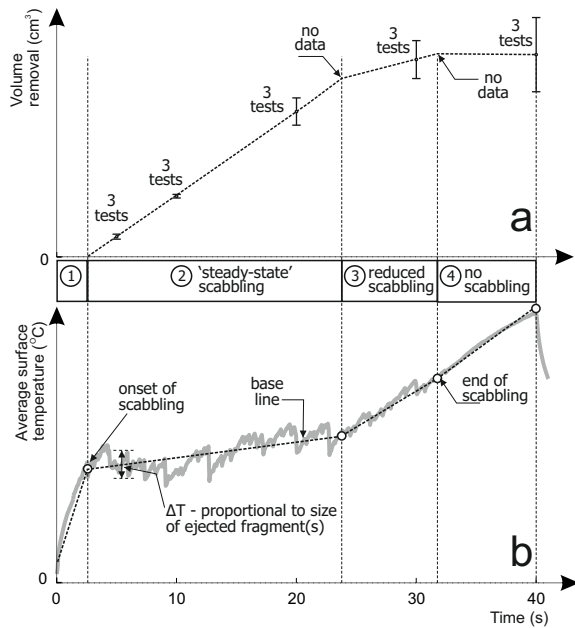


Figure 1: Example of test results, showing different stages of scabbling behaviour; (a) volume removal data from 15 tests (3 repeats at 5 interaction periods), and (b) time history of average surface temperature recorded in one 40s test.

120 tigation into the effect of concrete composition on laser
 121 scabbling [2]. The first series of tests were performed
 122 at the ages of 3 months for the cement paste specimens
 123 and 8 months for the concrete specimens. The remain-
 124 ing specimens were then stored in a saturated state in a
 125 mist room ($\approx 20^\circ\text{C}$, $\approx 95\%$ relative humidity) until they
 126 were tested 14 months later.

127 The experimental programme of this study is pre-
 128 sented in Table 2, showing the material composition of
 129 the specimens, laser interaction times (duration of ex-
 130 posure), ages of specimens at the time of testing and
 131 number of repeats of each test. The test results, pre-
 132 sented as time histories of volume removal and average
 133 surface temperature (e.g. Figure 4.3), were obtained by
 134 using an experimental procedure described in detail in
 135 the first report of this investigation [1].

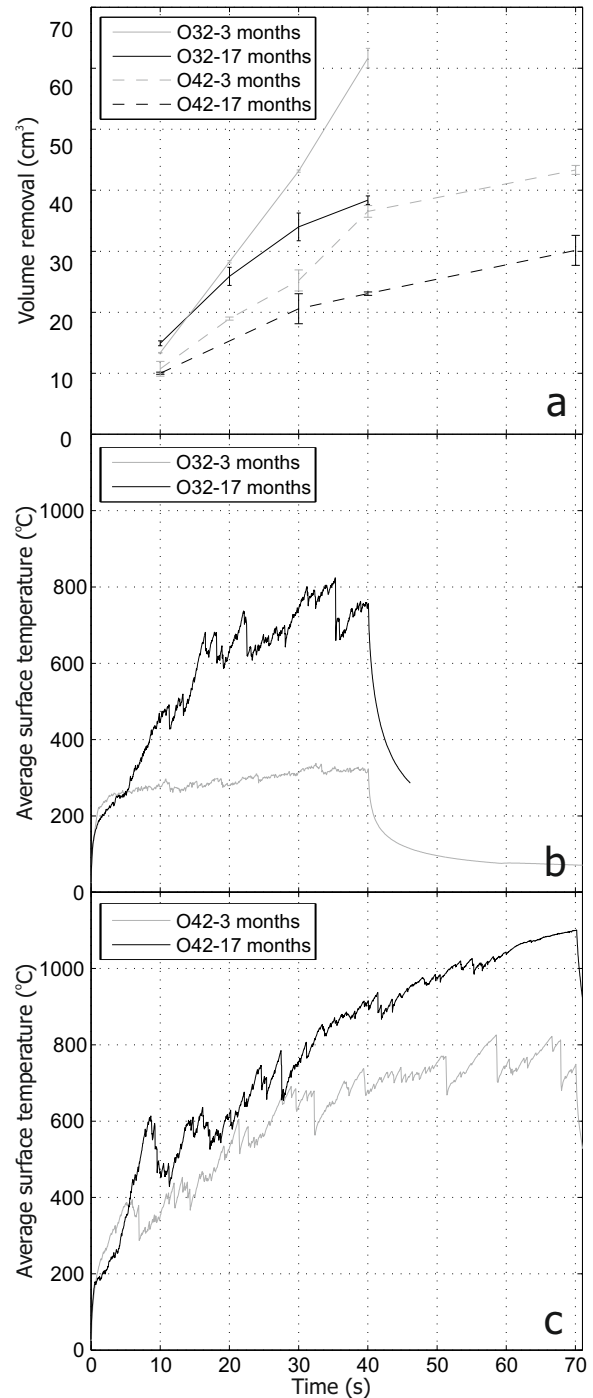


Figure 2: Saturated OPC paste results: (a) volume removal, (b) average surface temperature histories for OPC₃₂ pastes and (c) average surface temperature histories for OPC₄₂ pastes.

