Lime mortar repair of historical buildings construction essay

Environment, Air

Purpose of this paper – This study was performed in order to understand what work has been completed regarding how lime mortar repair is carried out on historic buildings and why lime is used.

Methodology/scope – Journal articles and books were studied in order to understand the level of work that has so far been completed.

Findings – It was found that

Research limitations – There is a large amount of published work on this topic, consequently not all of the relevant articles and studies could be read for inclusion into the literature review. However it is thought that the important details and findings are included.

Practical implications –

Value –

Keywords – mortars, lime, refurbishment, historic buildings, maintenance.

INTRODUCTION

The use of building limes as the principal component in mortars and renders has increased considerably over the past five to ten years. This traditional

basic material is fundamentally important to the long term survival of historic buildings, yet there are many who regard its' use with doubt, appropriate perhaps for a National Trust property but generally unnecessary. When we consider that nearly all the churches, abbeys, cathedrals, castles, stately homes and half the building stock in the U. K. was built with lime, including the now famous Coronation Street, it is hardly surprising that the use of lime is fast coming back.

This literature review is intended to synthesise published information regarding research carried out into lime mortar and its use in historic buildings. The emphasis in this document is on the analysis of the demands of building conservation activities, their relationship with and influence on the choice and application of technical and scientific measures needed to fulfill these demands.

Lime

Lime is the traditional, ancient binding medium of masonry (Ashurst, 1997). Lime is produced by burning limestone (calcium carbonate). This produces calcium oxide (otherwise known as quick lime) and this is then hydrated with water to produce calcium hydroxide (lime). This process is known as slaking. According to Taylor (2000), ‘ if no clay is present in the original limestone or chalk, the resulting lime is said to be non-hydraulic’. Non-hydraulic limes set by reacting with carbon dioxide to form calcium carbonate, they will stiffen and eventually harden.

Lime otherwise know as calcium hydroxide, has its own classification system which was developed by Louis Vicat – a French civil engineer who researched hydraulic limes and cements. He classified limes according to their hydraulicity, which is their ability to set under water. The classes he identified consist of: non-hydraulic to feebly hydraulic lime, feebly to moderately hydraulic lime and moderately to eminently hydraulic lime. The hydraulicity of the lime depends on the amount of impurities present in the limestone from which it is burnt such as clay and silica. The more clay and silica which is present, the greater the hydraulicity of the lime. In general the more hydraulic the lime the harder the resulting mortar (Pavia and Bolton, 2000) and the shorter the setting period. This will affect where the mortar can be used on the building.

Mortars

There are various definitions on what a mortar is, the most detailed being from the RILEM Technical Committee-167 COM (2001). It states that: ' Mortar is a mix of organic and inorganic binders, mainly fine aggregates, water and admixtures and organic and inorganic additives mixed in order to give to the fresh mortar a good workability and to the hardened mortar adequate physical (porosity, vapour permeability etc.) and mechanical (strength, deformability, adhesion etc.) behaviour and good appearance and durability. This definition is the most relevant for mortars in historic buildings as it is based on recent research into requirements for a compatible mortar used for conservation of masonry.

Functions of mortar

The UK Limes research team (2003) state the three principal functions of a mortar are to provide an even bed so that the load on the wall is distributed evenly over the whole bearing area of the masonry units, to bond the units together and help them resist lateral forces and to seal the joints against the penetration of rain. Mortars in historic structures function in many different ways as renders on internal and external walls, bedding mortar of masonry, supporting material for pavements and mosaics, and watertight lining materials in cisterns, wells, aqueducts etc…(Moropoulou et al. 2000). Ashurst (1983) states that mortars can be used in the following conservation techniques: pointing, repointing, rough racking, tamping, bedding, replacement of masonry units, internal and external coating – plasters, renders and their repair, plastic repair, injection and grouting.

Why use lime mortars?

