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Laser scabbling of mortars

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Abstract

Laser scabbling of concrete is the process by which the surface layer of concrete may be removed through the use of a low power density laser beam. Previous research has suggested that the driving force responsible for laser scabbling is developed within the mortar. The aim of this investigation was to establish the key parameters that influence laser scabbling of mortars. The results show that the removal of free water from mortars prohibits scabbling, but resaturation allows mortar to scabble. A reduced permeability, either due to a reduction in the water/binder ratio or the use of 25% PFA replacement, enhances the scabbling. A higher fine aggregate content increases volume removal and fragment sizes during laser scabbling.

Keywords:
Mortar, Scabbling, Spalling, Moisture content, w/b ratio, Fine aggregate content

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1. Introduction

This paper describes the third part of an investigation into the mechanisms responsible for laser scabbling; a technique used for the 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 high power laser (of low power density), 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.

In the first part of this study [2], a wide range of materials were investigated to identify key factors that affect the laser scabbling process with the aim of establishing an experimental procedure for the quantification of relationships between laser interaction time, surface temperature, volume removal and size of fragments.

The second part of the study [3] investigated the relationships 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. Specimens tested included cement pastes, mortars and concretes, with and without 25% PFA; hardened cement pastes with different water-binder (w/b) ratios; and concretes using basalt and limestone aggregates of different aggregate sizes.

The results of the first two test series showed that:

1. Volume removal of mortars was higher than that of concretes [2, 3];
2. The primary driving force for laser scabbling of concretes developed in the mortar and not in the coarse aggregates [2, 3];
3. The dominant mechanism for scabbling of mortars was a combination of thermal stress spalling and pore pressure spalling (which is reduced due to the reduction of available water in the mortars compared to the cement pastes) [3];
4. The use of PFA as a cement replacement material (75%OPC+25%PFA) [2, 3] and/or reducing the w/b ratio [3] enhanced volume removal during laser scabbling of hardened cement pastes (this

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Table 1: Mix compositions of specimens in the three investigations: (i) effects of free water content, (ii) effects of w/b ratio (and binder composition) and (iii) effects of fine aggregate content. All values are mass/binder ratios unless otherwise stated.

	(i) Free Water	(ii) Effect of w/b ratio				(iii) Effect of fine aggregate content			
	*Mp	Mp37	Mp47	Mo37	Mo47	Mp0%	Mp20%	Mp40%	Mp60%
Water	0.42	0.37	0.47	0.37	0.47	0.42	0.42	0.42	0.42
OPC	0.75	0.75	0.75	1	1	0.75	0.75	0.75	0.75
PFA	0.25	0.25	0.25	0	0	0.25	0.25	0.25	0.25
Fine agg.	1.84	1.84	1.84	1.84	1.84	0	0.36	0.95	2.13
$\%_{(m)}$ sand	56	57	56	57	56	0	20	40	60

Table 2: Description of the preconditioning methods used in the free water investigation, including the length of preconditioning, and the resulting average mass change, degree of saturation and moisture content. *The MpDes specimens were air dried for 69 days followed by 99 days stored with silica gel.

Spec.	Type of preconditioning	Precon. time (days)	Av. mass change (g / %)	Deg. sat. (%)	MC (%)
MpSat	Stored in mist room (>95% relative humidity)	261	0 / 0	100	9.3
MpAir	Stored at ≈20°C and ≈40% relative humidity	168	-34.1 / -3.2	66.9	6.2
MpDes	Same as MpAir + stored with silica gel	69 + 99*	-43.7 / -4.1	57.5	5.4
Mp50	Oven dried at 50°C	25	-38.0 / -3.5	63.0	5.9
Mp105	Oven dried at105°C	18	-102.8 / -9.5	0	0
MpRS	Resaturated Mp105 specimens	2	+52.8 / +4.9	51.4	4.8

was attributed to reduced permeability of the material);

5. Reducing the degree of saturation of specimens (saturated vs. air-dried) did not reduce scabbling [2];
6. There was no evidence of stochastic tendencies [2, 3], as reported in previous studies [4, 5, 6, 7];
7. Mortars and cement pastes using the same binder compositions exhibited different scabbling behaviour [2, 3];

2. Scope and aim of the research

The first two test series suggested that the mortar is responsible for the primary driving force in laser scabbling of concretes. This paper aims to determine the relationship between laser interaction time, volume removal and surface temperatures for different mortar compositions, in order to identify the parameters affecting the laser scabbling of mortars.