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 (w/b=0.42)	30	77	2	479	2
P ₄₂ 40		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 (w/b=0.32)	20	77	2	479	2
P ₃₂ 30		30	77	2	479	2
P ₃₂ 40		40	71-73	2	479	2
O ₄₂ 10		OPC paste	10	77	2	479
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 binder)	30	234	3	640	3
Mp50		50	238	2	640	3
Mp70		70	238	1	640	3
Mo10		Mortar	10	232	3	641
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
Lp ₁₀ 20	Concrete (PFA+OPC binder)	20	207	3	612	3
Lp ₁₀ 30		30	207	3	612	3
Lp ₁₀ 40		40	204-210	3	612	3
Lo ₁₀ 10		Limestone	10	207	3	612
Lo ₁₀ 20	Concrete (OPC binder)	20	207	3	612	2
Lo ₁₀ 30		30	207	3	612	3
Lo ₁₀ 40		40	204-211	5	612	3
Bp ₁₀ 10		Basalt	10	220	3	627
Bp ₁₀ 20	Concrete (PFA+OPC binder)	20	220	3	627	3
Bp ₁₀ 30		30	220	3	627	3
Bp ₁₀ 40		40	218-220	3	627	2
Bo ₁₀ 10		Basalt	10	220	3	626
Bo ₁₀ 20	Concrete (OPC binder)	20	220	3	626	3
Bo ₁₀ 30		30	220	3	626	3
Bo ₁₀ 40		40	219-220	3	626	3

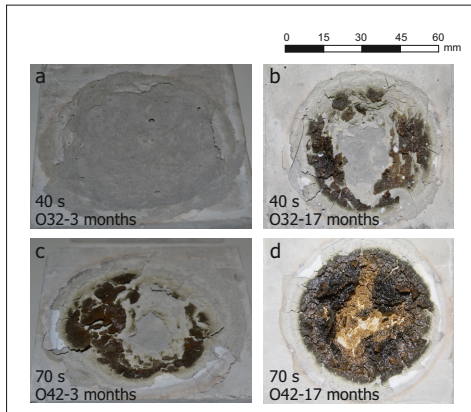


Figure 3: Photographs illustrating different extents of vitrification in OPC paste specimens: OPC₃₂ paste after 40 s at (a) 3 months and (b) 17 months, OPC₄₂ paste after 70 s at (c) 3 months and (d) 17 months.

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 O₃₂, and 30% for O₄₂). At interaction times below 40 s, the younger O₄₂ paste experienced a higher rate of volume removal (around 0.9 cm³/s) than the older O₄₂ paste (around 0.4 cm³/s), but between 40 s and 70 s both ages showed similar rates of volume removal (around 0.2 cm³/s). The younger O₃₂ paste shows a much higher rate of volume removal throughout the interaction times tested (1.6 cm³/s), compared to the older O₃₂ paste (1.1 cm³/s initially, reducing to 0.4 cm³/s). OPC pastes with lower volume removals exhibit higher average surface temperatures (Figure 4.3, b and c); as material is re-

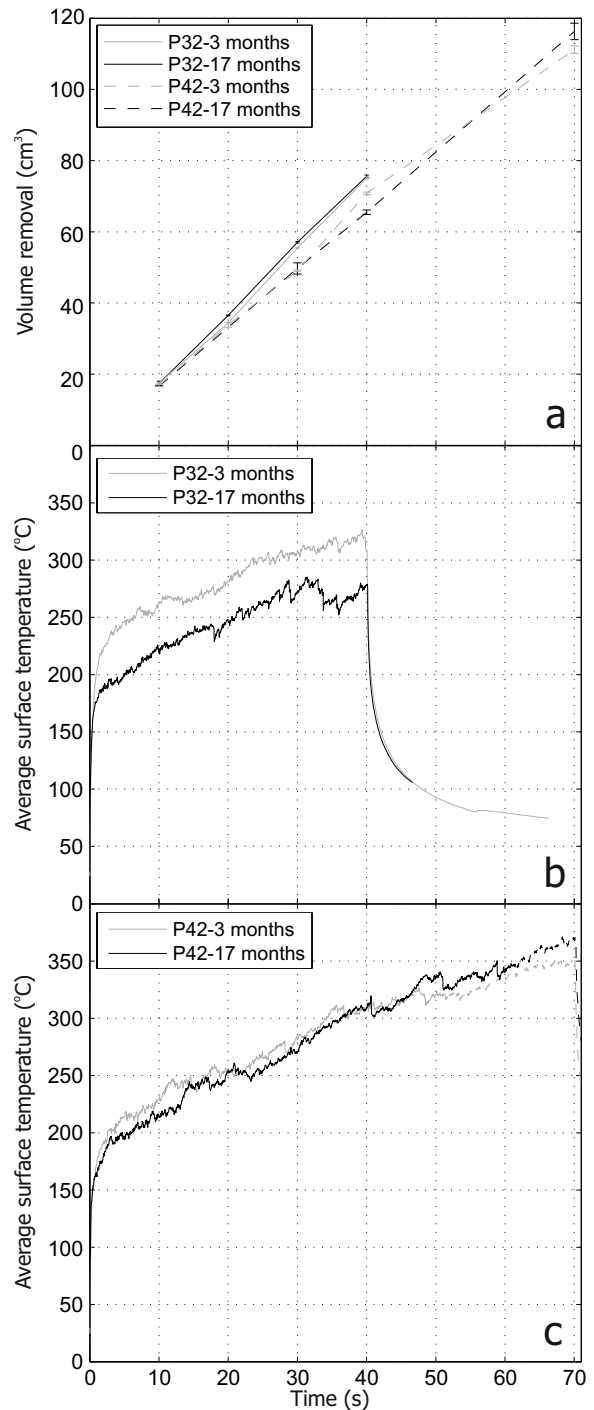


Figure 4: Saturated PFA+OPC pastes results: (a) volume removal, (b) average surface temperature histories for (PFA+OPC)₃₂ pastes and (c) average surface temperature histories for (PFA+OPC)₄₂ pastes.