According to the Northern Ireland Environment Agency (2009) in their work practice guidelines for remedial conservation works, lime mortar is the most important material to be used in remedial conservation works on historic structures. This is because it is water permeable and also allows for movement within the joints of the building. Given that there is continual movement in the cracks of an historic building which have a seasonal envelope this is a necessity. When movement is cumulative in one direction it is making a significant deformation. Accordingly, the more elastic materials are, the more likely they are to be compatible with the structure as a whole (Feilden 2003).

Traditional lime mortars are more permeable and more flexible than cement mortars, they are less likely to cause decay in adjacent stone and they are more environmentally friendly than cement mortars (Gibbons 2003). This permeability of lime mortar meant that these traditional buildings did not require a damp proof course. The permeability of the lime mortar allowed evaporation of rising and penetrating damp from the building.

Fortunately most walls constructed before 1914 were set in lime mortar, which can accommodate considerable amounts of movement without cracking due to creep, whereas more modern walls require the frequent provision of movement-joints (Richardson 2006). The problem arises however where these walls and building are repaired and refurbished using a material other than what was there originally.

What is wrong with using cement mortar?

After the invention of Portland cement during the 19th and early 20th centuries research has concentrated mainly on its development and this new modern way of building. Cement mortars were considered better, stronger, more durable and with a more reliable hardening process than lime mortars. Approximately from the First World War onwards cement rich mortars and renders were used in the repair and restoration of historic buildings (Burman 1998), where they had most often not been part of the original fabric. It was only after serious failures, where inappropriate use of the cement mortars damaged the valuable original masonry, that a growing interest in lime-based mortars reappeared. However the advent of Portland cement as the dominant mortar binder during the 20th century, resulted in all research efforts being focused away from lime mortars and particularly its use in building conservation.

This was redressed partly by events like the publication of the Venice Charter (1964) that was approved during the 2nd International Congress of Architects and Technicians of Historic Monuments held in Venice that year.

Although it did not affect directly the use of mortars, it set out conservation and restoration principals that supported scientific research to underpin better conservation of the architectural heritage.

There is nothing wrong with using a cement mortar as long as it is not on a traditional building which was originally constructed using lime mortar.

Cement pointing is hard and rigid compared to lime pointing's soft and flexible nature.

Repair of historic buildings & compatibility

The most effective methods of repairing and maintaining traditional masonry buildings almost invariably involve the use of materials and techniques employed in their original construction. This is based on conservation principles such as the BURRA charter (1999). The BURRA charter states that the conservation policy of the building should identify the most appropriate way of caring for the fabric. Stirling, S (2002) also argues that the repair must be compatible with the original construction, its life span, and follow the principles of good conservation practice. The BURRA charter prefers traditional techniques and materials for the conservation of historic buildings. However Pickard (1996) has a more relaxed view of conservation, he feels that new materials and methods of repair can merit consideration if they have proved themselves over time and also if the benefit of using them outweighs any harm that they could cause to the building. The repair techniques should respect the original material and structures otherwise they become incompatible (Binda et al. 2000).

Understanding of material interaction with other materials and environments is much more significant for materials used in the modern building industry. The materials and techniques used in conservation must meet special requirements such as compatibility, reversibility, etc.

Van Hees (2000) suggested a definition of compatibility related directly to mortars as follows: “ The new mortar should be as durable as possible, without (directly or indirectly) causing damage to the original material.”

There are still mortars currently applied in remedial conservation works which can cause damage or accelerate deterioration to the historic substrate.