The compositions selected for investigation in this study were designed to isolate the following factors that were highlighted from the previous two test series [2, 3]:

1. Mortars of the same composition with different free moisture contents, to determine the effect of free water content, and potential operational uses, on laser scabbling.
2. Mortars with different w/b ratios, to determine the effects of permeability and strength on laser scabbling of mortars;
3. Mortars with and without 25% PFA replacement, to add to previous work on the effect of PFA replacement on laser scabbling;
4. Mortars with different fine aggregate contents, to gain an understanding of the effect of fine aggregate content on laser scabbling;

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

The material compositions used in this study are given in Table 1. The materials used for preparing the test specimens were: Lafarge CEM 1 OPC (BS EN 197-1:2000 strength class 52.5N); CEMEX PFA (LOI-B and fineness-s); and fully graded marine dredged quartzitic sand from Hoyle Bank, Morecombe Bay, UK. It should be noted that the CEM 1 used in this study was of a different brand to that used in the two previous studies [2, 3].

All mixes underwent 30-60 seconds dry mixing followed by 3-5 minutes wet mixing. The slurry was trans-

Table 3: Experimental programme and test specimens of the free water content investigation. All specimens have the mix composition of ‘Mp’ detailed in Table 1, but underwent different preconditioning methods as detailed in Table 2. *Tests had only 2 repeats rather than three.

Test/ Specimen	Precon- ditioning type	Interaction time (s)	Age (days)
MpSat-10	Saturated	10	261
MpSat-30		30	261
MpSat-50		50	261
MpSat-70		70	261
MpAir-10	Air dried	10	263
MpAir-30		30	263
MpAir-50		50	263
MpAir-70		70	263
MpDes-10	Dessicated	10	263
MpDes-30		30	263
MpDes-50		50	263
MpDes-70		70	263
Mp50 -10	Oven dried at 50	10	263
Mp50-30		30	263
Mp50-50		50	263
Mp50-70		70	263
Mp105-10	Oven dried at 105	10	263
Mp105-30*		30	263
Mp105-70*		70	263
MpRS-10*	Resaturated	10	268
MpRS-70*	Resaturated	70	268

ferred to 100 mm cube moulds which were 3/4 filled and vibrated for approximately 10s before being filled and vibrated again for approximately 10s, 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 hours, gradually returning to 20°C after 240 hours. After curing, the 100 mm cubes were cut in half using a diamond saw, creating 100 mm x 100 mm x 49 mm (+/- 1 mm) cuboid specimens, which were stored in a mist room at 100% relative humidity until testing, or preconditioning.

The mix composition of the mortar used in the free water investigation (Mp) is detailed in Table 1. It is the same mix composition as the mortar (M) used in the first test series [2] and the PFA + OPC mortar (Mp) used in the second test series [3]. Specimens tested in the free water investigation were exposed to the preconditioning methods detailed in Table 2 until constant mass was achieved (a loss of <2 g/day for oven dried and <0.1 g/day for dessicated and air dried specimens). The moisture content and degree of saturation of speci-

Table 4: Experimental programme and test specimens of the water/binder investigation. Mix compositions are detailed in Table 1. All specimens in the binder composition investigation were tested saturated.

Test/ Specimen	Precon- ditioning type	Interaction time (s)	Age (days)
Mp37-10	w/b = 0.37 PFA+OPC	10	223
Mp37 -30		30	223
Mp37 -50		50	223
Mp37 -70		70	223
Mp47 -10	w/b = 0.47 PFA+OPC	10	223
Mp47 -30		30	223
Mp47 -50		50	223
Mp47 -70		70	223
Mo37 -10	w/b = 0.37 OPC	10	223
Mo37 -30		30	223
Mo37 -50		50	223
Mo37 -70		70	223
Mo47 -10	w/b = 0.47 OPC	10	223
Mo47 -30		30	223
Mo47 -50		50	223
Mo47 -70		70	223

Table 5: Experimental programme and test specimens of the fine aggregate content investigation. Mix compositions are detailed in Table 1. All specimens in the fine aggregate content investigation were tested saturated.

Test/ Specimen	Precon- ditioning type	Interaction time (s)	Age (days)
Mp0%-5	0% agg.	5	246
Mp0%-10		10	246
Mp0%-30		30	246
Mp0%-50		50	246
Mp0%-70		70	246
Mp20%-10	20% agg.	10	247
Mp20%-30		30	247
Mp20%-50		50	247
Mp20%-70		70	247
Mp40%-10	40% agg.	10	246
Mp40%-50		50	252
Mp40%-70		70	252
Mp60%-10	60% agg.	10	247
Mp60%-30		30	247
Mp60%-50		50	247
Mp60%-70		70	247

mens exposed to the different preconditioning methods are also given in Table 2.