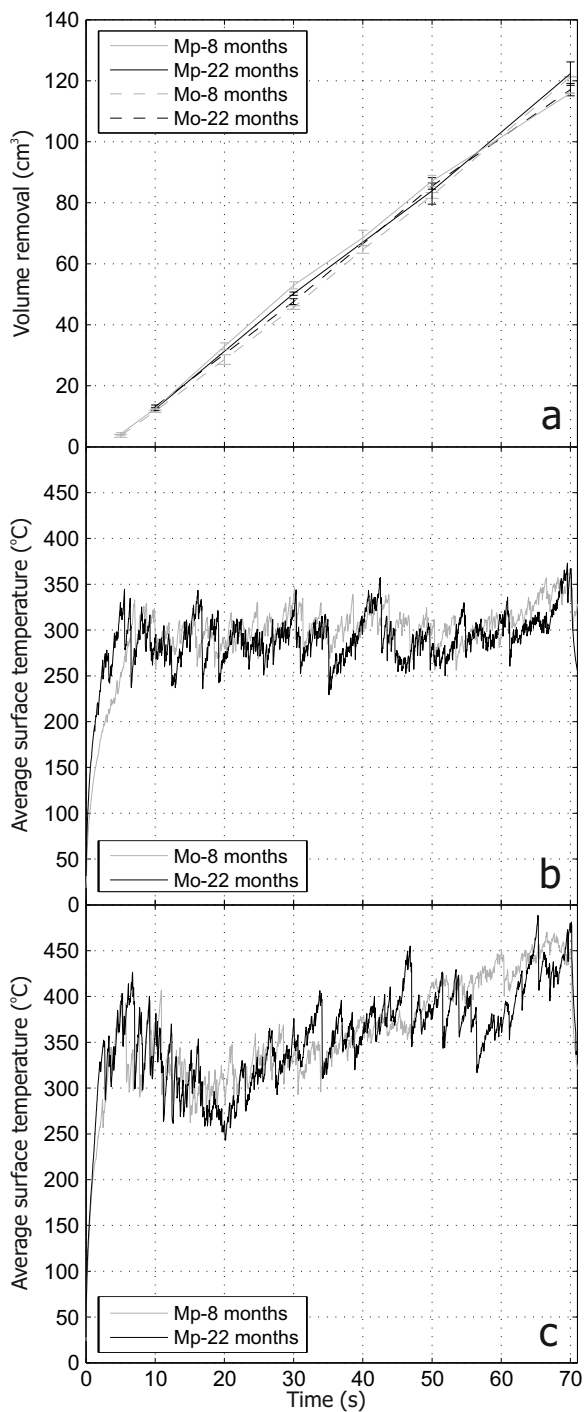


Figure 5: Saturated mortar results: (a) volume removal, (b) average surface temperature histories for OPC mortars (Mo) and (c) average surface temperature histories for PFA+OPC mortars (Mp).

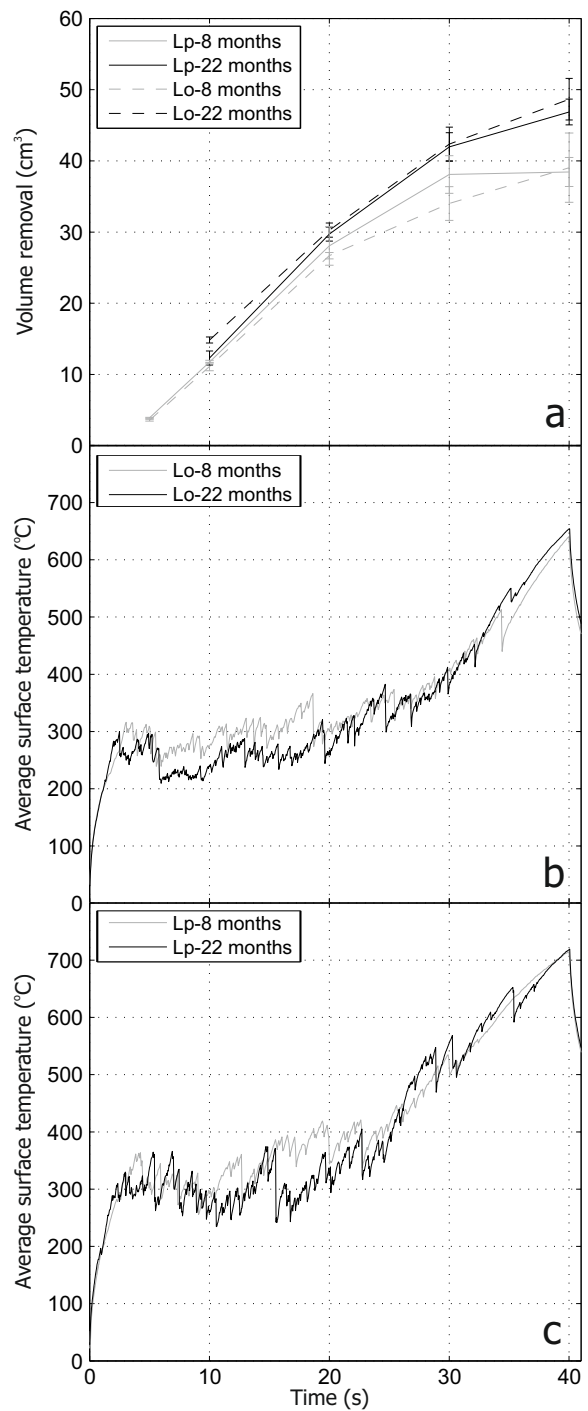


Figure 6: Saturated limestone concrete results: (a) volume removal, (b) average surface temperature histories for OPC limestone concretes (Lo) and (c) average surface temperature histories for PFA+OPC limestone concretes (Lp).