Mortars in historic buildings

The majority of mortars in historic buildings are made from lime. Lime mortar has been used in Ireland from when early Christian churches were built and more commonly from when round towers were built (Pavia and Bolton 2000). Lime mortar technology arrived relatively late in Ireland (Dotter et al, 2009) since its use has been known since Egyptian times when both lime and gypsum based mortars were used in the building of the pyramids. The path of introduction of mortar technology to Ireland is unclear, though according to Pavia and Bolton (2000) the general hypothesis is that it was introduced from post-Roman Britain or Western Europe. The use of lime mortar was mastered by the day to day practice of craftsmen in prehistoric and medieval times more or less following the rules set by Vitruvius in his classic work ‘ Ten books on Architecture’. Their use was complemented much later on by experimental research results from the end of the 18th century by Smeaton (1793) or Vicat (1837). Historic Scotland (Gibbons 1995) published a Technical Advice Note which revived the subject of the Use of Lime mortars. It especially stressed the use of non-hydraulic lime mortars made of lime putty. The publication became an authoritative source of information for preparation of lime mortars used in conservation. However, the variety of composition, techniques of production and application of mortar should not be underestimated. Lynch (1998) pointed out that historic mortars were not only mortars made of lime putty or 1: 3 mix. The source of limestone and the local source of sand had an influence on its composition as well as the differences in mixing and preparation. There is now increasing evidence that hot mixing and dry mixing (Leslie and Gibbons 2000, Callebaut et al. 2000, Hughes et al. 2001) techniques were also applied to prepare many historic mortars. Hydraulic lime mortars were also used, especially in towns and cities. In areas devoid of natural hydraulic limes, ‘ artifical’ hydraulic limes were utilized, being non-hydraulic lime mixed with a pozzolana (Lynch, 1998).

Furlan (1991) pointed out that the research into lime mortars has multiplied during the last two decades. Many publications suggest that new mortars for any remedial work on historic masonry should be based on the approach that pure lime mortars prepared in a traditional way show the closest performance properties to the historic masonry (e. g. Torraca, 1988). Conservation literature in many cases (e. g. Gibbons, 1995) simplifies the problem of compatibility as the decision to use lime-based mortar instead of cement mortar. This results from bad experiences of using cement mortars in the past. When assessing past conservation attempts the two following points often appear:

Firstly the lime technology and skills were partially forgotten (Gibbons, 1995)

Secondly portland cement suspended lime because of its superiority in strength (Gibbons 1995) but other qualities of lime mortar were not properly considered.

Correct application of lime mortar requires special training and care to be successful (Maxwell 1998, Gibbons 1995). Although the use of cement-based mortars was widespread. Their compatibility was not considered and they were often found later to be incompatable with the orginal masonry material. There is general agreement between scientific and conservation literature regarding these two points. A serious study of the use of cement mortar and the decay of stone and brick is still lacking, so statements regarding the incompatibility of cement and its rejection by the conservation practitioners are not backed by detailed evidence.

Limited research

Research into mortar and concrete based on Portland cement appears much more advanced than that on lime (e. g. Hewlett 1998). The research reflects the use of cement and concrete in the modern building industry. This point illustrates the fact that there are no international lime oriented research journals, some national journals exist, e. g. The Journal of the Building Limes

Forum. Research articles about lime and lime mortars are often found in journals oriented towards mainly concrete and cement such as Cement and Concrete Research, Concrete International, Materials and Structures, Magazine of Concrete Research, Construction and Building Research, Brick News, Magazine of Masonry Constructions, Masonry International, etc. In future it may appear that a lack of exact scientific knowledge of lime and lime mortars will be the greatest drawback in its proper use as a compatible material. A more detailed understanding of fundamental properties of new lime mortars is therefore required to back up the demands from conservation practice to use original materials for conservation works (Furlan 1991, Valek 2000).

Addition of brick dust

Addition of brick dust into lime mortars can improve their strength and durability. The results from the Smeaton Project (Teutonico 1994) suggested that the clay type and its firing temperature are the factors which affect the performance of mortars. Hughes and Sugden (2000) followed this research in experimental work on hydraulic lime mortars. The authors concluded that the fineness of the brick dust and the curing conditions are the most relevant parameters to be altered in order to maximize improvement in strength. Papayianni and Theocharidou (1993) concluded that the addition of brick dust contributes to strength but it also lowers the capillary rise rate. It could also increase the water retentiveness of mortars (Papayianni and Theocharidou 1993).

Ageing of lime putty

The effect of ageing on lime putty was studied by Hansen et al. (2000). The authors measured consistency and workability of an aged lime putty and flow of a mortar mix made of the aged putty. They concluded that the aged putty (16 years) performed better due to the reduction of lime particles in size with ageing. The water retention, consistency and flow tests implied that water absorbed in the older lime putty was harder to remove by mechanical action in comparison with the younger putty (2 years). However, ageing alone may be insufficient to ensure improvement for certain types of lime. Factors such as limestone source, buring temperature, particle reactivity and slaking conditions can influence the size of crystals and affect the ageing characteristics of lime putty (Hansen et al.).