The laser interaction times and age of specimens at the time of testing are given in Tables 3, 4 and 5; each test was repeated three times unless stated otherwise. 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.

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 [8]. The volume removal graphs show the mean of the repeats with standard deviation error bars. Porosity, moisture content and degree of saturation were subsequently determined using values found in the density tests.

Porosity = $100 * ((m_{sat} - m_{od})/(m_{sat} - m_{sub}))$,

Moisture content = $100 * ((m_t - m_{od})/m_t)$,

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. 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 (Figure 1).

The infrared camera can operate within temperature ranges of 0-550°C or 200-2000°C. In most cases surface temperature data was recorded for six tests per composition (three in each temperature range), the median of the data sets for each composition are presented here. If necessary data from the two temperature ranges were merged to give data of 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 be noted that the volume removal data presented are mean values of the repeats for each interaction time tested, with standard deviation error bars. The connecting lines are added to guide the eye. The average surface temperature histories, however, are continuous temperature history recordings for one or two tests (depending on the temperature ranges required).

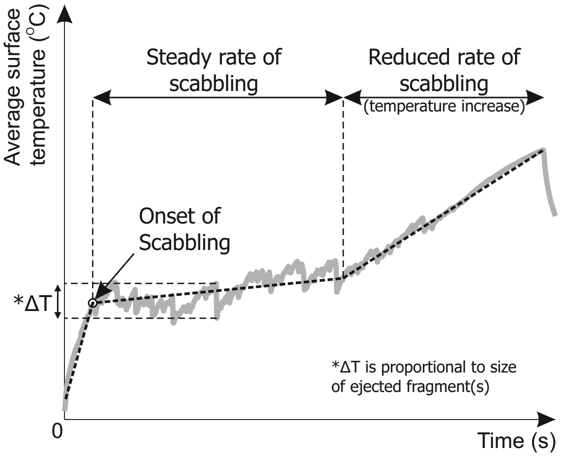


Figure 1: Example average surface temperature graph [3], showing trilinear behaviour. Different stages of scabbling behaviour are highlighted.

Table 6: Specimen properties; MC = moisture content, Fc = compressive strength (the mean of three repeats is reported). All specimen property tests were carried out saturated.

Spec.	Porosity (%)	MC (%)	Density (kg/m^3)	F$_c$ (MPa)
Mp	21.1	9.3	2262	63
Mp37	18.3	8.1	2267	65
Mp47	22.8	10.1	2250	55
Mo37	17.1	7.4	2293	76
Mo47	21.2	9.3	2277	67
Mp0%	42.2	21.8	1937	57
Mp20%	34.8	16.9	2058	60
Mp40%	18.9	8.4	2264	59
Mp60%	26.3	12.0	2188	62

A more detailed account of the experimental procedure used in this study is provided in Peach et al. [2].

3.1. Specimen properties

The specimen properties for the different compositions are detailed in Table 6. Specimen properties of the compositions tested in the w/b ratio investigation (Mp37, Mp47, Mo37 and Mo47) show that the use of a higher w/b ratio and/or the use of PFA as a cement replacement material increases the porosity and moisture content, while reducing the strength and density.

Of the specimens tested in the fine aggregate content investigation the Mp0% has the highest porosity and moisture content, but the lowest density. Increasing the content of fine aggregates (Mp20% and Mp40%) reduces the porosity and moisture content, and increases the density. Hardened cement paste is naturally porous due to the formation of pores during hydration [9], therefore, as the porous cement paste is replaced with dense/low porosity fine aggregates, the porosity and moisture content of the mortar reduces and the density increases. At high fine aggregate contents (Mp60%), however, the reduction in workability causes the porosity and moisture content to increase and the density to reduce. The compressive strength of the specimens tested in the aggregate content investigations are all similar.

The mass loss due to preconditioning, moisture content and degree of saturation of the specimens tested in the free water content investigation were determined, which are detailed in Table 2.

4. Test results

4.1. Results of the free water content investigation

Figure 2 shows the volume removal and average surface temperatures recorded in the free water content investigation. The results show that specimens oven dried at 105 °C (Mp105) undergo negligible volume removal and experience a dramatic increase in surface temperature due to laser application, resulting in extensive vitrification (Figure 3). In comparison, non-oven-dried specimens and specimens oven dried at 50 °C act similarly, and experience high rates of laser scabbling.

