PREVENTION OF UNDERSIDE CORROSION OF LEAD USING CHALK RICH COATINGS

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ABSTRACT

Lead as a traditional roofing material has performed well and proved extremely durable in the past. This durability comes not from the metal itself but from the protective patina which forms when lead is exposed to the weather. However, corrosion of metal roofs from the underside, due to the presence of condensate and/or carboxylic acids, which attack the metal, remains a problem.

The problems were highlighted in the 1970s and 80s with the introduction of 'warm roofs' containing insulation. These allowed moisture to accumulate in the insulation and substructure by thermal pumping (the introduction of water by sub-atmospheric pressure variation). These problems were largely overcome with the introduction of the ventilated warm roof (VWR) in the mid-1980s. This design allows pressures to be equalised and any ingressed moisture to be removed by ventilation of the underside of the lead. However, in historic buildings the presence of ventilators on the apexes and eaves and the additional height of the roof (approximately 150mm) frequently exclude the use of the VWR design. In addition, for VWRs to be effective meticulous attention is required to the detailing and installation of the air and vapour control layer and the design has to provide effective through-ventilation.

The circumstances just described prompted the initiation of a research effort to investigate the problem and to seek ways to overcome this form of attack. A 3-year R&D programme was carried out by Rowan Technologies and funded by English Heritage, the Historic Royal Palaces and the Lead Sheet Association. The project objectives included an investigation of underside corrosion and ways to overcome this type of degradation.

The project work was extensive and subsequently a novel way was found to suppress underside corrosion. This comprised 'chalk rich coatings' which protect the underside of the lead. The initial system used a thick chalk slurry coating which was applied to the underside of the sheet and this resulted in the production of a patina, similar to that which eventually develops naturally on the topside of the lead. However, to provide effective protection, the chalk also has to remain in contact with the lead to allow the patina film to thicken.

A further advance was made in 2001 by combining the ‘active’ chalk powder with high-quality emulsion coatings; this greatly simplifies the application procedure and improved both the cohesion and adhesion of the chalk-rich coating to the lead. These protection procedures were tested in laboratory condensation rigs for six years and included on-site trials that have been on-test for up to ten years. The chalk emulsion protection system is now commonly used for replacement lead roofs, gutters and weatherings for historic buildings and also more modern constructions. This paper describes the development of these coatings and reports on their application.

INTRODUCTION

Underside corrosion of lead has been an undesirable phenomenon for many centuries but in the 1970s and 1980s it appeared to have increased [1, 2]. Investigations showed that one of the main causes of rapid underside corrosion was due to changes in installation practice, which caused moisture to become trapped in the substructure. In addition, the introduction of modern man-made boards, which emit carboxylic (acetic and formic) acids when damp, was also a major factor. However, underside corrosion has also been found in more traditionally constituted roofs. This may have been associated with improved surveillance of the roofs (quinquennial surveys) or alternatively, owners now expect lead roofs to perform to a higher standard.

Improved standards of insulation of buildings now enable roofs to operate at lower temperatures. This, combined with more extensive heating, has increased the risk of condensation [3]. If condensation or water ingress occurs, the cyclic condensation/re-evaporation of the trapped moisture results in underside corrosion. The corrosion problem is exacerbated when organic acids are present; as they frequently are in some timbers. Code 7 lead roofs normally last between 80 to 120 years (or in some instances 400 years if protected from solar radiation) and ultimately fail due to thermally induced fatigue (cracking) of the sheet. Underside corrosion results in thinning of the lead sheet and this, combined with thermally induced fatigue, may result in premature failure. In serious cases, the underside corrosion results in small holes, or blisters, appearing on the surface of the metal, resulting in lifetimes of 20 years or less.

The top surface of a lead roof is exposed to the elements and usually forms a protective grey surface layer of cerussite ($PbCO_3$), by reaction with carbon dioxide and moisture in the environment (patination). On the underside, and in the absence of a protective film, a white corrosion product, consisting mainly of hydrocerussite ($2PbCO_3. Pb(OH)_2$) is formed in the presence of moisture. This is a loose powdery or flaky layer, which is non-protective and allows further corrosion to occur on the lead substrate. In the presence of carboxylic acids, red and yellow lead oxides (PbO - Lithage and Massicote) and lead acetate and formate may also be formed. On-site tests have shown that once this corrosion reaction has become established it is not possible to reform the protective patina on the underside. Some on-going corrosion, in the presence of moisture, becomes inevitable.

