PROPERTIES OF HYDRAULIC AND NON-HYDRAULIC LIMES FOR USE IN CONSTRUCTION

By

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DECLARATION

This thesis is submitted to Napier University, Edinburgh for the Degree of Doctor of Philosophy. The work described in this thesis was carried out under the supervision of Dr. Fouad M. Khalaf and Dr. Abdi Kermani. The work was undertaken in the School of Built Environment, Napier University.

In accordance with Napier University regulations the Degree of Doctor of Philosophy, the candidate submits this thesis as his own original research unless otherwise stated. During this period of research four papers have been written, presented, displayed as posters or in the process of being published.

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ABSTRACT

The term "lime" comes from the word limestone. Limestone rocks were converted to lime powder by burning (calcining). The process of converting limestone to lime was an old process and it has been well documented, archaeologically. It has been established that the production of lime is the oldest industrial process carried out by humankind, dating back thousands of years. In fact, 3650 years ago Moses instructed the people of Israel, after they crossed the Jordan River, to set up large stones and whitewash them with lime and write the laws of God in lime.

Lime was the most commonly used cementatious binder until about a century ago, when its use started to decline. It was replaced by Portland cement, a material essentially developed for structural purposes in the era of the industrial revolution. Portland cement has certain advantages over lime. The material develops strength and hardens faster for work to be carried out at a greater pace with better quality control and agreed standards. It has now become the dominant cementitious binder, part of it due to aggressive marketing of the material by the manufacturers. The use of Portland cement in the restoration and conservation of old buildings and structures in the UK over the past few years has resulted in a series of problems and cost millions of Pounds to eradicate.

The decline in the use of lime in many countries has not only caused a diminution of its production, but has also contributed to a gradual disappearance of the traditional skills required both to produce a high quality product and to use it in construction. Therefore it is necessary to reintroduce and revive the old tradition

of using lime by providing more information about its production and use.

At present there are no comprehensive standards or code of practices, British or European to aid engineers and contractors in the use of hydraulic and non hydraulic limes in construction. BS EN 459 (2001) gives guidance on the chemical and physical properties of limes but it does not provide vital information about lime-based mortars e.g. mix proportions, mixing process, bond with masonry units, curing methods and all other necessary aspects to assess in the use of the material in construction. At present it is very easy for engineers, contractors and consultants to misuse lime mortars in new construction or in restoration and conservation of old buildings. Part of the decline in production of lime and reluctance of use in construction is due to the lack of understanding of the material properties and its performance in structures. Therefore it is necessary to examine and revive the old tradition in using lime mortars in construction and look at the new technologies used presently in the production process in order to provide the necessary background and information to aid the use of the material.

The present study provides a literature review, test results, discussions, conclusions and background information to set up standards in the production and use of hydraulic and non-hydraulic limes and their mortars in the construction of new buildings and the restoration and conservation of old buildings. Hydraulic and non-hydraulic limes have an excellent track record in buildings through history but their use in the UK was missed for some thirty years or more. Part of the reason for undertaking this research programme was to examine the properties of pre-packaged hydraulic limes available in the market at

present. The properties of limes vary considerably dependent on the raw materials, composition and manufacturing process. The results of this study showed that there was a great variation in the properties and performance of limes and their mortars. The results also showed that the properties of lime mortar improved by adding different percentages of Portland cement.

The research examined the effect of sand grading on the lime mortars compressive, splitting and brick/mortar bond strength. The thesis also investigated the effects of using different casting moulds and curing methods on mortar strength. The results showed that the porosity of lime mortar was one of the reasons it was a success in the past and why it was so important nowadays to use it in the restoration and conservation of historic buildings.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

Lime is one of the country's principal traditional building materials. Yet, for well over a century, cement, gypsum and alternative modern materials have overshadowed its manufacture and use. In more recent years there has been a renewal of interest in the use of lime particularly for the conservation of historic buildings.

Building lime has been used as a binder for thousands of years, due to its unique setting properties, colour and exceptional smoothness. Its versatility is shown by the wide variety of uses in buildings. There is a wide variety of limes that might be produced from different materials and with various production methods. This research project is concerned mainly with the use of hydraulic lime, in which there are two main processes, hydration and carbonation. With regards to hydraulic lime the mortar cannot carbonate until it has hydrated. This will be explained later in Section 2.6.

Structural elements, for which lime mixes may be used, are foundations, walls, floors, vaults and roofs. Lime is also used for many finishes including paints, plasters, renders and decorative work such as cornices and hand-modelled stucco.

However, in general the building industry has a distinct lack of understanding of this traditional building material and how it can be used. Fortunately, this issue has been tackled and more people are being educated and trained in the use of lime.

The successful use of lime in construction depends on the craftsman's knowledge and skills, indeed, the same might be said of many other materials. Lime is a soft and forgiving material, which amply rewards care and patience in its use and produces work with great aesthetic quality. The craftsman will learn to recognize and select sound and appropriate materials to ensure the best results. There is no substitute for skill and experience, but these can be developed in a short space of time provided that the appropriate knowledge is available.

This issue of appropriate education and training of work in the use of lime is part of an overall requirement for a better and wider understanding of this traditional building material. Given the financial and environmental cost of new building construction, the existing resource of traditionally constructed buildings is not one that can be afforded to be thrown away or lost, through damaging and inappropriate repairs.

In restoring old masonry stonework and brickwork it is imperative that the chosen repair material maintains the integrity of the original construction. Old masonry work tends to be soft and permeable; therefore they should not be bedded with strong mortars, which will cause the masonry to crack if there is any movement.

There are many advantages of using lime mortars rather than cement mortars in the construction of new masonry buildings. The use of lime mortars have the advantage of accommodating any movement in a building without any major cracks, as stated above, but that is only scraping the surface of the advantages of lime. Others include the ability to reclaim the masonry units from the lime mortar and using them again (sustainability). Thermal movement can be accommodated without damage, walls can breathe better and moisture can evaporate. Lime mortars can be very durable and give good workability, which will make the craftsman life easier. The masonry life is increased due to some of these factors.

Against this background it was recognised that information and practical research are needed as problems exist as at present there are little or few standards available in aiding engineers and others in the use of lime.

In the present study, a literature review on lime and lime mortar was compiled on past and recent papers and books. Many different lime mortar aspects were investigated, this includes: types of lime, adding cement to lime, sand grading, type of casting moulds, different ratios and methods of curing … etc.

The study presented herein provides additional information to confirm, extend or adapt existing theory and procedures. The main objectives and scope of this study are outlined as follows:

1. To review current knowledge on limes in general and hydraulic limes in particular, their production and use in construction. The review also covers the history of lime and how it was used before the intervention of cement.

2. To review previous experience in the use of lime, hydraulic lime and their mortars in the UK and in other countries, which use the material regularly and have a better experience and knowledge.

3. To identify any obstacles in using limes and their mortars in the UK, review the effects of using cement on stone and brickwork and in general look at the advantages and disadvantages associated with using lime, hydraulic lime and their mortars in construction.