Oven dried specimens that were resaturated (MpRS) experience scabbling initially. The volume removal after 10s laser interaction, and the average surface temperature behaviour up to around 8 s, was similar to that of the MpAir, MpSat, MpDes and Mp50 specimens. After this the MpRS surface temperatures increase at a similar rate as the Mp105 did initially, but surface temperatures continue to rise to a final temperature around 100 °C higher than the Mp105 specimens. Cross sections of specimens after preconditioning, displayed in Figure 4, show that the resaturation did not penetrate to a depth beyond ≈1 cm, which explains the short timescale of scabbling behaviour in the resaturated specimens.

The air dried specimens (MpAir), dessicated specimens (MpDes) and specimens oven dried at 50 °C (Mp50) show similar volume removal until between 30 and 50 s laser interaction. After 50 s the rate of volume removal of the dessicated (MpDes) specimens decreases until the total volume removal is equal to that of the saturated specimens after 70 s laser interaction. The saturated specimens (MpSat) consistently experienced lower volume removal compared to the MpAir and Mp50 specimens. Saturated specimens also experienced larger temperature fluctuations than the MpAir,

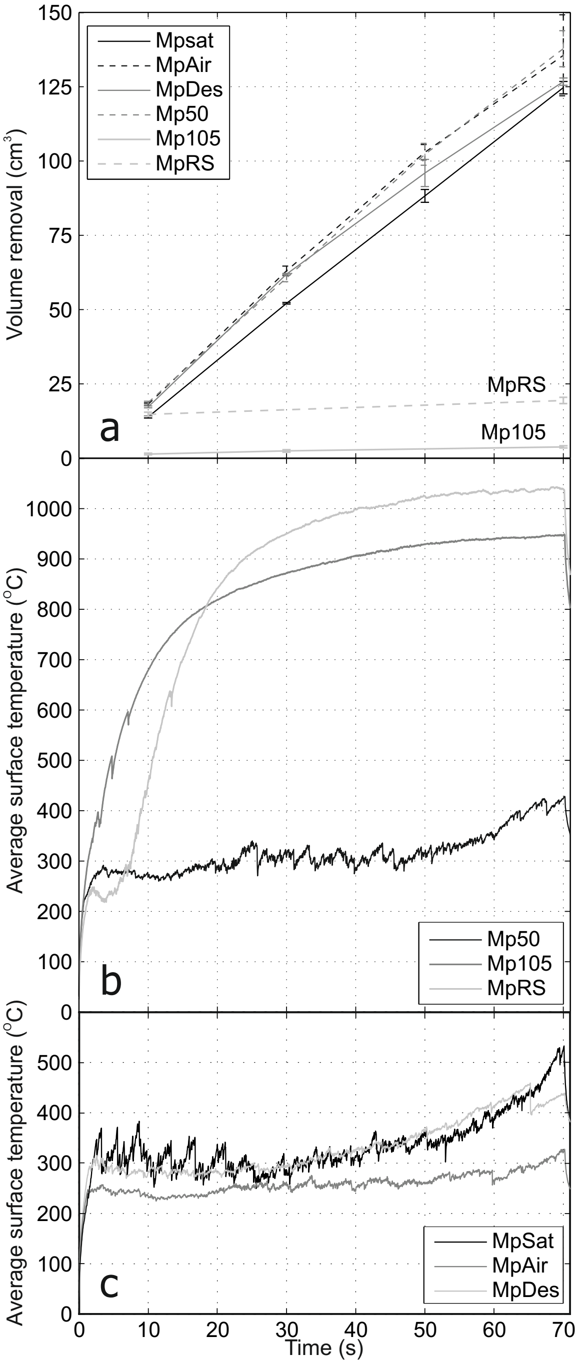
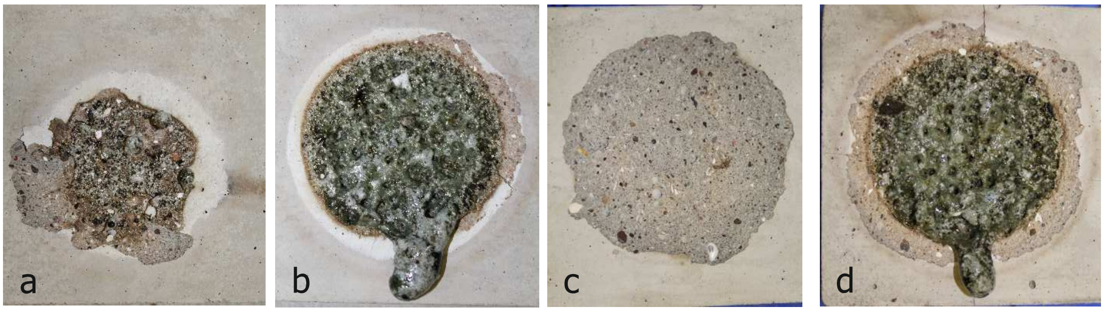
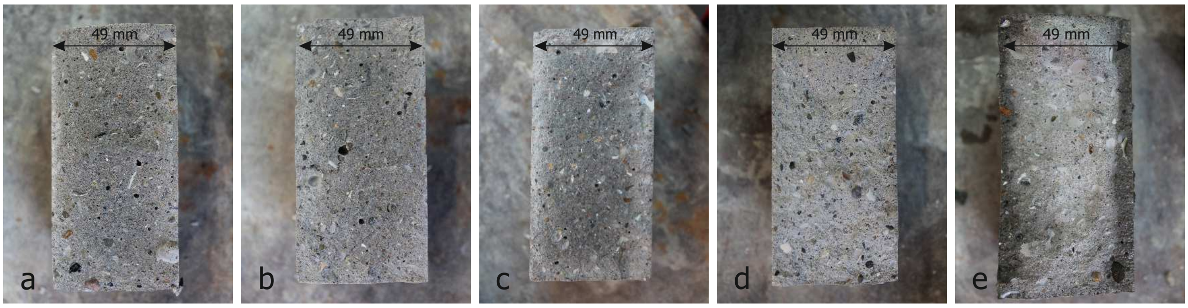