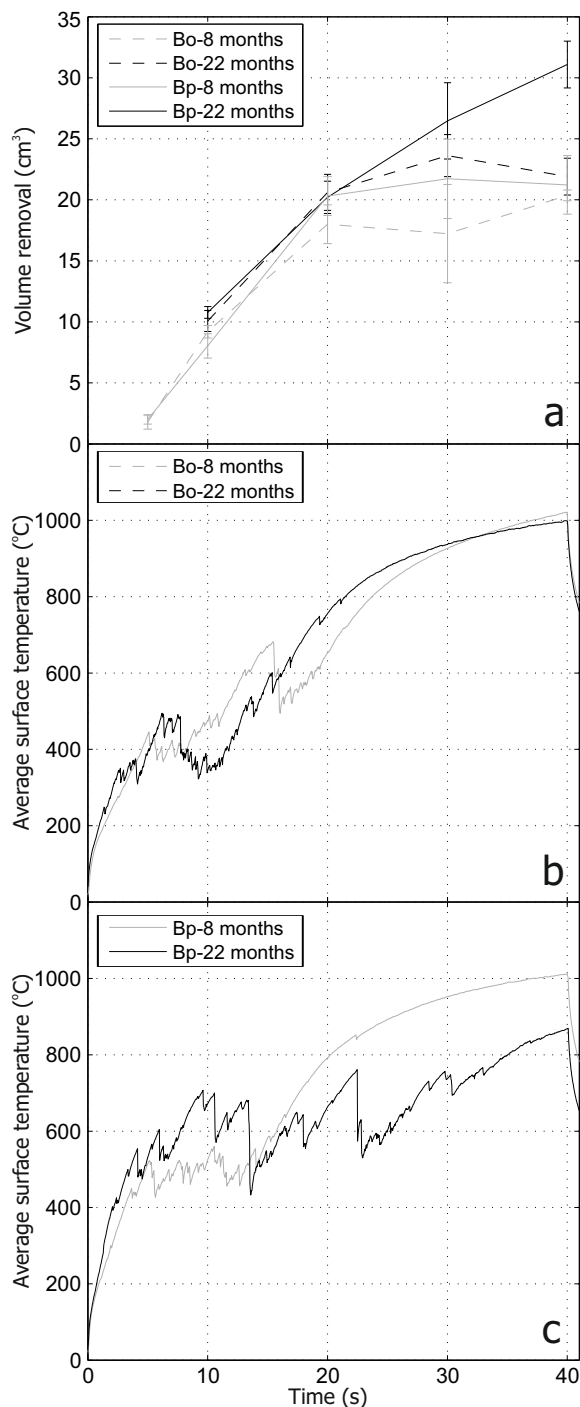


Figure 7: Saturated basalt concrete results: (a) volume removal, (b) average surface temperature histories for OPC basalt concretes (Bo) and (c) average surface temperature histories for PFA+OPC basalt concretes (Bp).

156 moved less frequently, the surface is exposed to pro-
 157 longed laser interaction and heated to a greater extent,
 158 inducing more extensive vitrification (Figure 4.3).

159 The results for the saturated PFA+OPC pastes (Fig-
 160 ure 4.3) show that the age difference of the specimens
 161 had little effect on their scabbling behaviour. The rate
 162 of volume removal of the two P₃₂ pastes is practically
 163 identical (Figure 4.3a). The temperature at the onset
 164 of scabbling is higher for the aged P₃₂ specimen (Fig-
 165 ure 4.3b), but once the process started the rates of tem-
 166 perature increase were the same. The surface temper-
 167 ature histories of the two P₄₂ specimens (Figure 4.3c)
 168 are very close, resulting in very similar volume removal
 169 rates (Figure 4.3a).

170 The volume removal and average surface temperature
 171 results recorded for the saturated mortars and concretes
 172 tested at 8 months (207–238 days) and 22 months (612–
 173 640 days) are presented in Figures 4.3, 4.3 and 4.3.

174 The results for the two tested mortars (Figure 4.3)
 175 show that age had practically no effect on their scab-
 176 bling behaviour. The rates of volume removal for all
 177 specimens are the same, and remain constant over 70
 178 s of laser beam interaction (Figure 4.3a), regardless
 179 of the type of binder (OPC in Mo, and PFA+OPC in
 180 Mp) or age (8 or 22 months). However, the tempera-
 181 ture time histories of the two compositions are different.
 182 The two Mo specimens show bi-linear behaviour, with
 183 lower temperatures at the onset of scabbling (~250°C),
 184 followed by fluctuations around a constant temperature
 185 of ~280°C (Figure 4.3b). Mp specimens experienced
 186 higher temperatures at the onset (~320°C), an increase

187 in the first 10 s, followed by a drop between 10s and 20s
188 and a steady increase from 20 s to 70 s (Figure 4.3c).
189 The surface temperature histories of the two mortars
190 were not affected by the age of specimens.

191 The tests on saturated concretes show that the volume
192 removal (Figures 4.3a and 4.3a) increased with the age
193 of the specimens for all four tested materials (limestone
194 and basalt concretes with OPC and PFA+OPC binders).
195 In the first 20s of exposure there is very little effect
196 of age or type of binder on the volume removal, with
197 all limestone concretes scabbling more ($\sim 30\text{cm}^3$) than
198 basalt concretes ($\sim 20\text{cm}^3$). In the later stages of the
199 process the rates of volume removal gradually reduce
200 for all specimens, but remain higher for the aged spec-
201 imens, except for the Bo (basalt, OPC+PFA) concrete.
202 At the end of the exposure interval of 40 s, the volume
203 removal of aged concretes is 20-30% higher than the
204 corresponding early age materials, with the exception
205 of Bo concrete, where the difference is below 10%.

206 The two limestone concretes (Lo and Lp), with dif-
207 ferent ages (Figures 4.3 b and c) show similar tri-linear
208 curves: onset of scabbling at 300°C after 2.5s, steady-
209 state temperature oscillations about 300°C in the period
210 2.5-20 s, and linear increase to $650\text{-}700^\circ\text{C}$ after 20 s.
211 The age affected the amplitudes of temperature fluctua-
212 tions, which are larger for the aged concretes, indicating
213 ejection of larger fragments, resulting in larger volume
214 removal.

215 The age effect is most pronounced for the basalt con-
216 crete with PFA+OPC binder (Bp), where the process
217 continues at a nearly constant rate throughout the expo-

218 sure period of 40 s (Figure 4.3a), and the the surface
219 temperature at 25 s is below $650\text{-}700^\circ\text{C}$ (Figure 4.3c),
220 close to the onset temperature. The temperature time
221 histories of the early age basalt concretes and the aged
222 Bo concrete (Figures 4.3 b and c) show that the scab-
223 bling stops after 15-20 s, and the temperature rises con-
224 tinuously to 1000°C , indicating vitrification of the sur-
225 face.