Thomson (2000) used a surface area test to compare particle sizes of dolomitic hydrates and putties, high calcium putty and a high calcium hydrate. The lime putty made in the lab possessed very small particles. Thomson (2000) concluded that in this case a further reduction of the particles was very unlikely and therefore the ageing of lime putty to reduce the particles in size may not be completely relevant. According to Thomson (2000) the maturing of lime putty provides mainly a completion of the slaking process.

Carbonation of lime mortars

Carbonation of non-hydraulic lime mortars is considered to be the most important process of hardening and it has a direct influence on durability and strength of the mortar. Carbonation of new lime mortar can take several months, but there are also examples when carbonation of a mortar inside masonry took more than several hundred years (Hosek and Muk 1989).

Hughes et al. (1998) suggested that the factors that affect initial carbonation and hardening in the short term might have less influence on the durability and physical properties of historic mortars in the long term. Calcium carbonate is soluble and when water is present the carbonated particles can be dissolved, changing the pore structure and strength of a mortar. When mortar carbonates, it gains mass and its porosity decreases (Parrot 1991-1992). However, in a longer term, porosity can increase due to the dissolution of calcium carbonate, mechanical deterioration, micro cracks caused by load, salt and frost attacks. As a result of this the strength and other properties of mortars vary significantly depending on ageing conditions. In Ireland there are examples of very friable mortars as well as very hard and dense mortars both made from non-hydraulic lime but exposed to different environmental conditions (Hughes 1998). Some of these relatively hard and strong mortars have a very high porosity.

During the initial hardening of mortars the rate of carbonation depends on the mortar surface finish and its permeability (Valek at al 2000). Carbonation can be slowed down by a reduction of permeability and diffusivity. Such reduction may occur due to a reduction of pore sizes induced by a progression of the carbonation inwards from the surface (Hilsdorf et al. no date) and inhibiting CO2 entering deeper into the mortar.

Strength

According to Hosek and Muk (1989) the strength of non-hydraulic mortars is gained from three processes.

Drying of lime mortars

A long-term dissolution of silicia in the alkaline environment of calcium hydroxide and consequent formation of solid phases of calcium sililcate

Carbonation of lime mortars.

In general carbonation is considered to have the biggest influence on strength development. However, this requires deeper studies, as the main influence on strength seems to differ depending on the ageing stages and the curing conditions. The initial stage of hardening seems to be more influenced by the drying out process than carbonation (Valek and Bartos 2001).

Schafer and Hilsdorf (1993) tried to relate type of binder, binder-aggregate proportion and porosity in order to indirectly estimate compressive strength and elastic modulus of historic mortars. The authors introduced a formula to calculate the strength purely from results of chemical and visual analysis.

Suter and Song (1995) pointed out that when describing strength of historic mortars it is important to perform a relevant test rather than rely on the wide range of data presented in publications. A great variety of mortars with various proportions of binder and aggregate have been reported in literature

(Suter and Song 1995). However the size and number of samples available from historic masonry restricts the mechanical testing. Often non-destructive, ‘ in-situ’ testing is necessary for testing mortars within historic masonry.

Testing standard specimens of a new mortar may not correspond to the characteristics of mortars from within masonry. Henzel and Karl (1987) demonstrated that strength obtained from standard laboratory specimens was lower than that obtained from a normal mortar joint. The mortar from within masonry was subjected to various influential factors which affected its properties.

Bond between lime mortar and masonry

The bond between mortar and masonry is important for both stress strain transmission and durability. If the bond is poor, water can penetrate much more easily inside masonry and cause degradation. This applies to bedding mortar but also to plasters and renders.