Figure 2: Results of the free water investigation: (a) volume removal; (b) average surface temperatures of specimens oven dried at 50 °C (Mp50) and 105 °C (Mp105), and those resaturated after being oven dried at 105 °C (MpRS); (c) average surface temperature results of the saturated (MpSat), air dried (MpAir) and dessicated specimens (MpDes).



Mp105-10 Mp105-70 MpRS-10 MpRS-70

Figure 3: Photographs of specimens after laser interaction tested in the free water content investigation: (a) Specimen oven dried at 105 °C, exposed to 10 s laser interaction (Mp105-10); (b) specimen oven dried at 105 °C, exposed to 70 s laser interaction (Mp105-70); (c) specimen resaturated after being oven dried at 105 °C, exposed to 10 s laser interaction (MpRS-10); (d) specimen resaturated after being oven dried at 105 °C, exposed to 70 s laser interaction (MpRS-70).



MpAir / Air dried MpDes / Dessicated Mp50 / Oven dried at 50°C Mp105 / Oven dried at 100°C MpRS / Resaturated

Figure 4: Photographs of cross sections of specimens tested in the free water investigation. Images show the distribution of moisture within the specimens due to the preconditioning methods.

MpDes and Mp50 specimens. The MpAir specimens had lower average surface temperatures than the MpSat, MpDes or Mp50 specimens.

The moisture content and degree of saturation of the specimens tested in the free water content investigation are displayed in Table 2. It is clear that the oven drying at 50 °C, desiccating and air drying preconditioning methods did not result in vastly different moisture contents.

4.2. *Results of the water/binder ratio and binder composition investigation*

The volume removal and average surface temperature results for the w/b ratio investigation are shown in Figure 5. It can be seen from Figure 5b that an increase in w/b ratio from 0.37 to 0.47 causes the volume removal to decrease by 19–24% for OPC mortars and by 8–19% for PFA + OPC mortars. The use of 25% PFA replacement (Mp's vs Mo's) causes the volume removal to increase by 5–18% when a water binder ratio of 0.47 is used, however the effect of PFA in a mortar of w/b ratio of 0.37 is less certain with volume removal increasing for 30 and 50 s (8 and 3%), but decreasing slightly for 10 and 70 s (2 and 3%).

Average surface temperatures for the mortars using different binder compositions are broadly similar. The initial temperatures at the onset of scabbling vary for mortars of different binder compositions; PFA + OPC binder specimens have higher onsets than OPC mortar specimens (Mo47 = 240 °C; Mo37 = 260 °C; Mp37 = 330 °C; Mp47 = 400 °C). Up to around 40 s, the average surface temperature behaviour of the four compositions are fairly similar, but higher w/b ratio mixes have larger temperature fluctuations. After 40 s the average surface temperatures of the compositions using PFA increase at a much higher rate than the OPC mortars, which corresponds to a slight reduction in the rate of volume removal in the PFA mortars.