226 4.3. Discussion of results for saturated specimens

227 Volume removal of the saturated OPC pastes reduces
228 with age (Figure a). Assuming that the scabbling is
229 caused by a build up of pore pressures and the tensile
230 strength increases with age (from 3 to 17 months), larger
231 pore pressures would be required to break the material
232 and eject fragments. This build up of pore pressure re-
233 sults in longer intervals without scabbling, which causes
234 longer exposure of the surface, leading to rapid increase
235 of surface temperature (Figure a,b) and vitrification of
236 the surface (Figure). This behaviour was observed for
237 the aged O_{32} , and the two O_{42} pastes. The very different
238 behaviour of the early age O_{32} (Figure b) could be a re-
239 sult of a balance between higher pore pressures (being
240 less permeable than the early age O_{42} , due to its lower
241 w/b ratio), and relatively low tensile strength (weaker
242 than the aged OPC pastes). The scabbling behaviour
243 of the early age O_{32} is characterised by steady state
244 for the entire duration of the test: frequent ejection of
245 small fragments, maintaining nearly constant, low sur-
246 face temperature, no vitrification (Figure) and high vol-
247 ume removal. This behaviour would almost certainly
248 continue beyond the 40s exposure used in the tests.

249 The results of the age investigation suggest that age 280
250 had little effect on scabbling of saturated PFA+OPC 281
251 pastes and mortars , but perhaps for different reasons. 282
252 One possible explanation can be based on the same as- 283
253 sumption of a balance between pore pressure and tensile 284
254 strength. 285

255 It is generally accepted that replacing part of the OPC 286
256 with PFA reduces the permeability of the cement pastes. 287
257 The permeability of the more permeable of the two 288
258 OPC+PFA pastes (P_{42}) could be low enough to pro- 289
259 duce sufficient pore pressures, at relatively low temper- 290
260 atures (200-300°C), to overcome even the higher ten- 291
261 sile strength of the aged material. This would result in 292
262 steady-state scabbling (frequent scabbling of very small 293
263 fragments and very low rate of increase of the surface 294
264 temperature, Figure b,c) and a nearly constant (high) 295
265 rate of volume removal (a). Presumably there is a limit 296
266 to the minimum size of fragments, so that a further re- 297
267 duction in permeability (and increase of pore pressures) 298
268 caused by a lower w/b ratio (for P_{32}) or tensile strength 299
269 (for the early age pastes) would not result in an even 300
270 more frequent ejection of smaller fragments. 301

271 The scabbling of mortars would be expected to be 302
272 governed by the behaviour of the aggregate-paste ma- 303
273 trix, in which, at the highest level of simplification, pore 304
274 pressures are generated in the paste and the tensile re- 305
275 sistance is provided by the aggregate, acting as rein- 306
276 forcement. The full model would be far more complex, 307
277 with different thermal expansion and thermal conduc- 308
278 tivity of the two phases generating complex stress fields 309
279 and thermal gradients, and further complications associ- 310

ated with the behaviour of the aggregate-paste interface.
The surface temperature histories (Figure b,c) show that
the onset of scabbling (at about 300°C; higher than in
the OPC+PFA pastes) is followed by a long steady state
phase of oscillations around a nearly constant tempera-
ture, characterised by two periodic functions: one with
low frequency (2-3 cycles/s) and larger amplitudes (50-
100°C), and one with much higher frequency (30-40 cy-
cles/s) and low amplitudes (10-20°C). The first is a re-
sult of ejection of larger fragments, normally contain-
ing pieces of aggregate surrounded by paste, the sec-
ond of frequent ejection of smaller fragments, contain-
ing pieces of paste and smaller aggregates. The con-
tinuous, frequent ejection of small aggregates in OPC
mortar (M_o), not seen in O_{42} paste, shows that the pres-
ence of fine aggregates governs the scabbling process.
This could be caused by changes in temperature distri-
bution (different thermal conductivity), reduced perme-
ability (impermeable sand particles reducing the over-
all porosity of the material), fractures due to differential
thermal expansion or a combination of these factors.

Saturated concretes show similar behaviour after age-
ing (Figures and), with a small increase in volume re-
moval with age. The only substantial difference is ob-
served in B_p concrete (Figure ,c), where larger frag-
ments are ejected in the later stages. This could be a
result of larger moisture content below the surface lead-
ing 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

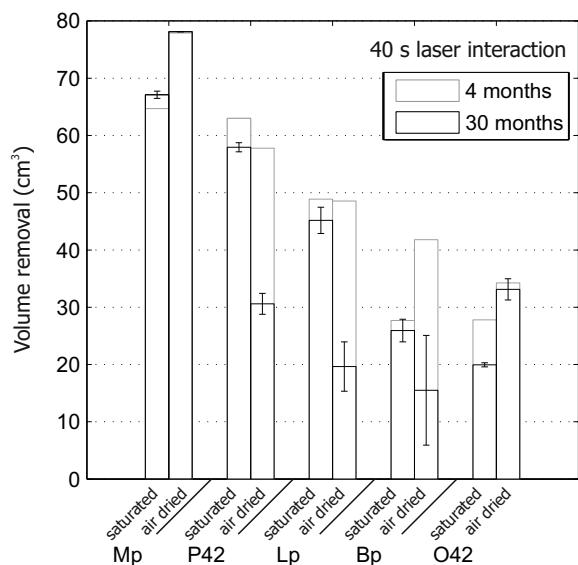


Figure 8: Volume removal results for specimens tested in the investigation of the effects of prolonged drying.

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

315 5. The effect of prolonged drying

316 5.1. Test programme of the effects of prolonged drying

317 All specimens used for this study were cast at the
 318 same time and stored in a mist room ($\approx 20^\circ\text{C}$, $\approx 95\%$ relative
 319 humidity) for 50 days. After that the air dried specimens
 320 (xxA) were moved to the laboratory and kept at
 321 ambient conditions ($\approx 20^\circ\text{C}$ and $\approx 95\%$ relative humidity);
 322 whereas the saturated specimens (xxS) remained in
 323 the mist room until testing. The specimens were tested
 324 at two ages: 4 months (after 49-64 days of drying) and
 325 30 months (after ≈ 800 days of drying).