4. To review current knowledge on natural building stone. Formation, kinds, properties … etc. The review also looks at the effects of weathering, climate changes and pollution on stonework masonry walls and the methods used for cleaning.

5. To compare the properties of different hydraulic limes from around Europe.

6. To determine the physical and mechanical properties of hydraulic lime mortars and compare some of these values with cement mortars.

7. To examine the addition of different percentages of Portland cement to lime to investigate the effects on the resulting mortar.

8. To examine the effects of using different methods of curing on the properties of lime mortars.

9. To develop an easy test to determine the porosity of lime mortars and natural building stones.

The structure of the thesis can be summarised as follows:

Chapter 1 Introduction, scope and aim of the present investigation.

Chapter 2 Literature review of previous investigations into the use of hydraulic lime, background knowledge of lime and aspects of lime in building.

Chapter 3 An introduction and description into natural building stone and their properties.

Chapter 4 An introduction into stone cleaning, including methods used and problems involved.

Chapter 5 The experimental procedures including materials used, sample preparation and test procedures.

Chapter 6 An experimental and theoretical investigation to determine and study the properties of hydraulic lime and its mortar.

Chapter 7 A general summary and conclusion with recommendations for further research.

Glossary List of the technical and special words related to subject of the present study.

References List of books and technical papers related to the subject.

Appendix A Tables showing results of all tests carried out to determine materials properties and strength.

Appendix B Complete results and list of standards for using lime – Athens and Venice charter.

Appendix C Published work and posters from the present investigation.

CHAPTER 2

LITERATURE REVIEW

2.1 HISTORY OF LIME

Lime was one of the oldest chemicals recorded and the process of lime burning was one of the oldest manufacturing industries. Lime was discovered soon after man learned to make fire and used stone for building hearths and fireplaces. Primitive kilns discovered by archaeologists are believed to have been used during the Stone Age for burning lime. It was speculated that early man found their slabs of limestone, used them as fireplaces, turning into white putty after a heavy rain. The first step in the lime cycle was limestone burning followed by the slaking of the resultant quicklime by rain. Although its valuable properties were probably wasted by primitive man, they were brought into use in connection with the erection of buildings later (Historic Scotland 1995; Historic Scotland 1994).

The first documented use of lime was in Egypt when it was used as a mortar and a plaster in the great pyramids. Lime, still in good condition, has been found in Egyptian pyramids built over 4500 years ago. The pyramids themselves were built largely of limestone (Historic Scotland 1996).

However, the Romans made the most significant contribution to the development of lime by the discovery of hydraulic lime. They found that by mixing quicklime with pozzolans and aggregate the mixture would set underwater. They mainly used volcanic ash as the pozzolans to create a hydraulic set. These mortars were intended to be used in applications where water was present. Examples of these types of applications included cisterns, fishponds, and aqueducts. Vitruvius, a

Roman architect, provided basic guidelines for lime mortar mixes: "... When it (the lime) was slaked, let it be mingled with the sand in such a way that if it was pit sand three of sand and one of lime was poured in; but if the same was from the river or sea, two of sand and one of lime was thrown together. For in this way there will be the right proportion of the mixture and blending" (Historic Scotland 1995).

The most significant developments in the use of pozzolans in mortars occurred in the 18^{th} century. It was discovered that burning limestone containing clays would produce a hydraulic product. In 1756, James Smeaton developed perhaps the first hydraulic lime product by calcining Blue Lias limestone containing clay. An Italian pozzolanic earth from Civita Vecchia was also added to provide additional strength. This mortar mixture was used to build the Eddystone Lighthouse. James Parker patented a product called Roman cement or natural cement in 1796. The product produced by burning a mixture of limestone and clay together in kilns similar to those used to produce cement. The resulting product was ground and stored in waterproof containers. Typically cements had higher clay contents than hydraulic lime products which allowed for better strength development. Cement mortar was used in construction where masonry was subjected to moisture and high levels of strength were needed (English Heritage 1994).

Until the 1940's lime remained the principle binder for mortars, particularly in rural areas, despite the growth in cement as a binder since its discovery at the turn of the century. The desire for speed, the employment of less knowledgeable artisans and aggressive marketing by the cement companies, contributed to the decline in the use of lime as a mortar and its relevant traditional techniques (Historic Scotland 1995; Allwinkle and Khalaf 1996).

Thirty years ago the use of lime as a building material had virtually ceased. However, hydrated lime would be added to cement mortar mixes to improve their workability, the whole tradition of using lime properly had more or less died out after thousands of years of use as a building material for walls, floors, ceilings and decorations (Historic Scotland 1995). Cement seemed easy, quick and relatively trouble free. Cement mortars and renders could be relied on to set hard and without delay and buildings were put together at faster rates. Ever since the Industrial Revolution had created the demand for huge numbers of urban buildings, the use of lime had been in steady decline.

Modern buildings were made of hard, impermeable materials, so hard and impermeable mortars, renders and plasters were well suited to them. Crumbly, soft and flexible old buildings were invariably given the cement treatment, hard pointing, thick renders and for the inside, gypsum plaster and emulsion paint covered over uneven walls and damp patches. It all seemed so easy and straightforward. Older builders vaguely remembered the days of lime pits, nailing up wooden laths and grinding their own paint. Now almost everything came ready-mixed in bags, tubs or sheets and the main skills required were those of producing smooth surfaces, sharp corners and waterproof details (Historic Scotland 1995; Historic Scotland 1996).

2.2 SOURCES OF LIME

Lime originates from limestone, a common sedimentary rock composed primarily of the mineral calcite ($CaCO_3$). Limestone constitutes approximately 10% of the sedimentary rocks exposed on the Earth's surface. It forms either by direct crystallisation from water (usually seawater) or by accumulation of shell and shell fragments (Fig. 2.1). Limestone usually forms in shallow water less than 20m deep and thus provides important geological information on the variation in sea level in the past (McDonald 1991).

The principal component of limestone was the mineral calcite, but limestone frequently contains the minerals dolomite and aragonite. Pure calcite, dolomite and aragonite are clear or white. However, with impurities, they can take a variety of colours. Consequently, limestone is commonly light coloured; usually it is tan or grey. However, limestone has been found in almost every colour. The colour was due to impurities such as sand, clay, iron oxides, hydroxides and organic materials (McDonald 1991).

Fig. 2.1 – Fossil showing decayed sea-life

All limestone forms from the precipitation of calcium carbonate from water. Calcium carbonate leaves the solutions in many different ways to precipitate, and each way produces a different kind of limestone. All the different ways can be classified into two major groups: either with or without the aid of a living organism.

Most limestone was formed with the help of living organisms. Many marine organisms extract calcium carbonate from seawater to make shells or bones. Mussels, clams, oysters and corals are some of these living marine organisms. So too do microscopic organisms such as foraminifera. When the organisms die their shells and bones settle to the seafloor and accumulate. Wave action may break the shells and bones into smaller fragments, forming a carbonate sand or mud. Over millions of years, these sediments of shells, sand and mud harden into limestone. Coquina was a type of limestone containing large fragments of shell and coral. Chalk was a type of limestone formed of shells of microscopic animals (Historic Scotland 1995; McDonald 1991).

