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8th international seminar on structural masonry

# Conservation and Repair of Historic Buildings

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This paper is dedicated to the memory of the late Dr Fouad Khalaf. His wisdom, knowledge, kindness, and contribution to academic life will be sadly missed.

## ABSTRACT

*Modern civilisations realised the importance of maintaining historical buildings to preserve them as good examples for future generations and also as a source of revenue through tourism. This investigation looks at the characteristics and origins of various types of stone used in the construction of historic buildings. The study also investigates different materials and techniques used in cleaning and repair of buildings and problems associated therewith. Tests were first carried out on various types of stone to determine properties such as porosity, water absorption and strength. A chemical analysis was carried out, under and on the surface, of the stones to determine the elements present in soiling. The information collected from all the tests was used to select the most appropriate materials and techniques used for in situ cleaning of a listed historic building.*

## KEYWORDS

Historic buildings, Stone masonry, Cleaning, Maintenance, Repair.

## 1 INTRODUCTION

One of the attractions of using stone in buildings is the wide variety of colours and textures available to the designer. There is a great variety of natural rocks, but not every rock can be used successfully in construction [Andrew *et al.* 1994, Hill and David 1995]. Some stones may be unaffected by centuries of exposure to the weather but others, if used in the wrong environment, may have to be replaced after a few years. Through time, and because of pollution and weathering, the external façades of buildings are affected: throughout the world stones have changed colour and texture. The cleaning of soiled building surfaces is not only necessary for aesthetic reasons but to ensure better preservation of these materials. Stone cleaning is a major activity for the construction industry, both in terms of financial outlay and effect on our built heritage. Removal of the soiling layer has been perceived by the general public and building owners as beneficial because of the simplistic notion that clean, bright façades reflect well on the urban environment in general and on the image of the building occupier in particular [Ashurst 1994].

### 2.2 Limestone

Limestone is a sedimentary rock, which is widely distributed throughout the Earth's crust. The rock is durable

## 2 STONES FOR BUILDINGS

Constraints inherent in stones limit their suitability for use in buildings. Igneous rocks may contain minerals [redacted]

The cementing materials which are holding the sand grains together may be calcareous, dolomitic, siliceous or ferruginous. Sandstones in general are considered to have better resist

## 3 TYPES OF SOILING

Soiling can be divided into two types: biological and non-biological. Stone façades are likely to have both present, either separately or combined. Soiling can cause stone decay: discoloration caused by soiling, affecting the aesthetics of the building, may not be causing physico-chemical damage.

### 3.1 Biological soiling

Biological soiling occurs when organisms and higher plant life forms (algae, bacteria, fungi, and lichens) grow on the masonry. These cause surface discoloration; some cause serious damage. Biological soiling needs: moisture, the correct temperature, nutrients, the correct pH, and light. Variations in any of these, outwith certain limits, may result in that organism's death. However, some micro-organisms can exist over a wide pH range; some bacteria will grow between $6 \leq pH \leq 9$; some fungi can tolerate $2 \leq pH \leq 11$ [RILEM 1988, Ashurst 1994].

#### *3.1.1 Algae*

Algae appear in a range of different colours (green, red, brown, or blue). The most common green algae colonise stones and turn black upon surface drying. They require light as they are photosynthetic. Algae prefer high moisture content surfaces and will grow on most damp substrates. They become darker in appearance as they collect more soot particles. While algae do not usually rely on the masonry substrate for food, organic acids they secrete can dissolve calcium carbonate in limestone, concrete, and mortar. Algae can also act on the substrate by cellular action within the masonry's pores. The moisture induced cellular swell-shrink cycle can have a mechanical influence on the stone and cause micro-cracking as reported by Verhoef [RILEM 1988].

#### *3.1.2 Bacteria*

Bacteria are organisms which are often recognised by the chemical and biological changes they cause [Ashurst 1994]. However, heavy deposits can exist in high concentrations with algae and fungi [Honeyborne 1990]. Some bacteria produce ammonia and other nitrogenous compounds; others are capable of oxidising ammonia to produce nitrous and nitric acids. In doing so they produce salts and mineral acids causing damage to the stone as well as promoting growth of other organisms through increased nitrogen availability [Winkler 1997].

#### *3.1.3 Fungi*

Fungi may appear in a range of colours (grey, green, black, and brown) often taking the form of furry spots or surface patches [Honeyborne 1990]. Fungi cannot produce their own food, so only appear on surfaces with organic food present. Fungi, although they produce organic acids while growing, do not cause serious damage to the stone. However, they disfigure and stain building façades and this would be reason enough for their removal.