LABORATORY TESTING

The results of the R&D programme were summarised in an Advice Note issued by English Heritage and the LSA in 1997 [4]. This outlined the early trials carried out using chalk slurry coatings to help protect the underside surface. It was well known that if new lead was left out in the open for a few weeks to weather to form the grey patina and this side was placed on the underside when installed on a roof, it resisted against underside corrosion for a while. However, this thin patina layer ultimately fails and underside corrosion has initiated on a number of these replacement roofs.

An early indication that a carbonate rich environment might be helpful came during an investigation of lead roofs at an English Heritage administered castle. Samples of old lead, which had been laid on concrete and were found to be continually wet underneath, showed a thick grey protective film and no underside corrosion. It was known that concrete 'carbonates' over its life and it was considered that this may have affected the lead. Reference was then made to the Pourbaix diagram for lead (pH vs corrosion for various environments) and this indicated that lead becomes passive when exposed to carbonate ions in the pH range 8 to 10, i.e. the same pH where one may expect ingressed rainwater to be in the presence of carbonated concrete (calcium carbonate). Note - fresh concrete contains calcium hydroxide which lies in a pH range 12 to 13; this causes severe corrosion of lead.

The carbonate ions react with bright lead in the presence of water to form the thin grey patina. This patina resisted against underside corrosion by films of water during simple condensation/re-evaporation tests carried out in condensation rigs in the laboratory. However, tests carried out in the presence of significant concentrations of carboxylic acids (as given off by damp acid-containing woods under cyclic conditions) showed that even this protective layer may eventually be degraded thus allowing underside corrosion to initiate. In practice, however, these severe environmental conditions in the presence of new English oak, Douglas fir or birch plywood are rarely encountered on-site and protection has been afforded to all replacement roofs to date.

ON-SITE APPLICATIONS

Site Tests Using Chalk Slurry

Two examples of the use of chalk slurry passivation procedures are given in this section although many more have been completed.

Village Church 1 The first replacement roof to use the chalk passivation treatment was a small village church near Cambridge in 1995. A fire in 1994 destroyed part of the south aisle roof. Approximately half of the roof was replaced in new English oak and the complete roof, comprising new and old oak rafters, had sand-cast code 7 lead installed. To avoid contact of lead on oak the architect had fitted softwood spacer battens over the oak boards and a softwood decking above. Being aware that acid vapours could cause corrosion, even if the lead was not in direct contact, he used the chalk slurry method to protect the lead.

Plain building paper was laid over the softwood decking in order to control air and vapour movement. A geotextile layer was then laid over the building paper to even out the substrate, provide a slip layer and to provide retention of a reasonable quantity of chalk slurry on the slope. A thick chalk slurry coating was applied over the geotextile to a thickness of some 3mm using a plaster's float. Finally, a thin painted chalk slurry coating was applied to the underside of the lead after it had been formed to shape and before final fixing.

A number of inspections have been carried out since this time. To date, the chalked areas of the roof have been found to be free from underside corrosion, Figure 1. Underside corrosion was noticed in some areas of the rolls and the laps where chalk slurry had been deliberately avoided (to inhibit capillary rise of rainwater into the roof). However, some of the dried chalk powder had fallen down the underside slope and had become lodged in the laps; this had drawn in some rainwater by capillary suction in the lower corners. Despite local moisture levels of up to 27% in the wood, the chalk protection system had succeeded in stopping corrosion on this roof. Note - moisture levels above 21% are normally sufficient to initiate corrosion on unchalked lead roofs.

The Great Hall The lead roof on the Great Hall of this palace was replaced in 1998. The previous roof had been subject to significant underside corrosion, which had resulted in thinning and finally thermal fatigue of the lead sheets. This had allowed further rainwater into the roof, which had exacerbated the problem.