Limestone can also be formed without the aid of living organisms. If water containing calcium carbonate was evaporated, the calcium carbonate was left behind and crystallises out of the solution. For example, at Mammoth Hot Springs in Yellowstone National Park (Kruse 1997), hot water containing calcium carbonate emerges from deep underground. As the hot water evaporates and cools, it can no longer hold all of the calcium carbonate dissolved in it and some crystallises out, forming limestone terraces. Limestone formed from springs were called travertine. Calcium carbonate also precipitates in shallow tropical seas and lagoons where high temperatures cause seawater to evaporate to form limestone called oolite. Calcium carbonate that precipitates from water dripping through caves was responsible for the formation of beautiful cave features such as stalactites and stalagmites (Allwinkle and Khalaf 1996).

Diagenesis was the name for those processes that affect sediment after it was deposited and prior to any metamorphism. Two processes of diagenesis are important in the formation of limestone. One was cementation, in which calcium carbonate precipitates in the pore space between the loose grains of sediment and binds them together into a hard compact rock (McDonald 1991). The second process involves the alteration of the minerals in the limestone. When calcium carbonate precipitates, it can form two different minerals called calcite and aragonite. Calcite and aragonite are polymorphs, meaning that they have the same chemical composition, but the atoms are stacked differently in the crystal. Fresh calcium carbonate sediments sometimes contain calcite or aragonite but often they contain a mixture of the two. As some animals make shells of calcite while others make shells of aragonite. Similarly, the direct precipitation of calcium carbonate without the aid of organisms sometimes produces calcite or aragonite but often produces a mixture of the two, depending on factors such as temperature and pressure. However, calcite was more stable than aragonite and by the process of diagenesis the aragonite slowly changes to calcite. In addition, calcite slowly absorbs magnesium from surrounding water, slowly changing to dolomite (McDonald 1991).

However the percentage of silica and alumina contained in the limestone will alter a number of lime mortar characteristic, such as setting time, strength, colour, durability, frost resistance and workability (Historic Scotland 1995).

Limestone (Fig. 2.2) was an important building stone in many parts of the World. It was normally quarried from surface outcrops. Limestone was used as cut stone for building, and was common throughout Europe in cathedrals and palaces where the relatively soft nature of the stone allows decorative carving. Limestone was widely used as crushed stone or aggregate, for general building purposes, roadbeds and railway lines. Crushed limestone was also used as filler in industrial products such as asphalt, rubber, plastic and fertilisers. When heated the calcium carbonate in limestone decomposes to lime or calcium oxide and was important as a flux in smelting copper and lead ore and in making iron and steel. Lime was a key ingredient in the manufacture of cement and concrete (McDonald 1991).

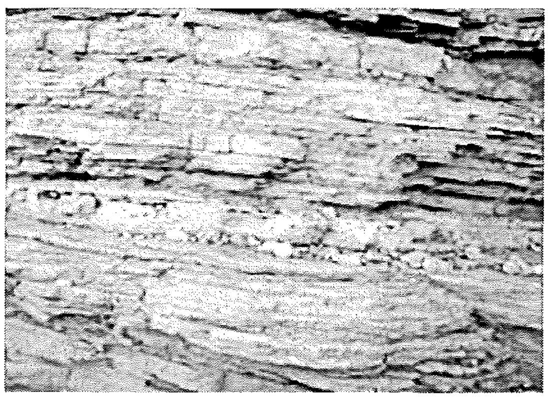


Fig. 2.2 - Limestone rocks

2.3 LIMESTONE IN SCOTLAND

The basic raw material for making lime was limestone or any other material containing a high proportion of calcium carbonate ($CaCO_3$), such as chalk, marble, shells, coral and marl ... etc. Within the complex geology of Scotland, limestone or more accurately calcareous rocks occur in the majority of geological formations. Carboniferous limestone occurs in Southern Scotland, the Midland Valley extending as far north as the Highland Boundary Fault and the Great Glen Fault. Cambrian limestone was found in the North and Northwest Highlands, with metamorphic limestone occurring in Shetland. Various types of less significant deposits also occur. These include shell sands on some Western and Northern beaches.

Within each of the divisions, the chemical characteristics of the limestone vary between geological beds and within individual beds. This has produced many limes with different chemical properties and impurities. These impurities give rise to the variety of types of lime of differing quality and characteristics. Higher calcium limestone were at least 95% pure calcium carbonate and can produce high quality lime. Argellaceous limestone contains clay in various proportions and produce limes with hydraulic properties. Poor limestone contains a quantity of inert non-calcareous material which does not contribute to the production of lime and tend to produce smaller quantities and 'leaner' lime. Magnesium limestone contains a proportion of magnesium carbonate and produce magnesium and calcium carbonates, it was known as dolomitic limestone (Robertson 1989).

2.4 CHARACTERISTICS OF LIME

Although each lime was different, and some may perform in very special ways, there are certain characteristics, which are typical of most limes and set apart from other binders such as cement, gypsum or clay (Alvarez, Bello, Bernal & Lanas 2004).

2.4.1 Stickiness

The root meaning of the word lime was "sticky material". It binds gently, and sticks to give good adhesion to other surfaces (Dean 1996).

2.4.2 Workability

Workability was easier to feel than to describe. It was the ability of a mortar or a plaster to remain smooth and mouldable even against the suction it may experience from other porous building materials. These aspects depend on the plasticity and water retention of the mortar. The mix can penetrate and fills voids in a background to give a good key. Less workable mixes would become stiff and awkward as the water was sucked away from them. Good workability greatly assists good workmanship, helping to achieve full joints with good bonding to the other materials. This was what makes lime-based mixes such a pleasure to use (Historic Scotland 1995).

2.4.3 Soft texture

This contributes to the comfortable feel and charming appearance of lime surfaces. It also helps lime to cushion the joints between stones or bricks and prolong their life (www.buildingconservation.com 1998-2005).

2.4.4 Durability

Lime was exceptionally durable material. An outstanding example was the Pantheon Temple in Rome (Fig. 2.3), which has a lime concrete dome spanning over 43m. This has survived for nearly nineteen hundred years (English Heritage 1994).

Fig. 2.3 - Interior of the Pantheon in Rome

2.4.5 Breathability (high porosity and high permeability)

This group of characteristics allows lime mortars to protect the other materials in a building by handling moisture movements through the building, protecting masonry materials from harmful salts. Breathability greatly assists the drying out of buildings and the avoidance of condensation problems, which contributes to the comfort of people using the buildings. This property depends on the high porosity and permeability characteristics of lime mortars (Historic Scotland 1995;

Allwinkle and Khalaf 1996).

2.4.6 Low thermal conductivity

This property affects the surface temperatures of buildings, making lime plasters in cool climates feel warmer to the touch than cement plasters. The higher surface temperatures contribute to a feeling of comfort.