4.3. *Results of the fine aggregate content investigation*

The volume removal and average surface temperature results for the fine aggregate content investigation are

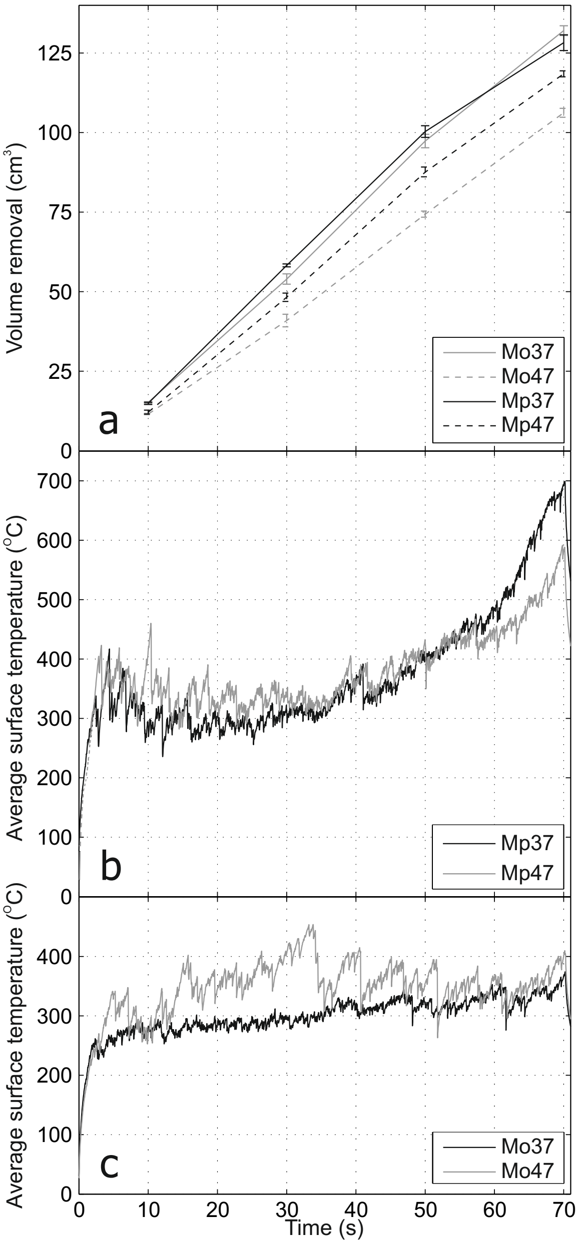


Figure 5: Results of the water/binder ratio investigation: (a) volume removal; (b) average surface temperatures of PFA + OPC mortars with w/b ratios of 0.37 (Mp37) and 0.47 (Mp47); (c) average surface temperature results OPC mortars with w/b ratios of 0.37 (Mo37) and 0.47 (Mo47).

shown in Figure 6. The average surface temperature behaviour progressively changes as the fine aggregate content is increased, a simplified diagram illustrating this behaviour can be seen in Figure 6c.

The specimen with no fine aggregate (Mp0%) is the same composition, and undergoes similar average surface temperature behaviour, as the Mp paste tested in the previous study [3]. The Mp0% composition has a temperature at the onset of scabbling of around 210 °C, after which there is a steady increase in average surface temperature of around 1.9 °C/s with frequent, small temperature fluctuations. The specimens with 20% and 40% fine aggregate content (Mp20% and Mp40%), experience similar volume removals and temperature fluctuations which are both higher than for the Mp0% composition. The Mp40% composition has a higher temperature at the onset of scabbling (335 °C) than the Mp20% composition (240 °C), but both compositions experience similar average surface temperatures after around 30 s laser interaction. The specimens with 60% aggregate content exhibit the highest volume removals, the highest temperature at the onset of scabbling (430 °C) and the largest temperature fluctuations.

5. Discussion of results

5.1. The effect of free water

The difference in scabbling behaviour between the specimens that were oven dried at 105 °C and those that were resaturated (Figure 2) suggests that free water is necessary for scabbling to occur, and that pore pressure spalling is the dominant mechanism. Specimens that were oven dried at 105 °C, effectively, did not undergo scabbling. Whereas, the specimens that were oven dried at 105 °C and subsequently submerged in water for 48 hours, scabbled for the first 8 s of laser interaction. The only difference between the two specimens was the increased degree of saturation of the surface of the resaturated specimen. The depth of saturation in the resaturated specimens, highlighted by Figure 4, indicates that scabbling was only possible in the resaturated surface and once it was removed, scabbling of the oven dried core was not possible due to the absence of free water.

There is evidence in the literature [10, 11] that oven drying at 105 °C damages the microstructure of cementitious materials. The authors were concerned this would invalidate the results of scabbling tests on Mp105 specimens. However, the successful scabbling of the resaturated specimens suggests damage due to oven drying is not detrimental to the laser scabbling process.