326 The specimens and the experimental programme
 327 (laser interaction times, specimen ages and number of

328 repeats) used for this study are shown in Table 3.

329 5.2. Test results of the prolonged drying investigation

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

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

349 The reductions in volume removal for the saturated
 350 concrete specimens (Lp and Bp, Figure 8) are small (7-8%),
 351 yet showing a reversal of the trend observed for the same
 352 saturated materials of the first series (compared at the
 353 ages of 8 and 22 months), when the aging resulted in a
 354 20-30% increase in volume removal (Figures 4.3a and
 355 Figures 4.3a). The aging of the saturated P₄₂S specimens
 356 resulted in small reduction (7%) of volume removal,
 357 whereas no effect of aging was noticed in the
 358

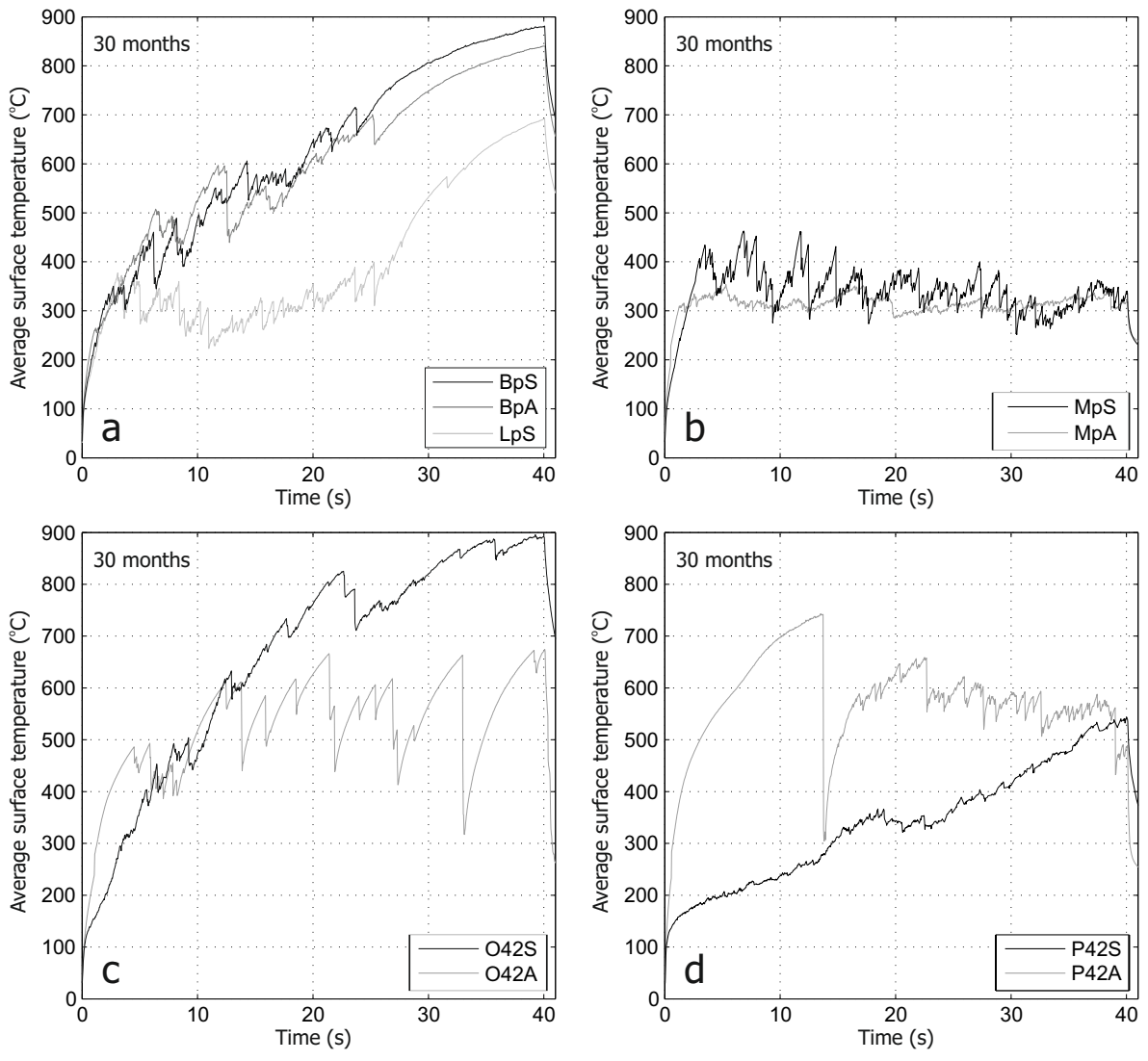


Figure 9: Average surface temperatures recorded in the investigation of effects of prolonged drying: (a) basalt and limestone concretes, (b) mortars, (c) OPC pastes and (d) PFA+OPC pastes.

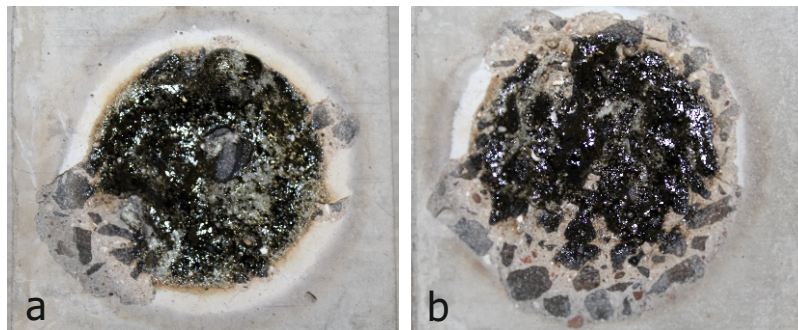


Figure 10: The two air dried basalt concrete (BpA) specimens from Series 1 exposed to 40 s laser interaction; (a) stopped scabbling after 5 s, whereas (b) stopped scabbling after 25 s.