It is possible that lime can penetrate into bricks and carbonate in their pores, therefore creating a physical adhension between the mortar and brick (Armelao et al 2000). Similar observation was presented earlier by Baronio and Binda (1987) who studied a mortar-brick interface on samples of historic and modern mortars. The authors noticed that the extent and conditions of a lime-based mortar/brick contact was better than the one of a cement-based mortar as the lime penetrates to the open porosity of the bricks. Cement based mortars presented long narrow voids on the contact with bricks.

Durability of mortars

The most common causes of degradation are frost and sulphate attack. Both cause internal deterioration through an expansion in the pore structure of mortars. The causes and effects of weathering in porous materials used in buildings have been widely described in literature (Torraca 1988).

Waldum and Anda (2000) studies degradation of lime render sample panels. The authors pointed out general implications that non-hydraulic lime mortars do not have a good reputation in terms of their durability in freeze/thaw and salt deterioration. From their measurement the authors observed that the beginning of the degradation process correlates with an increase in the concentration of calcium in run-off water. They did not observe any salt degradation as the freeze/thaw was too dominating.

The Smeaton Project (Teutonico 1994) concluded that small quantities of cement in mortar mixes with cement content less than 1: 3: 12 (cement: lime: sand) had a negative effect on their strength and durability. A similar conclusion was reached by Holmstrom (1995) who stated that the durability of lime mortars gauged with cement decreased, even in comparison to lime based mortars, if the proportion of added cement is less than 40-50% in weight to the lime. This may be related to salt deterioration, as even small quantities of cement increase the salinity of mortars (Papayianni and Theocharidou 1993).

Lime mortars & conservation

Practical experience gained from conservation projects is a valuable source of knowledge about performance and behavior of mortars. ‘ Hands on’ experience is highly valued in conservation and practical experience is considered to be particularly useful for the design of a compatible mortar. A review of contemporary practice of using lime mortars in conservation was presented at Historic Scotland’s International Lime Conference (Ward and Maxwell 1995).

Lime based mortars are good examples of a traditional material used in conservation, where good skills and practical experience have a significant influence on performance. Burman (1995) described the advantages of using lime in various conservation techniques and the successful revival of lime into wider conservation practice. For traditional lime mortars, often the conservation technique, good site practice, workmanship and skills are considered to be the key instruments for their successful application (Gibbons 1995, Johnston 1995). Many failures of lime mortars are caused by their inappropriate use or by a lack of practice and training in their correct application (Gibbons, 1995).

The most basic specifications for new mortars are from practical building and masonry conservation guides (e. g. Stone buildings by Pat McAfee 1998). The usual advice is to carry out basic analysis to obtain the composition of the mortar (usually by dissolving the mortar in acid) in the first instance. If the original mortar has performed well then the new mortar mix should resemble it as closely as possible. It is advised that the new mortar should be softer than the stone. Ashurst (1990) in the ‘ English Heritage Technical Handbook’ specifies that the original aggregate should be copied, however the mix may need to be modified to improve the weathering characteristics. Milner (1972) points out that natural materials should be used to match the colour and texture. He also suggested that soft mortars should not be used for repairs on buildings originally constructed with hard mortar.

The basic specifications for mortar required by conservation practice can be summarised as follows:

The formula of the new mortar should match that of the original one

The new mortar should be softer than the original mortar or masonry but, on the hand, the mortar should not be too soft if the original masonry was constructed with hard mortar.

Under no circumstances should the new mortar cause deterioration to the existing material

Side effects and long-term effects caused by repair should also be considered

Holmstrom (1992) presented a list of compatibility criteria for lime mortar renders used by contractors in Sweden:

Materials and components used must be removable, and must not change the physical or chemical balance of the building and must not change the aesthetics.

Each layer of mortar should be weaker than the substrate.

Materials with the same properties as the original should be used. If the original materials are not used, this must be justified and all relevant properties of the original and the substitute must be declared.