An unexpected result is that the final average surface temperature of the resaturated specimens (MpRS)

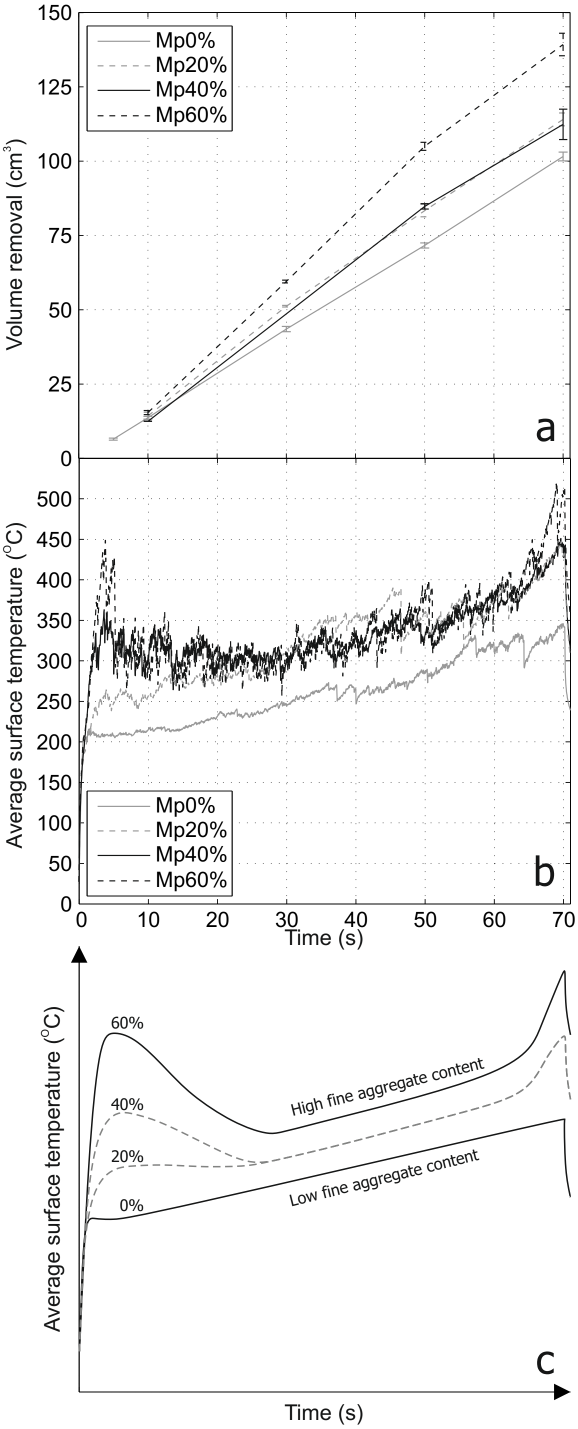


Figure 6: Results of the fine aggregate content investigation, specimens with fine aggregate content ranging from 0% to 60% (Mp0% ,Mp20%, Mp40% and Mp60%): (a) volume removal; (b) average surface temperatures; (c) simplified graph showing average surface temperature behaviour for mortars of different aggregate content.

was higher than the specimens oven dried at 105 °C (Mp105). A possible explanation for this is the shape of the surface that undergoes vitrification. The Mp105 specimens vitrify almost immediately, meaning vitrification occurs on a flat surface. The MpRS specimens, on the other hand, scabble before vitrification takes place, meaning vitrification takes place on (approximately) a parabolic surface (trough). This shape will insulate the heat affected zone, and potentially increase internal reflection of the laser, raising the surface temperature.

All other preconditioning methods (air dried, dessicated and oven dried at 50 °C, see Table 2) left enough free water for scabbling to take place. The threshold degree of saturation for scabbling to take place in the $(PFA+OPC)_{42}$ mortar composition tested here must be between 0–57.5%). Although, the cross sections of the specimens (Figure 4) show that the distribution of moisture is not uniform, which may be a factor. The fact that the saturated specimens scabbled less than the MpAir, MpDes and Mp50 specimens suggests the optimum degree of saturation is between 58% and 100% saturation.

5.2. *The effect of permeability*

The previous test series [2, 3] have shown that permeability was a key factor in laser scabbling of cement pastes. Results from the w/b ratio investigation (Figure 5) indicate that a lower permeability (lower w/b ratio or the use of PFA) will result in a greater rate of volume removal, suggesting that pore pressure spalling is present in laser scabbling of mortars. Furthermore, mortars of a higher w/b ratio (higher permeability) experience higher average surface temperatures and larger fragment ejections (larger temperature fluctuations), suggesting the mechanism of laser scabbling differs slightly as a result of reduced permeability. A lower permeability will allow the pore pressures required for scabbling to build quicker, allowing more frequent, smaller ejections to occur. Although, it must be noted that a lower w/b ratio will also increase the strength of the mortar (Table 6), increasing the pore pressure required for scabbling to occur. A higher permeability means vapour will escape at a higher rate. To overcome this, higher surface temperatures are required to liberate vapour from greater depths and build the necessary pore pressures. The increased permeability will also result in more uniform pore pressures, further increasing fragment size.