#### *3.1.4 Lichens*

Lichens are a symbiotic intergrowth of algae and fungi. They may appear grey, green, orange, or yellow. They require light and mineral salts. Lichens do not like harmful urban environments and tend to be commonly found in rural areas. Lichens produce carbon dioxide which can react with calcium based substrates (limestone, lime render, some sandstones, and marble). Deposits below the surface (particularly in micro-porous stone) can restrict the ability of a stone to breathe leading to damage by surface spalling [Webster 1992].

### 3.2 Non-biological soiling

Non-biological soiling comprises airborne particulate matter deposited on the building façade such as soot, vehicle exhaust, and industrial emissions. Other non-biological soiling is due to soluble material from within the masonry drawn to the surface by evaporation. During this process mineralogical changes may take place within the stone and surface staining may result [Ashurst 1994].

#### *3.2.1 Atmospheric constituents and pollutants*

The atmosphere contains airborne particles which contaminate masonry. There are two key types of pollutants: naturally occurring particles (dust) and man-made pollutants (vehicle exhaust emissions, industrial chemical emissions, and soot). It can take as little as a year for a building exposed to the atmosphere to become soiled.

#### *3.2.2 Aerosols*

Aerosols can be both particulates and gaseous pollutants which are buoyant in air. The particulate matter of aerosols includes sulphates, chlorides, nitrates, ammonia, silicates, ions, soot, and hydrocarbons. By-products of fossil fuel combustion are also present and are among the finest constituents (particle diameter $\leq 0.1$ μm) in the air. Their deposition on stone can be wet or dry, with dry being the most common.

### *3.2.3 Soot*

Soot particles are more responsible for soiling of building façades than coarser particles. Their diameter ranges from 0.1 µm to 1 µm. The soiling is mainly due to dry deposition: wet soot deposition is of minor significance.

### *3.2.4 Particulates and other pollutants*

Larger particles deposited on the building surface do not remain there very long. However when present, sulphates may create soiling by reacting with constituents within the stone, such as iron.

## 4 FULL-SCALE TESTING: PRESSURE WATER CLEANING

Pressure water cleaning is the most common method used to clean stone buildings. While it is a cheap and easily realisable method, when used on buildings unable to resist the pressure, it can be one of the most damaging methods. Pressure water cleaning was carried out on a sandstone wall situated beside a moderately busy road. The masonry had a wide variety of soiling present and was ideal to establish the effects of pressure water cleaning on a range of soiling types. The soiling included black gypsum soiling almost uniformly across the wall, the continuity of this is a result of its being situated close to the road and being more exposed to soiling than masonry walls situated further up or away from traffic. Algae, lichen, and vegetation were also present.

The equipment used was a pressure washer limited to 12 $Nmm^{-2}$ with the working distance set to 300 mm: water was used at a lance pressure of 3.4 $Nmm^{-2}$. When cleaning over joints the lance should be aligned to ensure the water jet acting on the surface is perpendicular to the mortar joint. The risk of damaging the mortar is reduced as the severity of the cutting effect acting thereon is reduced [Campbell and Fairfield 2008]. The surface can be covered several times. If cleaning is not removing the soiling, avoid the temptation to reduce the working distance: the increased jetting force will give unreliable results as the relationship between cleansing power and working distance is non-linear. Covering the surface too many times can lead to its saturation. Notes should be taken on the effectiveness of the cleaning. Pre- and post-treatment photographs should be taken. These can be used to support notes taken on site, and give a visual impression of the extent of cleansing. To improve comparability of photographs, they should be taken from similar positions and in similar lighting conditions.

### 4.1 Results: pressure water cleaning

The pressure water cleaning was effective. Dirt and vegetation were removed; not all the lichens and embedded black gypsum were removed (Figs 1 to 4). Where the mortar was weak, pressure washing damaged it and the joints required re-pointing. This method was found to be cheap and effective in removing biological soiling.