2.4.7 Autogenous healing

When buildings made with lime are subjected to small movements they are more likely to develop many fine cracks than the individual large cracks which occur in stiffer cement-bound buildings. Water penetration into these fine cracks can dissolve free lime and bring it to the surface. As the water evaporated, the lime was deposited and would heal the cracks. That was how some old buildings on poor foundations distort rather than fail life (www.buildingconservation.com 1998-2005; Anagnostopoulos and Augostinos 2002).

2.4.8 Protection

In many ways soft lime mortars and paints can be used to give protection to buildings, particularly from severe rain. They can act sacrificially to protect the structure. Further information on the protection aspects of lime can be found in Section 2.9.

2.5 TYPES OF LIME

The type of lime available was dependent on the composition of the limestone from which it was produced and, to a certain extent, on the techniques of production. There are four types of lime:

2.5.1 Hydraulic limes

The term "hydraulic lime" covers materials that vary in properties such as setting times and strength development, but they are never to be thought of or used as a cement substitute. Hydraulic limes are characterised by good workability, low shrinkage, salt and frost resistance, adequate compressive and good flexural strength.

The properties of hydraulic lime are influenced by the existence of certain impurities and by the methods of burning and slaking. If clays or other suitably reactive forms of silicates and aluminates are present in the original limestone the resulting lime will have hydraulic properties, i.e. it will have some ability to set in wet conditions. Based on work by Vicat in 1837 the French classify hydraulic lime in three categories, these are: feebly, moderately and eminently hydraulic limes (Vicat 1837).

Feebly hydraulic lime: Normally contains 12% reactive clay. The putty will set like soft soap between 1 and 6 months, and the material can be knocked up for re-use.

Moderately hydraulic lime: Normally contains 12% to 18% reactive clay. The putty will set like hard soap within 1 month, but can still be knocked up for re-use.

Eminently hydraulic lime: Normally contains 18% to 25% reactive clay. The putty will set hard in less than a week.

Generally speaking the more hydraulic the lime the harder and more impervious will be the resulting mortar (Historic Scotland 1995; Dean 1996). However, care should be taken to match the properties of the mortar to the characteristics of the stone as well as to the degree of exposure on site.

2.5.2 Non-hydraulic limes

Non-hydraulic limes are derived from limestone which does not contain clay or other reactive silicates. The best and purest forms of non-hydraulic limes are made from limestone containing very high proportions of calcium carbonate. These limes are also known as "high-calcium" limes and used in the traditional basis of fat lime putty for plastering of buildings under favourable conditions and for working with soft sandstone or brick (Historic Scotland 1995; Dean 1996).

Non-hydraulic limes rely for their hardening on drying and on absorption of carbon dioxide. The resultant gradual conversion of calcium hydroxide to calcium carbonate requires an optimum balance of moisture and temperature, and may take many years to complete. In the right conditions non-hydraulic mortars may continue to develop strength over a period of many years (Historic Scotland 1995; Dean 1996).

2.5.3 Magnesian lime

Magnesian lime was derived from limestone containing a combination of calcium carbonate and magnesian carbonate. Where the raw material consists of double carbonate of calcium and magnesium the material was known as dolomite and the resulting lime was dolomitic lime. Magnesian limestone and dolomite occur in some areas of Scotland. Traditionally magnesian and dolomitic limes required longer slaking and maturing times than pure calcium limes. Magnesian limes are not currently produced commercially in the UK (Historic Scotland 1995; Dean 1996).

2.5.4 Selenitic lime

Another variety of lime used historically was known as selenitic lime. This was made by incorporating calcium sulphate into the material, either by introducing sulphur dioxide into the kiln during limeburning or by adding sulphuric acid to the slaking water or by the addition of gypsum to a feebly hydraulic lime and grinding the mixture. The calcium sulphate promoted a rapid set and increased the strength of the mortar. Unfortunately it can result in stone decay in situations where any remaining free calcium sulphate, which was more readily soluble than calcium carbonate, was transferred to adjoining stones. Selenitic limes are not readily differentiated from pure calcium limes except by chemical analysis (Historic Scotland 1995; Dean 1996).

2.6 STRENGTH DEVELOPMENT

There are two strength development processes that hydraulic lime mortar has to go through for its hardening. These are hydration and carbonation.

2.6.1 Hydration

In the presence of water, the silicates and aluminates of the lime form products of hydration or hydrates, which in time produce a firm and hard mass of hydrated lime. As stated in Section 2.5, the two calcium silicates are the main hydraulic compounds in lime, the former hydrating much more rapidly than the latter. The hardening of a lime through hydration will be more rapid than that of the carbonation process which will continue for month's even years after the hardening of the lime by hydration has ceased.

2.6.2 Carbonation

The hardening of lime by the carbonation process transpires in two stages. Firstly, the excess water in the mortar escapes and secondly, the carbon dioxide (CO_2) reacts with the slaked lime ($Ca(OH)_2$) and change it to limestone ($CaCO_3$). The latter process was called carbonation, which turns the lime mortar to a stronger substance, not soluble in water. The carbon dioxide (CO_2) was of course present in the atmosphere but it was not high in percentages: about 0.03% by volume in rural air areas, 0.1% or more in an unventilated laboratory and up to 0.3% in large cities (Brooks and Neville 1983). The little amount of CO_2 has to reach the inner pores of the lime mortar for increased carbonation.

Carbonation proceeds from the surface of the mortar inwards. This was a slow and continuos process strengthening the mortar over many years. The actual rate of carbonation depends on the permeability of the mortar, its moisture content and on the slacked lime in dry conditions. For the reaction to occur carbon dioxide (CO_2) has to be dissolved in water first. Yet, when completely soaked in water, it cannot react due to the absence of carbon dioxide (CO_2) in water (Historic Scotland 1996).

There was no visible change in the mortar when carbonation takes place. It can be tested by applying phenolphthalein to freshly carbonated mortar. If the lime has not fully carbonated, its high alkalinity produces a sharp red colour.

2.7 CHEMICAL PROCESS

The lime cycle was the fundamental reason why lime can be used as a binder. In this cycle the lime goes through a series of changes and returns back to its original form. There are three main stages in the lime cycle: burning, slaking and setting (hardening). Fig. 2.4 shows a diagram representing the lime cycle.

2.7.1 Limestone burning

The first step in the preparations of lime was the burning of limestone in a kiln. The temperature required to start the decomposition of the carbonate was 700°C. To achieve the process in a reasonable time the temperature normally used is higher than 700°C and would be nearer to 900°C (Historic Scotland Vol. 4 1996).