The previous lead roof had been laid in the 1950s on hardboard over bitumen-cored building paper over oak boarding and was thought to date from the late nineteenth century. New oak boarding is well known for emitting carboxylic acids. The problem is exacerbated when moisture is present (from condensation or rainwater ingress) and even old and established oak boards are capable of emitting sufficient carboxylic acids to corrode through code 7 lead sheet within 20 to 30 years in damp conditions. The Great Hall was heated by hot water pipes laid under the floor; this had resulted in ground moisture being driven into the building. The hardboard itself (containing adhesives) was a source of organic acids and acted as a reservoir for acids emitted from the oak, so exacerbating the corrosion problem. In addition, the bituminous building paper layer traps moisture in the hardboard.

A revised specification was developed for the replacement lead roof to help protect the lead against the environmental conditions: Softwood boards of 26mm thick were laid over the oak boards. A plain reinforced building paper was used as a slip layer between the lead and the softwood. This allowed the roof to breathe while controlling the diffusion of air. The underside of the replacement lead was treated with two applications of chalk slurry which were allowed to dry. (The R&D project had previously found that any carboxylic acids emitted from the boards could react directly with chalk in the presence of moisture, thus neutralising the acids). Sand cast lead was used, the rough side of which helps adhesion of the chalk. Note, to suppress capillary rise of rainwater into the roof the application of the chalk was restricted to: 1) just over the top of the laps 2) up to the 12 o'clock position of the batten roll.

The underside of the replacement roof was inspected after 5 years. On lifting the lead sheets some of the dry chalk powder dropped off the back of the lead and fell into the gutter. Some of the chalk powder was brushed off the lead sheet to reveal the normal grey protective patina, i.e. similar to that formed on the topside of lead, Figure 2. The non-chalked areas in the laps and the rolls showed significant amounts of both white (hydrocerussite) and red (lithage) corrosion products indicating that this roof structure was still capable of inducing significant rates of corrosion.

Site Tests Using Chalk Enriched Emulsions

Owing to the poor adhesion of dry chalk layers and its ability to draw-up rainwater into the roof, more-adhesive and cohesive emulsion paint coatings were developed and tested in collaboration with ICI/Dulux. The commercial emulsions already contain small amounts of chalk and these were increased to levels of between 50 and 70%. Other additions were made to the emulsion to improve the application process and the binding of the chalk particles to the lead surface. A variety of different test coatings were evaluated in a series of accelerated laboratory and site corrosion trials over approximately two years. They performed as well as the chalk slurry coatings, but were significantly easier and quicker to apply and remained in place during final bossing and periodic inspections. The other advantage of the chalk emulsions is that they can be built up to form thick layers – if required. This may be needed if the previous roof has been subject to severe underside corrosion. The best chalk emulsion combination from the extensive laboratory tests was selected for site trials.

Village Church 2 This historic church, near Oxford, had a bitumen felt roof which had failed. The roof contained large oak beams and boarding. The architect had initially intended to fit a new VWR roof to the nave, although this was ultimately ruled out because of the resulting increased roof height. It was therefore decided to use a traditional non-ventilated roof with a chalk enriched emulsion coating to protect it from underside corrosion.

During installation, the sand cast lead was typically bossed into shape but then lifted and the chalk emulsion applied to the underside, to cover the top of the laps and the top position of the roll, Figure 3. When dry, the lead was re-fitted to the roof.

The roof was installed in January 2000. The lead workers found the application of the chalk enriched emulsion relatively simple and reported no major problems. The chalk emulsion took between 2 and 6 hours to dry although they found that pre-heating the lead reduced the dry-out time. The work was carried out on a batch basis by making up and coating four bays at a time.

Cathedral Cloister Roofs This cathedral in Norfolk had suffered severe underside corrosion of its cloister roofs and had been the catalyst for the R&D effort in the 1990s. These lead roofs date from 1958 and had exhibited underside corrosion and perforation of the code 7 lead sheet within 20 years. These had been patched up using lead sheet and even these patches had shown perforation by the 1990s.