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

Test/ Spec.	Material Composition	Precon- ditioning	Las. Int. (s)	4 months				30 months			
				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

359 comparison between 3 and 17 months old specimens of
360 the same material. The saturated OPC paste (O₄₂S) saw
361 a larger 28% reduction in volume removal in the aged
362 specimens, similar to that recorded earlier for the age-
363 ing period between 3 and 17 months (30%, Figure 4.3a).
364 These results suggest that ageing has different effects on
365 the effectiveness of laser scabbling of different saturated
366 materials: (a) it reduces the volume removal of OPC
367 pastes, but the reduction occurs in the first 20 months
368 (or earlier) and further ageing has no effect; (b) has very
369 little effect (small reduction) on PFA+OPC pastes and
370 mortars; and (c) it may have a positive effect on con-
371 cretes initially (e.g. the first 20 months), but the effect
372 diminishes with time.

373 The volume removal, recorded after 40 s of laser
374 beam exposure of air dried specimens at the ages of 4
375 and 30 months is shown in Figure 8. The prolonged
376 drying had different effects on volume removal, rang-
377 ing from (a) no effect on mortar (Mp) and (b) very little
378 reduction (3.4%) in OPC paste (O₄₂) to (c) very sig-
379 nificant reductions in PFA+OPC paste (47%) and the

380 two concretes (60% for Lp and 63% in Bp). The com-
381 parison with the saturated specimens of the same age
382 (40 months) shows that the drying had positive effect,
383 increasing the volume removal by 15% in mortar (Mp),
384 and by 65% in OPC paste (O₄₂). The effect on the other
385 three materials was negative; with volume reductions of
386 47% in PFA+OPC paste (P₄₂), 54% on limestone con-
387 crete (Lp) and 39% in basalt concrete (Lp).

388 Average surface temperatures for the concrete and
389 mortar specimens tested at 30 months are presented in
390 Figures 5.3a and b. Unfortunately, due to experimen-
391 tal error, the infrared data for the air dried limestone
392 concrete (LpA) was not recorded. The degree of sat-
393 uration had little effect on the surface temperature of
394 basalt concrete (BpS and BpA), whereas the saturated
395 mortar (MpS) experienced much larger but less frequent
396 temperature fluctuations compared to the air dried mor-
397 tar (MpA), while remaining at a similar background
398 temperature, which resulted in similar volume removal
399 rates.

400 Average surface temperature results for the hardened

401 cement pastes (Figures 5.3c and d) show very differ- 432
402 ent behaviour between the saturated and air dried spec- 433
403 imens. The behaviour of saturated OPC paste ($O_{42}S$) 434
404 is characterised by small temperature fluctuations and 435
405 a steady increase in background temperature (reaching 436
406 $900^{\circ}C$ at the end of the interval), indicating that the rate 437
407 of volume removal is low. The air dried paste ($O_{42}S$) 438
408 shows infrequent but very large temperature fluctua- 439
409 tions (of over $300^{\circ}C$ in the latter stages), which is a 440
410 result of ejection of large fragments. The volume re- 441
411 moval rate is sufficient to maintain lower background
412 temperature (about $500^{\circ}C$). The behaviour of the satu-
413 rated PFA+OPC pastes is the opposite to that of OPC
414 pastes. Here the saturated paste ($P_{42}S$) undergoes small,
415 frequent temperature fluctuations with a nearly linear
416 average surface temperature increase of around $10^{\circ}C/s$
417 throughout the entire period of exposure. The air-dried
418 paste ($P_{42}A$) shows no signs of scabbling at the begin-
419 ning (hence the large temperature increase to $740^{\circ}C$ at
420 15 s), but then after the ejection of a large fragment,
421 the temperature drops by over $400^{\circ}C$. This is followed
422 by another interval of monotonous temperature increase
423 (no scabbling) to $600^{\circ}C$, after which it continues with
424 steady scabbling at a rate that is sufficient to maintain
425 constant background temperature over the last 25 s. The
426 overall effect is that the removed volume at the end of
427 the test is about half of that in the saturated paste (Fig-
428 ure 8). Generally, air dried cement pastes behave in
429 a more erratic way, their scabbling behaviour charac-
430 terised by ejection of large fragments.

431 It can be seen in Figure 8 that the air dried basalt con-

crete (BpA) exposed to 40 s laser interaction had a much
larger error than the other compositions tested. From in-
spection 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 af-
fected zone (Figure 10a). The second specimen scab-
bled frequently until 25 s, and as a result underwent less
vitrification and has only a small part of the white ring
(Figure 10b).

442 5.3. Discussion of the results of prolonged drying in- 443 vestigation

444 The results of the investigation into the effect of pro-
445 longed drying highlights the effect of pore pressure
446 spalling in PFA+OPC pastes. In the first test series
447 [1], the effect of permeability on scabbling of hard-
448 ened pastes led the authors to suggest that pore pressure
449 spalling is the dominant mechanism in laser scabbling
450 of cement pastes. PFA is known to reduce the perme-
451 ability of a cement paste [5], resulting in sufficiently
452 low permeability of the PFA+OPC paste for pore pres-
453 sure spalling to take place in the saturated specimen,
454 inducing small, frequent fragment ejections. By remov-
455 ing the free water through prolonged air drying, the
456 driving force for pore pressure spalling is reduced. As
457 pore pressure spalling does not remove material from
458 the surface, the temperatures increase causing a devel-
459 opment of severe thermal gradients. This in turn causes
460 large fragments to be ejected as a result of thermal stress
461 spalling, with pore pressures acting as a secondary fac-
462 tor.