The "burning" has the effect of displacing a molecule of carbon dioxide from calcium carbonate, this leaves calcium oxide (quicklime). The burning reaction was as follows:

$$CaCO_3 + \text{Heat} \longrightarrow CaO + CO_2$$

$CaCO_3$		CaO	CO_2
Calcium carbonate Limestone		Calcium oxide Quicklime	Carbon dioxide

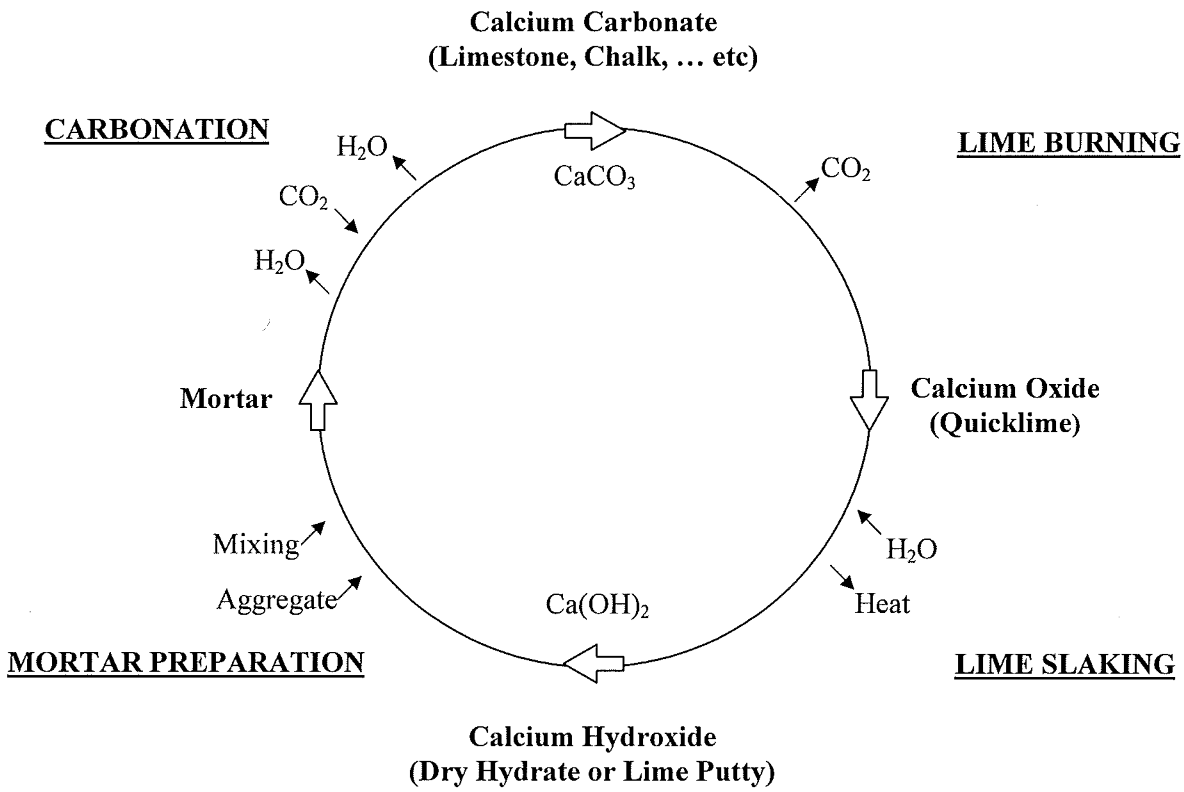


Fig. 2.4 - The lime cycle

Older furnaces in most cases had irregular distributions of temperature inside, even with the best experience some of the limestone remained unburnt and some overburnt. The unburnt limestone formed compact beads of sintered calcium oxide that later would react very sluggishly with water in slaking. Some calcium oxide at the mortar core may survive. The overburnt lime constitutes a dormant danger because their hydration results in a sudden expansion.

After the slaking process, sieving of the material could eliminate both the underburnt and the overburnt lime and could yield a high quality material. Although, modern quicklime manufactured in kilns provide an excellent temperature control and produce a more reliable material (Historic Scotland 1996).

2.7.2 Slaking

The controlled process of combining quicklime with water was known as slaking. Quicklime was so called because of its fast reaction with water. In the slaking process a large amount of heat was developed. The slaking of quicklime was a dangerous operation as the reaction of the calcium oxide with water was violent. If there was little amount of water in the presence of a large amount of lime, the heat evolved may bring the mixture rapidly above the boiling point and cause eruptions of caustic sprays of lime and limewater. The slaking reaction was as follows:

$$\underset{\text{Calcium oxide (Quicklime)}}{CaO} + \underset{\text{Water}}{H_2O} \longrightarrow \underset{\text{Calcium hydroxide (Hydrated lime)}}{Ca(OH)_2} + \text{Heat}$$

The traditional method of lime slaking was to mix the water and the quicklime in a long tub or bath. The process had a long pause as it was believed that a prolonged permanence under water improved considerably the performance of the lime.

A good plasticity allows the mixing of lime with sand (or other aggregates) with the addition of a minimum amount of water. The plasticity of lime mortar was the main requirement for producing a good workable paste and eventually a strong mortar.

Modern methods of slaking use steam to produce hydrated lime powder (calcium hydroxide powder) (Historic Scotland 1995; Historic Scotland 1996). This method was much safer and carried out in a closed environment to minimise any health risks.

2.7.3 Hardening

The setting and hardening of lime pastes was determined by the action of carbon dioxide, a gas present in the atmosphere. This process is called carbonation of the lime paste, whereby the calcium hydroxide absorbs carbon dioxide and water was separated out. The hardening reaction was as follows:

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

$Ca(OH)_2$	+	CO_2	$\longrightarrow$	$CaCO_3$	+	H_2O
Calcium hydroxide (Hydrated Lime)		Carbon dioxide		Calcium carbonate (Limestone)		Water

To allow this reaction to take place throughout the material, and not only on the surface, air must penetrate deeper. This may not occur until both the water formed by the reaction and excess water was removed by evaporation.

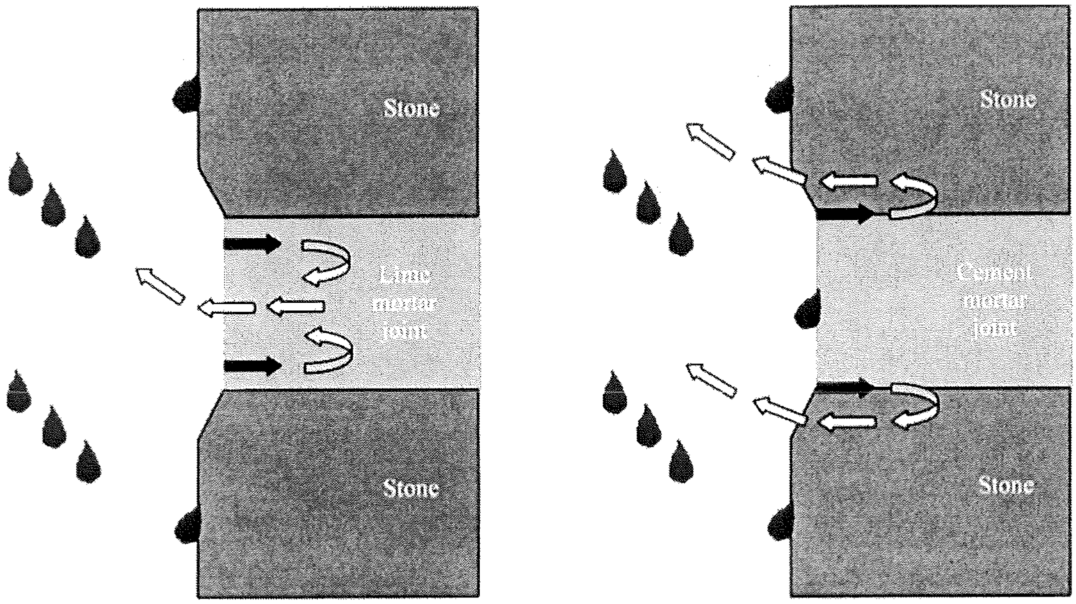
Lime must always be mixed with an inert material to act as filler like sand, which reduces the shrinkage in the mortar. The amount of sand needed was limited because an excess of sand reduces the workability of the mortar paste and the mechanical strength of the hardened mortar. The required amount depends upon the particle size of the sand and the volume of the lime.