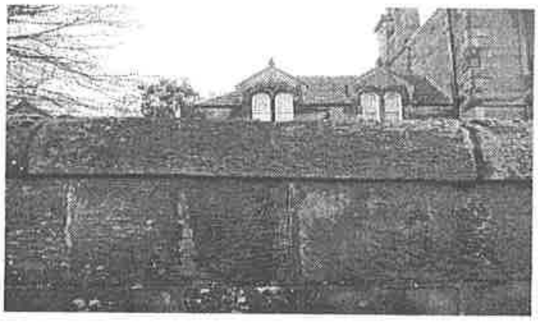

**Figure 1.** Algae and severe soiling on the external wall

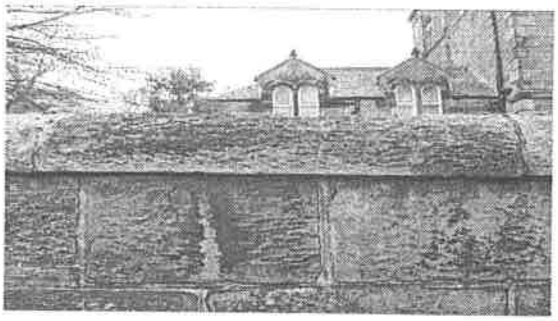

**Figure 2.** Algae removed: severe soiling remained

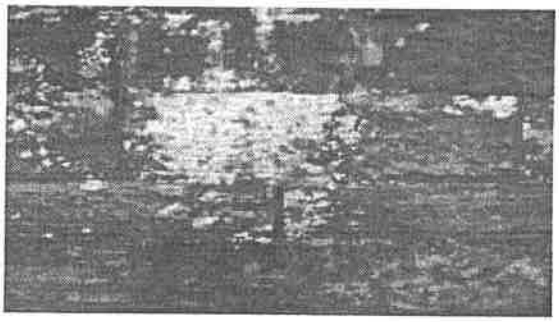

**Figure 3.** Lichens present on the wall before cleaning

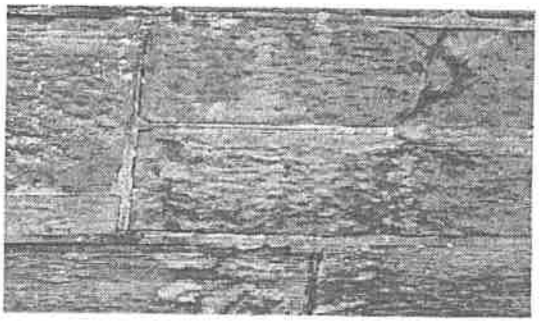

**Figure 4.** Traces of lichen remained after cleaning

### 4.2 Advantages and disadvantages: pressure water cleaning

Advantages:

- Quick removal of surface stains, loose surface debris, and biological soiling.
- May be used effectively in conjunction with chemical cleaning agents or abrasive materials.
- The amount of time spent scraping and scrubbing may be substantially reduced when appropriate rinsing pressures and water volumes are used.

Disadvantages:

- When used on its own, this method was generally not effective in removing severe staining.
- Very high water pressures and flow rates may have an abrasive effect and may damage the surface and increase masonry decay rates.
- Water-saturated masonry may take several weeks to dry thoroughly.
- Cleaning must be carried out when there is no threat of freezing temperatures.
- Excessive pressure can damage mortar joints and force water into the building's interior.
- Water runoff must be controlled to prevent intrusion into basement areas and surrounding properties.

## 5 FULL-SCALE TESTING: SANDBLASTING

The house cleaned was an occupied, listed, two storey sandstone masonry dwelling built in 1872. It was situated on a road and had trees and plant life around it. There were decorative features around the house such as three attractive balconies at the front of the building and two decorative pyramid-shaped sandstone windows. These pyramid-shaped windows had engravings showing fine architectural detail. The rear of the house comprised a massive wall with a number of windows placed therein and one bay window jutting out from the building. The masonry was solely sandstone and was in excellent condition. There was very little, if any decay, except for clearly visible soiling that had occurred on parts of the building. As the building was listed (although not in a conservation area) the owner needed permission to alter the façade's appearance.

The building had suffered general soiling by atmospheric pollutants, causing window sills and various features to become blackish in colour. The sills and bay window were the worst affected areas. The front of the building was on the roadside and was more susceptible to traffic pollution than the rear. The three balconies extending from the building were also more susceptible to rainfall and various airborne pollutants. Visual inspection showed that the three balconies were heavily soiled by various atmospheric pollutants such as soot and traffic fumes. The two pyramid windows were not as badly affected as the balconies but the decorative features on them were unclear from a distance because of this soiling.

The rear of the building was similar to the front in showing general soiling by atmospheric pollutants, causing the windows sills and other features to be rendered blackish in hue. At the rear there was a rain pipe, loose from the top near the roof which allowed the rainwater to leave staining down the full height of the façade. This caused drastic soiling which promoted the build-up of dense fungal and algal growths at the top of the rain pipe. The severity of fungal and algal contamination and allied staining decreased with distance down the façade.