The lead had been laid over oak boards with a bitumen underlay. Moisture had entered into the roof releasing carboxylic acids from the oak, which had then become trapped between the lead and the underlay. Cyclic condensation/ re-evaporation of the acid laden moisture had resulted in severe corrosion.

The roofs were replaced between 2001 and 2002 and two coats of the chalk enriched emulsion were used to protect the new lead. These roofs were inspected after two years and the coated surfaces were found to have adequately protected the lead, Figure 4. Note – the chalk enriched emulsion is supplied with a green tint to differentiate it from the white lead corrosion product. Again, the laps were found to have suffered some underside corrosion indicating that these roofs were still corrosive to unprotected lead.

Cathedral Aisle Roofs This large cathedral, in Wiltshire, was extensively re-roofed in the period 1998 to 2002. Some of the roofs were laid directly over new Douglas fir, a wood that is well known for emitting carboxylic acids. Although the original lead roofs had not been subject to underside corrosion, due to the buffering effect of the large volume of air within the cathedral roof spaces, the new boards were fairly damp and it was decided to use the new chalk enhanced emulsion over the replacement boards on the aisle in 2000.

An inspection of the roofs in 2002 showed that the chalk emulsion had effectively adhered to the underside lead surface and no underside corrosion was found. One area of lead had been left uncoated as a test comparison; this now showed a fine white bloom where underside corrosion had initiated. This appeared to have stopped. Underside corrosion is not normally a major problem in large cathedral roof spaces, however, the presence of lead corrosion products in historic buildings should generally be avoided.

DISCUSSION

The use of chalk rich coatings to help protect lead from underside corrosion has been demonstrated both in the laboratory, during full scale trials and on replacement lead roofs. The chalk layer is not 'barrier coating' and freely allow moisture to reach the lead substrate; this results in thickening of the protective patina layer. This layer is identical to that found naturally over the 'carbonated' concrete at the English Heritage administered castle. Chalk slurry is an economical method of preventing underside corrosion. The drawbacks are that the dry chalk layer may easily become detached from the lead and therefore may not provide long-term protection and, if rainwater comes into contact with the dry chalk layer, it may be wicked into the roof.

The chalk enriched emulsion overcomes the problems of the chalk slurry treatment. The adhesion of the dried chalk emulsion to the lead is vastly improved, allowing the sheet to be bossed and welded into place after the coating has been applied. The improved cohesion vastly reduces the capillary rise of rainwater thus enabling most of the lap and roll areas to be protected. In addition, if underside corrosion has been a problem in the past, then applying further coats can increase the thickness of the chalk layer to give long term protection. The time requirement to coat the individual sheets is only a matter of minutes and dry-out time can be improved by pre-heating the lead. Five litres of the chalk emulsion is normally sufficient to cover between 22 to 26 square metres of lead.

Porous underlays, such as plain building papers or 'water resistant' geotextiles are recommended for replacement lead roofs. These allow internal moisture to pass through the roof structure and be vented through the laps and rolls. Impervious underlays, such as bitumen containing building papers, can allow moisture to be trapped between the lead and the underlayer. However, even in this situation the chalk emulsion protects against corrosion.

A dilute chalk application can also be successful for the topside of lead to improve initial passivation and give a uniform appearance to new lead roofs. The chalk application may also have some benefit for reducing ‘lead run-off’ from flashings and weatherings; this sometimes results in staining of tiles and slates by the white hydrocerussite corrosion products.

CONCLUSIONS

1. Chalk powder, in the presence of water, reacts with lead to pre-form the normal grey patina on lead sheet and provides significantly improved protection from underside corrosion. This is similar to that formed on the topside of lead by the reaction of carbon dioxide and rainwater, i.e. the normal weathering process.

2. Chalk underside treatments have prevented underside corrosion on all replacement roofs to date although cyclic laboratory tests, involving severe environmental conditions in the presence of significant concentrations of carboxylic acids, have shown that neutralisation of the chalk and breakdown of the coating is possible.

3. The chalk may be applied either as a slurry or as a chalk-enriched emulsion coating. Rowan Technologies now supply the optimised chalk emulsion for use by lead contractors. This was developed in collaboration with English Heritage and uses high-quality Dulux emulsion paints which have been extensively tested both in the laboratory and on-site.