The distribution of particle sizes in the sand was very important. A mixture of coarse and fine sand produces the best results. Although, using coarse sand produces a stronger mortar than using fine sand (Historic Scotland 1996).

2.8 REASONS FOR USING LIME

Problems arise when modern materials and techniques are used in the restoration and renovation of old and ancient buildings. It can often take many years for the problems to become apparent. Damp and salts gradually build up behind impermeable finishes, unable to evaporate, speeding up the decay of built-in timbers, providing ideal conditions for wood-boring beetles and rot of all kinds. Eventually, render or plaster fail, the damp blisters through impermeable paint, joist ends rot in walls, and in the most dramatic cases involving earth walls, buildings just fall down.

Gradually it became accepted that old buildings which had stood for many years, expanding and contracting with the seasons, shifting gently with the humidity in the atmosphere and the slight changes in the ground on which they stood, were completely incompatible with the hard but brittle and impervious materials in common use nowadays. Fig. 2.5 shows an example of what can take place if cement mortar was used on older buildings rather than lime based mortar.



Moisture circulation and evaporation through mortar and face of joint weathers

Moisture circulation and evaporation through stone and face of stone weathers

Fig. 2.5 - Movement of moisture and associated decay at masonry joints

Old stonewall which was constructed with lime mortar joints absorbs the rain mostly through the mortar joints and moisture evaporates through them as well. As the lime mortar joints are the softer of the two materials they erode with time at a faster rate than the old stones. Thus, when the mortar joints eroded to a certain extent they can be replaced easily over and over again rather than having to replace the valuable stones (Historic Scotland 1996; Allwinkle and Khalaf 1996).

The exact opposite effect occurs when a cement mortar was used on to point an old stone masonry wall. Cement mortars have a high density, are strong and have a low permeability. This forces the circulation and evaporation of rain water to take place through the soft stones rather than the mortar joints. This over time results in the decay and the rapid spoiling of the soft stones leaving the mortar standing proud like a shelf, to collect yet more water, increasing the stone's deterioration. Chemical reaction between the stone and cement mortar was another reason for stone decay, which often takes place causing unsightly salt staining and in the case of some sandstone very rapid spoiling (Historic Scotland 1996; Allwinkle and Khalaf 1996).

When lime was used inside a building as a plaster or limewash, problems of condensation and blistering surfaces will be dramatically reduced, if not cured. The building was able to maintain its own moisture levels by evaporating away any excess dampness. This was particularly true where heating was not constant e.g. in churches, which are filled with warm moist air perhaps once a week, and stand cold and unventilated the rest of the time.

2.8.1 Ten reasons for using lime

- Walls breathe better and moisture can evaporate easier.
- Mortars and renders do not set too hard.
- Thermal movement can be accommodated without damage.
- Expansion joints can be avoided.
- Insulation is improved and cold bridging reduced.
- Reduced risk of condensation.
- No risk of salt staining.

- Alterations can be carried out easily and masonry units can recovered later.
- Masonry life was increased.
- CO_2 emissions in the manufacture of lime are 20% less than cement and during carbonation the mortars and renders reabsorb considerable quantities of CO_2 from the atmosphere.

Due to the above reasons, lime was now valued for its role in the restoration and renovation of old buildings, to the extent that it was specified by many local authorities and became a condition for granting applications and planning approval.

2.9 REVIVAL OF LIME

The use of lime as a construction material had virtually died out in the United Kingdom by the 1950s. Lime was only being used in Europe, infrequently on small projects.

High labour costs and the long setting times created an environment in which the use of old traditionally building methods in architectural conservation was strongly resisted. Experience and knowledge of old buildings were eroded and repair and maintenance needs were disregarded and education was limited to the construction of new buildings.

The recommendation by Historic Scotland and other conservation agencies that ordinary Portland cement (OPC) should be used as a pointing material for the restoration and renovation of old masonry buildings, finished what small amount of lime still in use (Historic Scotland 1996). Using cement required less labour and was supposed to be of superior quality however this did not turn out to be the case.

Since this time an alarming amount of erosion has taken place on historic buildings across the country. The amount of vehicles on the road today has greatly increased the pollution, through exhaust fumes. This pollution was thought to be the cause of stone erosion in the masonry walls. Pollution does cause some erosion but not as severe as what was actually happening. Later it was discovered that much of the erosion was due to moisture circulation and evaporation through the soft stone rather than the mortar joints which causes their disintegration with time (Historic Scotland 1996; Allwinkle and Khalaf 1996). The conservation agencies were alarmed by this and initiated programmes to stop the disintegration of the valuable stones. They recommended that in order to restore old buildings the material used should be compatible with the original material used in the past, which in most cases was lime.

Traditionally constructed masonry buildings rely, for their weatherproofing on their ability to hold and evaporate water. Lime mortars and harlings can absorb water and subsequently allow it to evaporate from the building. Cement based materials are more brittle and less porous and this can lead to cracking and eventually water penetration. By inhibiting evaporation, hard dense mortars tend to trap moisture forced in the wall by wind driven rain, capillary action and rising groundwater. This eventually leads to a build up of moisture in the building fabric resulting in the reduction in the thermal performance of the wall, encouraging timber decay and other moisture related problems. The moisture build-up in the wall has to escape via some other means and in this case it will be through the stone.

Buildings constructed with lime were more flexible and any movement was taken up by minute adjustment over many joints and impermeable hairline cracks without major damage to the building. These hairline cracks will also be sealed off later by a lime solution. The use of cement for repairs can result in a few major cracks and in extreme cases in the development of movement joints in the structure. This in turn can lead to water penetration and thus to the start of stone decay.

Cement mortars also release some soluble materials (e.g. alkali, sodium sulphate) on setting, which can be detrimental to the surrounding stones. For these reasons any restoration material should exhibit chemical and physical properties of the same magnitude compared to the original material. This is because if two materials are placed together the weaker one will tend to decay and erode at an accelerated rate. Therefore, it would be preferable to have the restoration material deteriorate first as a sacrificial material, which can be replaced in the future.