### 5.1 Sandblasting: operational details

The following sandblasting equipment was used: water washer, air compressor (4.3 $m^3$/min), portable compressed air suction system, helmet with integral respirator, and a synthetic mineral abrasive available as either iron silicate or aluminium silicate with a grain size between 0.2 mm and 1.5 mm (JBlast Supa, supplied by Wolverhampton Abrasives Ltd). Scaffolding was erected to allow access to the full height of the façade. Before sandblasting started, windows and doors were covered with plastic sheeting, to prevent abrasive particles from damaging the windows and doors and entering the building. The operator was equipped with regulation personal protective equipment at all times. A small test patch was sandblasted to ascertain the correct air flow rate and abrasive content. Working top-down, rear to front of building, with a stand-off distance of *c.* 250 mm the operator sandblasted at a steady flow rate, trailing from left to right. On a wide open surface it was much easier for the operator to manoeuvre the gun and maintain the recommended 250 mm working distance. For less accessible regions, such as window sills, narrow strips between the bay window, and the balconies' architectural features, the pressure was greatly increased locally causing some areas to get more attention than others. A board was placed behind the balconies' architectural features to cause abrasive rebound and allow sandblasting of the otherwise inaccessible masonry. It is important to understand that a heavily soiled area does not need too much extra attention: if sandblasted for too long, damage can occur resulting in the stone acquiring an irreversibly burnt appearance.

It was particularly hard (even with an experienced operator) to cover the windows adequately: abrasive particles still managed to infiltrate the property necessitating the internal use of cloths around window frames as barriers. The sandblasting pot had to be filled periodically which slowed progress. Some blockages arose during sandblasting: these were resolved by adjusting the choke air valve and boosting airflow through the system to release the blockage. Blockages were caused by damp abrasive and accumulation of material. It may be the case that a water-repellent coating needs to be applied to the sandstone within 6 months of sandblasting to prevent a recurrence of the soiling. This is because sandblasting opens pores in the stones which make them more vulnerable to future attack. Expert consultation must be sought as water-repellent coatings are not universally recommended and with all such systems more harm than good may accrue if they are used unwisely.

### 5.2 Results: Sandblasting

During sandblasting, biological growths and some of the black soiling were removed; however, there were still large amounts of soiled material remaining encrusted in the masonry. The results of sandblasting are shown in Figs 5 to 10.

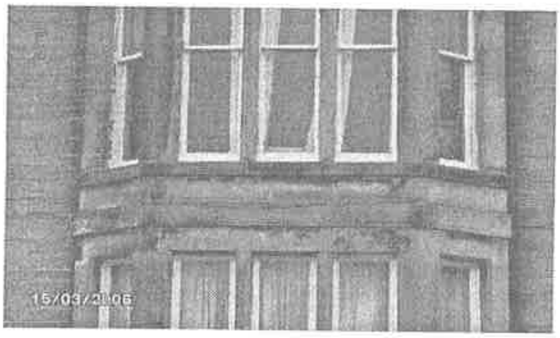

**Figure 5.** Soiled bay window

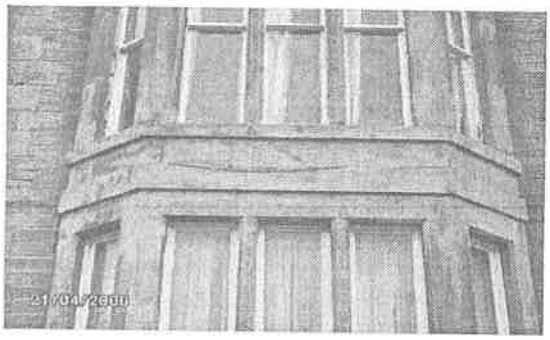

**Figure 6.** Sandblasted bay window

**Figure 7.** Soiled front balcony

**Figure 8.** Sandblasted front balcony

**Figure 9.** Soiled front window

**Figure 10.** Sandblasted front window

### 5.3 Advantages and disadvantages: sandblasting

Advantages:

- Effective at removing surface stains, loose surface debris, and biological soiling.
- Partially effective at removing black soiling from rough sandstones used in walls.
- More effective at removing black soiling from smooth and carved soft sandstones (*e.g.* on balconies, window sills and other features).
- Rapid operation.

Disadvantages:

- When used on its own, this method is not completely effective at removing severe staining.
- Experienced operatives are needed as over-sandblasting gives the stone an irreversibly burnt appearance.
- Sandblasting material consumables are expensive.
- Residual sandblasting material on green areas could harm surrounding vegetation.
- Difficulty covering doors and windows to prevent fines infiltrating the building or damaging glasswork.
- Sandblasting material should be completely dry to prevent blockages during cleaning.
- Periodic down-time required to refill the sandblasting pot and clear blockages.