4. The chalk systems were originally developed for traditional non-ventilated roofs where corrosion has previously been found or where the risk of it occurring is significant. It is also applicable to more modern roofs where lead may be laid over man-made boards and which have the potential to emit carboxylic acids if they become damp or other situations were there is a risk of corrosion.

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While offered in good faith, this paper represents the views of the author only and no liability will be admitted for problems arising from the use of this information herein out of context.

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Figure 1. Village Church 1. View of the thick chalk layer floated onto the geotextile underlayer

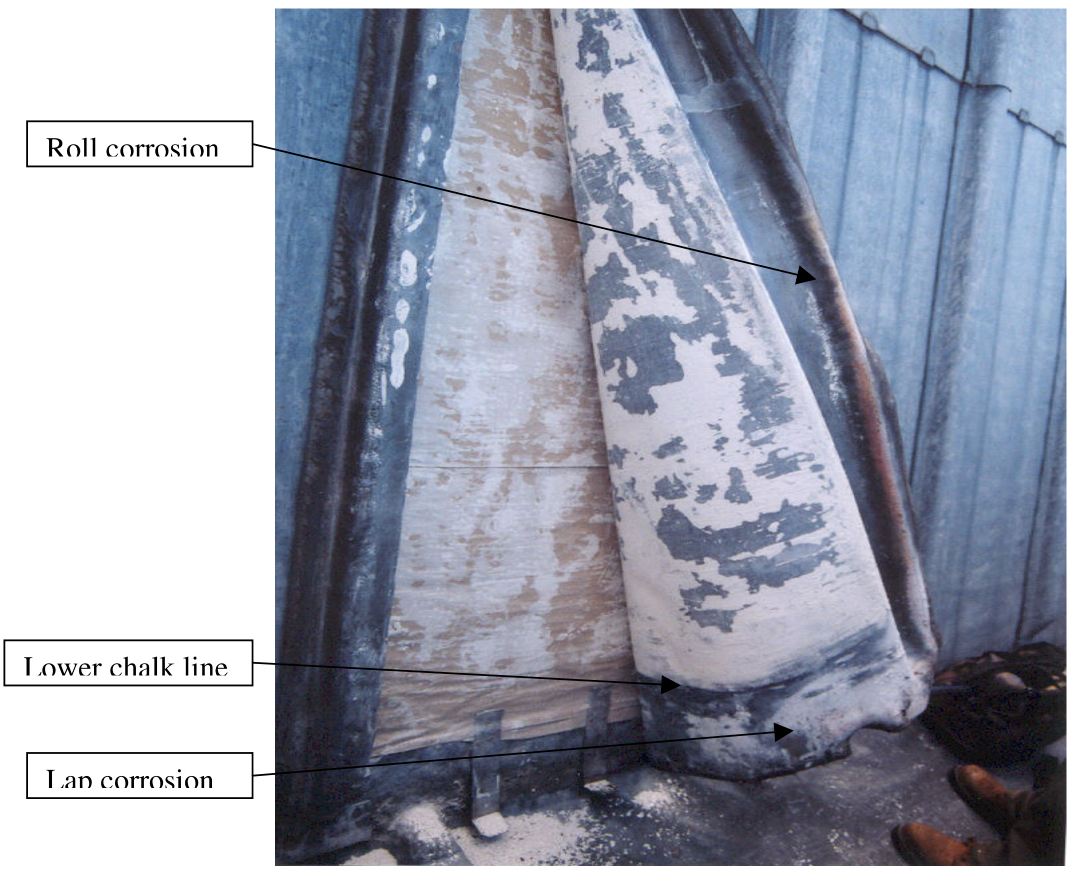

Figure 2. The Great Hall. View of the thinner chalk protection coating in combination with plain building paper. Note exfoliation of the dry chalk.

Figure 3. Village Church 2 View of the batch application of the chalk emulsion coating on the underside of the sand cast lead.

Figure 4. Cathedral Cloister Roof View of the chalk enriched emulsion coating – note white corrosion initiating in the laps.