These suggestions support minimum intervention and the preservation of existing historic fabric. In addition Holmstrom’s (1992) criteria emphasise the need for reversibility of the material applied. The final point makes demands for analysis of historic mortars in order to formulate compatible replacements that resemble the original. Basic performance testing and in-situ trials are common and recommended. There is less demand however for testing and characterizing the new mortar properties, as it is a copy of the original one and therefore it is assumed to perform in the same way. This may not always be correct. Valek (2000) discussed a compatibility model for two mortars, one designed on a ‘ like to like’ basis and one on a ‘ compatible properties’ basis. The performance of both mortars relied strongly on the curing and ageing conditions. However, the curing conditions of the new mortar may not match the ones of the past.

Analysis of the original mortar

The analysis of historic mortars is carried out broadly for two reasons (Hughes and Callebaut 2000):

For specific conservation and repair related investigations, looking to select replacement materials and/or determine the cause of evident problems in the deterioration of a historic building to allow the formulation of conservation and repair strategies.

Academic studies looking to clarify the architectural, chemical and physical performance of historic mortars for the development of replacement materials or the archaeological study of building technology and its associated social implications.

British Standards BS 4551: Part 2: 1998 " Methods of testing mortars, screeds and plasters" sets guidelines for the sampling of hardened mortars. This standard is aimed primarily at the characterization of mortar in more modern buildilnbgs, but the approach is applicable to older historic buildings. When sampling masonry mortar the whole thickness through the wall should be sampled, requiring the removl of masonry units, something not always feasible with a historic building.

Ashurst 1998 states that the samples taken " should be the minimum necessary to gain the required information without doing damage to the historic structure". Technically taking any sample is doing damage but this needs to be considered against the benefits gained by sampling and gaining additional information through analysis. Ashurst goes on to specify that sampling must be performed by someone familiar with the building, and that the analyst should also be informed. The sample itself should be of at least 50g and in a coherent lump. The location of the sample must be precisely recorded and sufficient sample must be taken in order to ensure some form of representative analysis.

Ashurst (1998) and Hughes and Callebaut (2000), emphasise the usefulness of first performing an on-site visual analysis of mortars before physical sampling. A good idea of the general components of the mortar can be derived by an experienced person using a low level of optical magnification. Binder, aggregate and other inclusions, including particular mortar additioves can be recorded in this way. Ashurst (1998) goes on to say that gentle scraping to remove weathered surfaces to improve identification of the components. This analysis will also clarify the method of construction and the profile of the joint, as well as highlighting any repointing or other later repairs. Groot et al. (2000) suggests that features such as the number and thickness of coats or applications of bedding mortar or renders, the presence of cavities, fractures and cracks within the binder, the presence of hair and other additives and the distribution of lime lumps can be observed. The general type of binder and the nature and size of the aggregate will be identified.

Methods of mortar analysis

Acid dissolution and wet chemical analysis

The simplest form of mortar analysis involves the separation of the aggregate from the binder to determine their relative proportions to allow a replacement mortar to be formulated. This form of analysis also allows the qualitative determination of the type of binder and the characteristics of the aggregate or other additives. The carbonate binder can be dissolved from the aggregate by the use of a dilute acid, most commonly Hydrochloric Acid (HCL). The main limitation of this technique is that if carbonate aggregate is present in a mortar then it will be dissolved along with the binder (Ashurst

1998, Leslie and Gibbons 2000). Ashurst (1998) gives a simple procedure that can be followed. It is often possible to get a good though not exact idea of the degree of hydraulicity of a mortar, and the presense of cement and the use of admixtures and pozzolanas using acid dissolution combined with careful visual analysis before and after.

The use of dissolution analysis also leads on to the further application of standard chemical analysis techniques. As the binder is put into solution this makes it open to to instrumental chemical analysis. The soluble silica content can be determined, which is related to the hydraulicity of the mortar (van Balen et al 2000).

Optical miscroscopy/petrographic analysis

The use of optical microscopy is a powerful technique for the investigation of the components of historic lime mortars. After sampling mortar is cut, mounted onto a glass slide and ground to a thickness of 30/1000 of a millimeter. This forms a thin-section that permits the transmission of light through the components of the mortar. This is best performed on sound samples of mortars that preserve the full texture of the original material. The thin section can be examined using a petrographic, polarizing, microscope. The composite of the mortar can then be documented.

The petrographic examination of historic mortars has lagged behind that for conc