Alternatively, the higher scabbling temperatures and larger fragment sizes of specimens with higher permeability could be a result of thermal stress spalling. The higher permeability reduces the effect of pore pressure spalling, causing temperatures to rise, and thermal gradients to form, causing thermal stresses to develop.

The average surface temperature results show that PFA + OPC mortars scabble at higher temperatures than the OPC mortars. This result is counter-intuitive, as the lower permeability, due to PFA inclusion, should allow pore pressure spalling to occur at lower temperatures. This result is the opposite of what was seen for laser scabbling of cement pastes [3].

5.3. The effect of fine aggregates

The average surface temperature behaviour seen in Figure 6b and simplified in Figure 6c illustrates the effect of fine aggregates on laser scabbling. It can be seen that the hardened cement paste specimen (Mp0%) undergoes consistent, small, frequent fragment ejections, once a relatively low average surface temperature has been obtained (low temperature at the onset of scabbling). Hardened cement paste is water rich (Table 6) and free of reinforcing aggregates, therefore, once the free water is heated, and the relatively low localised pore pressures necessary for scabbling are developed, small fragments are ejected.

The presence of fine aggregates reinforces the paste making it difficult for small fragments to be consistently removed. As the fine aggregate content is increased, so is the amount of reinforcement. For larger fragments to be ejected, higher temperatures are required to develop higher driving forces (either pore pressures or thermal stresses) and/or to induce thermal damage to reduce the resistance to scabbling (weaken the material). Once the material has been heated to a sufficient background temperature, a consistent rate of scabbling can occur. As scabbling of specimens with a higher fine aggregate content results in higher volume removals (Figure 6), it shows that less frequent ejection of larger fragments is more efficient than more frequent ejection of smaller fragments.

It is important to note that a lower fine aggregate content will increase the moisture content (Table 6) which will contribute to differences in the average surface temperatures. As water is lost from the specimen through evaporation, heat energy is lost resulting in the reduction of average surface temperatures. This effect will increase with moisture content, and therefore, reduce with fine aggregate content.

5.4. The effect of thermal conductivity

Results of the saturated mortar shows that the saturated specimens have a reduced volume removal and larger fragment sizes (temperature fluctuations) compared to the MpAir, MpDes and Mp50 specimens (Figure 2). A possible explanation for this lies in the effect saturation has on thermal conductivity: as water is more conductive than air, heat will transfer through a saturated specimen easier [12]. 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 the temperatures (and pressures) necessary for scabbling must occur over a larger area, causing larger and thicker fragments to be ejected. The lower thermal conductivity of the dried specimens, on the other hand, allows localised areas of high temperature (and pressure) to form allowing smaller, thinner fragments to be ejected at a higher rate.

Furthermore, the increase in scabbling with aggregate content may be a result of an increase in thermal conductivity due to an increase in silica content [12, 13]. Silica is a dense material and as a result, it is naturally a good conductor. Whereas the large proportion of pores in hardened cement paste makes it less conductive. Therefore, as the content of cement paste is replaced with fine aggregates, the thermal conductivity of the specimens is increased. A higher thermal conductivity will allow localised high temperatures to dissipate over the heat affected zone, causing more uniform pore pressures to develop and larger fragments to be ejected.

6. Conclusions

The main finding of this study is that specimens oven dried at 105 °C until constant mass did not experience scabbling, but resaturating the surface allowed the surface to be scabbled. This suggests that free water is necessary for laser scabbling to occur. Therefore, it is unlikely that concrete that has been exposed to high temperatures during its lifetime will scabble successfully.

This study also highlighted the following properties of mortars during laser scabbling:

1. The relationship between degree of saturation (moisture content) and volume removal is not linear: the optimum degree of saturation for maximum volume removal is not saturated; and a threshold degree of saturation exists, above which scabbling occurs to a similar extent.
2. A lower permeability aides pore pressure spalling and increases volume removal;
3. The use of 25% PFA generally increases both volume removal and average surface temperatures;
4. A higher fine aggregate content increases volume removal and the size of fragments ejected, which

is most likely due to the reinforcing effect of fine aggregates;

5. The increased thermal conductivity of a saturated mortar causes larger fragments to be ejected.

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