Cost comparisons are difficult to make, but using lime for repair can compete on reasonable terms to the conventional hard materials, and if the longevity of the building was considered, careful lime repair can work out considerably cheaper in the long run. With sufficient foresight, lime can be slaked on site at extremely low cost and stored for later use. Unlike cement and gypsum, as lime was so slow to go off, wastage was at a minimum as mixes can be knocked up for use the next day. On restricted sites mortars can be taken in ready mixed, avoiding a great deal of noise and mess. As more builders become familiar with the use of lime they are less likely to waste time accustoming themselves to handling and using the material.

Original mortars and plasters used in an old buildings can be analysed, so matching the material used for repair can be identified. However, the original mortars are not always perfect, and analysis can provide misleading results where old mortars have been added to later mixes as fillers. It is obviously desirable to choose sand that matches the original, the actual mix may differ to suit the altered conditions and uses of the building today. A carefully judged repair mortar should be slightly softer, and slightly more permeable than the masonry units it surrounds. Replacing eroded mortar was easy and possible; replacing eroded units was a far more difficult task (Historic Scotland 1996; Allwinkle and Khalaf 1996).

2.10 USES OF LIME IN CONSTRUCTION

2.10.1 Pointing

The way a wall was finished greatly affected the final appearance of the built face. The scale of pointing finishes range from exposing as much of the stonework as possible, to smearing the stonework across its face with the lime mortar. There was a wide variety of surface finishing techniques used. The technique used depends upon the region or the particular taste or the amount of money available to spend, as lime was an expensive commodity.

As said before several techniques were used, one of which was exposing as much of the stonework as possible. This created a wall which was more capable of resisting erosion. The lime mortar readily infilled any irregularities in the construction, whilst reducing the external surface area of exposed lime on the face, thereby predominately creating a stone weathering skin.

Detailed examinations of original recessed pointing in a rubble-built wall will reveal that a series of vertical load bearing structural paths are created during the building process. The mortar was applied more liberally on the vertical direction than on the horizontal, this caused the rubble and the mortar to form these structural paths, which can add strength to the walls.

At its most basic, smeared mortar was simply used across the face of the emerging building to infill the low points of the rough rubble face. Bridging across the high spots greatly reduced the visible exposed stone face.

2.10.2 Rendering

Rendering or harling was similar to a certain extent to pointing. The materials used and textures created vary considerably throughout the country, although the technique used was the same.

Rendering was applied to the outside of buildings for protection and appearance. A lime render layer with fine stones was applied to the face of the wall. In medieval time fine grit or crushed seashells were sometimes used in the render mix (Cowper 1998).

A top layer of fine stones are applied by casting them from a shovel or even throwing them in handfuls. Once the render has hardened, the stones are fixed, this gave a protective layer. However, this was not always the case for some buildings. Rendering a wall using a hard material like cement can actually lead to erosion of the stonework as some parts of buildings are not meant to be covered. This defeats the purpose of the render as a protective layer.

An old wall with a soft lime render absorbs a certain amount of moisture, but this moisture evaporates easily and so a balance was maintained. A cement render on such a wall would have microscopic cracks as the wall responds to atmospheric and foundations movements. Moisture would be sucked in through these tiny cracks, but then was unable to evaporate through the render, which resulted in a build up of dampness in the wall.

2.10.3 Limewash

Lime washing involved the routine, annual brushing on of slaked lime, watered down to a creamy consistency and sometimes, waterproofed with additives, such as tallow. As a result buildings frequently built up a thick, weathering skin due to successive applications.

The process controls water absorption, surface run-off and the quantity of light reflected. Limewashing was not for protection but for the look of cleanliness and was applied to farmsteads and distilleries, but has been used for good reason on lighthouses due to its reflecting properties (Historic Scotland 1995).

2.10.4 Plastering

Lime plaster was used to improve living conditions in solid masonry houses. The lime plaster smoothed over the rough interior of the stone buildings, giving an even appearance as can be seen in Fig. 2.6. Although clay or a mixture of clay and lime was also used, it was the adhering qualities of lime, which gave greater permanence and a more solid foundation for the application of decorative painted work. This was particularly the case during the Renaissance period from 1600 (Historic Scotland 1995; Historic Scotland 1996).

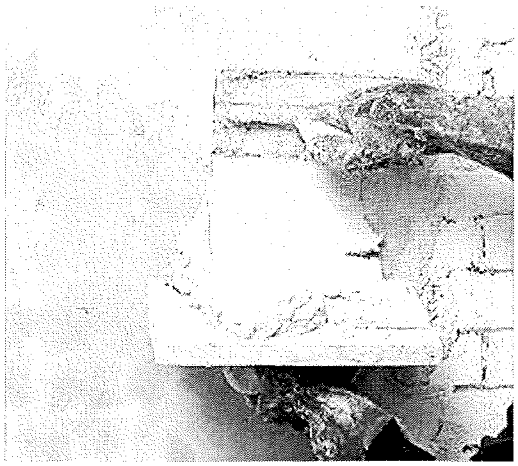


Fig. 2.6 - Plastering of a brick wall

Due to fashion and the rising standard of living this sort of plastering became impractical. A new technique was employed in the 17th Century, which relied on a sub-frame of lathes, fixed on supporting timbers to provide a base on to which lime plaster was applied (Historic Scotland 1995; Historic Scotland 1996).

The new method improved living standards at the time because the plaster was no longer applied to a hard surface. Later stages involved adding hair for reinforcement. The popularity of lime plastered walls was due to their ability to reflect light which greatly improved the brightness of the room, and helped in preventing mould and germs.

Later more sophisticated techniques were developed and wealthier people could elaborate their building interiors with cast and moulded lime plasterwork applied to the flat surface areas. Unfortunately, many of these traditional construction techniques are often considered too labour intensive and costly to maintain when carrying out conservation work. They are usually removed and replaced with modern materials using new techniques; part of it was due to the lack of understanding of lime as a building material.

2.10.5 Mortar

The most effective methods of repairing traditional masonry buildings involve the use of materials and techniques employed during their construction.

Mortar was defined as any material in a plastic state, which can be trowelled, becomes hard in place, and used for bedding and jointing masonry units (Cowper 1998). It was commonly known that the purpose of a mortar was to stick masonry units together, but this was only a small part of its function. The joints between the units should provide a cushion to spread the loads evenly, particularly with soft bricks and stones. They should act like a wick to draw moisture out of a wall and provide a good surface for evaporation. In this way they will take harmful soluble salts away from the masonry units and can act as a sacrificial material. For the mortar to do all these functions, it must be softer, more porous and more permeable than the masonry unit (Historic Scotland 1995; Historic Scotland

1996).

Impermeable mortars with high compressive strength and good adhesions have a lot of applications in modern buildings, but in traditional construction, the building forms are such that very little strength was required from the mortar. This was due to their shape and thickness providing building forms that depend almost entirely on compressive stresses.

Another way in which the softer mortars can contribute to long life was by tolerating the small deformations in a building. All buildings move, both from temperature changes and from variations in the firmness of the ground below their foundations. Stiffer mortar might lead to just a few relatively large cracks, where as soft mortar may deform with many hundreds or thousands of very fine cracks. The free lime in the mortars can then, with the action of moisture, crystallise and carbonate to heal these fine cracks.