## 6 CHEMICAL ANALYSIS

Energy dispersive X-ray analysis (EDXA) was used to give a detailed quantitative chemical analysis of the contaminated sandstone. EDXA was undertaken to determine which elements and hence compounds were contributing to the black soiling on the surface of the stones. A 20 mm _ 20 mm sandstone specimen was cut from the property and EDXA carried out on the surface and at 10 mm sub-surface. Thus a comparison between the chemicals present on the polluted surface and on the deeper, cleaner sandstone beneath was possible.

### 6.1 Results and discussion: EDX analysis

Figure 11 shows the typical EDXA results from both the surface (solid rendered plot) and 10 mm sub-surface (grey unshaded plot) analyses. As expected with sandstone the most dominant element present was silicon. The surface of the stone contained amounts of iron, carbon, and magnesium. The results suggested that the black coloured staining on the surface of the stone was non-biological and due to years of exposure to the environment, especially traffic and industrial airborne pollutants.

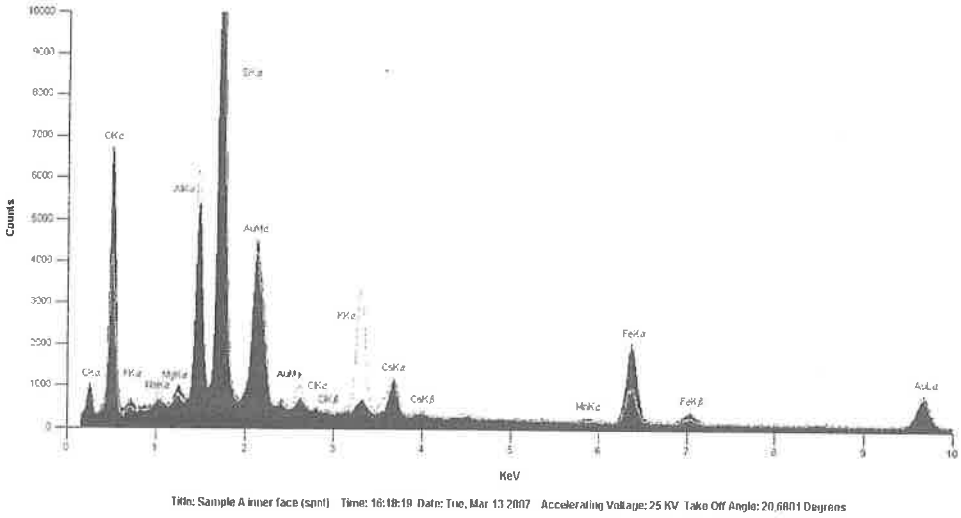


**Figure 11.** EDXA data from contaminated sandstone: surface (solid) and 10 mm sub-surface (grey)

Of interest, and as yet unexplained, is the potassium Kα transition observed in the sub-surface spot EDXA data at 3.3 keV which was barely present in the surface, more contaminated, sample. Also of note, is the presence of the contaminant elements in the sub-surface sample, albeit to a lesser extent, which would suggest prolonged exposure has allowed pollution to penetrate the sandstone to 10 mm depth.

### 6.2 Potential Future Analytical Developments

Linkage with other areas of research is mooted: microbiological and toxicological analyses of nanoparticles is an active field of work with potential collaborative effort applicable to stone masonry [Donaldson *et al.* 2005]. Computational fluid dynamics modelling to predict traffic pollution dispersal in urban environments [Addison *et al.* 1999] has been undertaken and is ripe for integration with the authors' field of research into its effects on masonry façades. High-pressure water jetting work on ceramic materials (initially applied to sewers by Fairfield [2008]) also overlaps with this topic: surface roughness profiling, scanning electron microscopy, and erosion damage rate predictions are all usefully transferable to this topic [Campbell 2008]. Recent problems in Edinburgh with sandstone decay [City of Edinburgh Council 2006] and the associated burden incumbent upon building surveyors, owners, the local authority, and engineering/building professions are bringing this research into context and indeed pushing it to the fore.

## 7. CONCLUSION

No single method proved to be the ideal cleaning method for the properties assessed as case studies here. Both water pressure washing and sandblasting have their advantages and disadvantages: these are evenly balanced in terms of both their number and technical implications. Future analysis is needed to verify the efficacy of each method at the microscopic level. Chemical methods of analysis are useful diagnostic tools for the classification of pollutant/contaminant types.

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