463 The situation is different with the OPC pastes, espe- 494
464 cially the ones with the higher w/b ratio of 0.42 (O_{42}), 495
465 which are expected to be more porous (and more per- 496
466 meable). In O_{42} the volume removal increases with air 497
467 drying, suggesting that free water is detrimental to the 498
468 laser scabbling process. The permeability of O_{42} paste 499
469 could be too high for pore pressure spalling to be effec- 500
470 tive in the saturated specimens, while intense evapora- 501
471 tion would reduce the thermal gradients under the sur- 502
472 face, reducing the potential for thermal stress spalling. 503
473 If there is no spalling, the surface temperature of the 504
474 specimen increases dramatically reaching surface vit- 505
475 rification levels. The reduced moisture content in the 506
476 air dried O_{42} paste specimens at 30 months (Table 3) 507
477 means less energy is lost from the system due to evap- 508
478 oration, allowing thermal stress spalling to occur more 509
479 efficiently. This leads to ejection of very large fragments 510
480 at high temperature (around 500°C , Figure c), not seen 511
481 in any of the saturated cement paste specimens. 512

482 The greater reduction in volume removal due to age 513
483 in air dried concretes (compared to saturated) suggests 514
484 that the free water aids the scabbling process in con- 515
485 cretes. The moisture content of the air dried specimens 516
486 (2.3% and 2.6%) at 30 months may be below a thresh- 517
487 old value that was not reached when tested at 4 months 518
488 (3.0% and 3.2%). Eurocode 2 suggests a moisture con- 519
489 tent of 3% is necessary for spalling to take place [6]. 520
490 The fact that air dried mortars tested at 30 months (with 521
491 moisture content of 5.0%) did not experience a reduc- 522
492 tion in volume removal compared to the 4 month speci- 523
493 mens (8.2%), suggests the greater cement paste content 524

of mortars compared to concretes means mortars have
more free water to loose, and as a result, both the satu-
rated 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 re-
sults were reported before [4]. A possible explanation
for this lies in the effect of saturation on thermal con-
ductivity: 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 temper-
atures (and pressures) necessary for scabbling must oc-
cur over a larger depth, causing larger (thicker) frag-
ments to be ejected. The lower thermal conductivity of
the air dried specimen, on the other hand, would cre-
ate 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°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

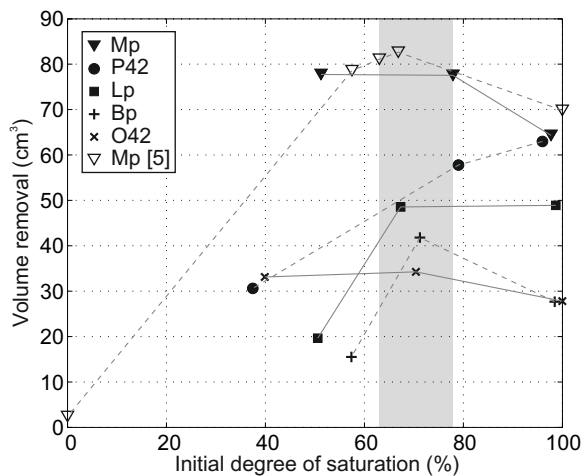


Figure 11: Volume removal results from prolonged drying investigation plotted against degree of saturation. Hollow triangles [4] and solid triangles show results of the same composition (Mp). Shaded area shows the range of optimum moisture content for the PFA+OPC mortar (Mp). All results are after 40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

525 investigation, the higher volume removal for lower de-
 526 grees of saturation in some compositions (basalt con-
 527 crete Bp, OPC paste O₄₂, and the Mp mortar) suggests
 528 that an optimum initial degree of saturation exists be-
 529 low 100%. Along with the results of the investigation
 530 into the effect of free water content in mortars [4] (hol-
 531 low triangles), where there are more data points, an op-
 532 timum degree of saturation for the PFA+OPC mortar
 533 composition (Mp) can be identified between 63% and
 534 78% (shaded area).

535 6. Stochastic behaviour

536 This investigation has given an indication that there
 537 may be some stochastic behaviour present in the laser
 538 scabbling of concretes as reported in previous studies
 539 ([8, 9, 10, 11]). All PFA+OPC basalt concretes (Bp)
 540 reported here have displayed unpredictable behaviour.
 541 The saturated PFA+OPC basalt concrete tested at 22

542 months (Figure 4.3c) shows quite different behaviour
 543 and large margins of error compared to the specimens
 544 tested at 8 months, something that is not seen in the
 545 OPC basalt concrete or either of the limestone concretes
 546 (Figure 4.3). The air dried basalt concrete tested at 30
 547 months (Figure 8) shows a much larger margin of er-
 548 ror in volume removal compared to any other composi-
 549 tion. The two air dried basalt concrete specimens also
 550 displayed different behaviour in the infra red record-
 551 ings (Figure 5.3a) and different extents of vitrification
 552 after 40 s laser interaction (Figure 10). The results sug-
 553 gest that stochastic behaviour may increase with age for
 554 PFA+OPC basalt concrete. Alternatively, this could be
 555 a combination of the natural variability of the concrete
 556 and the high sensitivity of basalt aggregates to laser
 557 scabbling [2].

558 7. Conclusions

- 559 1. The largest effect of concrete age on laser scab-
 560 bling is due to the reduction in the degree of satu-
 561 ration caused by drying. Results suggest that dry-
 562 ing reduces laser scabbling in concretes. This is of
 563 the utmost importance when considering the use of
 564 laser scabbling in situ on structures liable to drying
 565 during their operational use.
- 566 2. An optimum degree of saturation exists, below
 567 100%, where volume removal due to scabbling will
 568 be at a maximum.
- 569 3. The effect of ageing on saturated specimens is gen-
 570 erally small: saturated OPC pastes scabble more
 571 successfully at an earlier age, saturated mortars are

572 unaffected by age, and saturated concretes scabble 604
573 more successfully with the increase in age. 605
574 4. The effect of saturation on thermal conductivity 606
575 may cause saturated mortars to experience differ- 607
576 ent scabbling behaviour to that of the air dried. 608
577 5. This investigation has given an indication of an in- 609
578 crease in stochastic scabbling behaviour with age. 610

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