The use of soft mortars, made from pure or 'fat' limes was far from straightforward. They set in two ways, firstly by simple drying when they lose their plasticity and then by the process called induration in which the lime becomes carbonated; part of the calcium hydroxide combines with carbon dioxide from the air, in the presence of moisture, to form a firm matrix of calcium carbonate.

There are various ways to promote and speed up the carbonation process, but it will always be a slow process which continues for months or sometimes years and it starts at the surface and progresses into the joint. Typically the process penetrates only 10mm to 12mm into the joint. This means that the greater part of the mortar remains uncarbonated and may, in particularly unfavourable conditions, dry out with no cohesive strength at all. Whilst the firm outside skin remains intact there would be no problem with compressive strength, but when, in time the outer skin became eroded, the structure would lose strength. However, the process of induration would still continue as the outer skin erodes and there would usually be a warning that remedial work was needed.

The normal requirement for inherent durability in a structure was for the inner parts of the structure to be stronger, or at least no weaker, than the surface parts. This was why hydraulic lime and lime-pozzolan mixtures can be desirable, since they can achieve a set throughout the depth of a joint, in the absence of air. For particularly harsh conditions the strength of the eminently hydraulic limes may be needed, but in general, the weakest hydraulic limes and some class of lean limes can provide the necessary set without losing the advantages of a soft and porous mortar.

The major part of most mortars will be the sands or aggregates and these will have a very considerable effect on the mortar quality.

For use as a mortar, lime has several benefits over cement. The lime mortar was much weaker than cement mortars, which can be a good thing especially with masonry. Weaker mortars are one of the solutions recommended by BS 5628 (1985) to reduce cracks in masonry buildings. Using strong mortars concentrate differential movement in fewer and wider cracks. Lime mortars have the ability to accommodate thermal, moisture and settlement movements without major cracks. Lime mortars, as mentioned in other parts of this study, allow the natural circulation of rain water through the stones and mortar joints, effectively allowing stonework to breathe and stop stone decay.

In rendering, repointing and surface repair lime mortars work far better than cement mortars. This was due to their permeability to air and water vapour, their good appearance and ability to reach maximum strength without the need of frequent weathering.

2.11 ENVIRONMENTAL

The use of lime mortars in the repair and conservation of historic buildings has environmental benefits over cement mortars. Energy requirements and pollution levels associated with productions are significantly less for the manufacture of traditional lime products than for cement. During manufacture a significant difference between cement and lime was the firing temperature. Lime was produced at a temperature of around 900^0C, while cement was produced at over 1200^0C. As a result considerably more energy was required to produce cement thereby increasing CO_2 emissions. Furthermore the bulk density of lime was half that of cement enabling fuel savings during distribution by lorries and trucks. Overall energy savings using lime are approximately 20% (Historic Scotland 1994; Cowper 1998).

Buildings constructed with all but the strongest hydraulic limes can be altered easily and recovered masonry re-used. Indeed the masonry can be reclaimed entirely if a building has completed its useful life. In the UK 3,000 million bricks are fired annually consuming large quantities of fuel and adding significantly to CO_2 emissions. Bricks bound together with cement mortars can generally never be recycled except as hard-core. This was especially important with many modern commercial buildings such as supermarkets, which may be demolished after only a few years.

Two of the basic principles underlying the conservation of historic buildings are those of reversibility of repairs and the use of sacrificial materials. Lime mortar being a soft material was more capable than cement mortars to fulfil these criteria, and in most situations lime mortars for repointing or repair will be deliberately sacrificial to historic fabric. By employing appropriate lime based materials where there was a need to replace missing and decayed mortars the surviving historic fabric of masonry buildings may often be protected from further significant decay.

Lime was not only used in repair and conservation of historic buildings. It was used for air pollution control, water, sewage, industrial wastewater treatment and hazardous waste treatment etc. Therefore, it can be said that lime was extremely environmentally friendly.

However perhaps the most significant environmental factor was the quantity of CO_2 lime absorbs from the atmosphere during the setting process. Each tonne of lime will absorb nearly its own weight of CO_2. Hydraulic limes do not take up as much CO_2. The amount will decrease as the silica/alumina level rises.

2.12 APPEARANCE

The appearance of a building was a very important issue as any architect can verify. Many old buildings were originally finished internally in lime plaster and externally in lime harling or render. Colours were once derived from locally available materials, but now the widespread use of cement gives a uniform blandness without regional variations. As traditional lime mortars and renders age they acquire an attractive sheen on the surface of buildings which improve the overall appearance of towns, villages and cities. Where historically appropriate, repair work involving lime based coatings finished in limewash will not only perform more effectively but will provide a sympathetic and attractive finish to the building (Fig. 2.7).

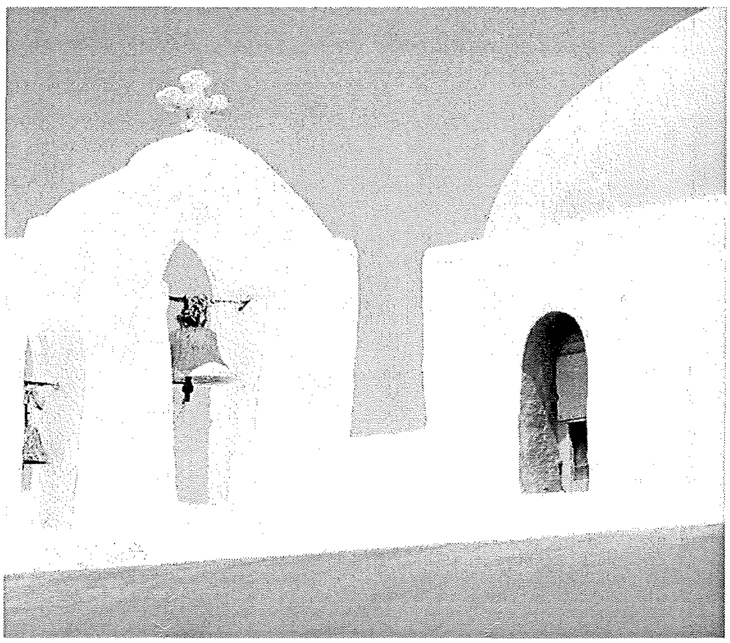


Fig. 2.7 - Simple and attractive finish to buildings

Similarly the use of suitable lime-based materials for repointing can assist in maintaining or restoring the original appearance of buildings. Historically rubble stonework was often built with mortar joints fully flushed up and sometimes with joint lines lightly ruled in the stonework. The original character and appearance of such masonry cannot be reproduced in cement based mortar without the risks of water becoming trapped and accelerate stone decay. In recent years there has been an artificial approach to repointing old masonry using recessed joints placing undue emphasis on individual stones at the expense of the structural integrity and appearance as a whole.

Therefore, using lime mortars for the repair and restoration of historic buildings not only improves the structure but also gives a more desirable appearance. This in turn improves the appearance of the street and the city from where the building was situated and brakes up the monotony of the modern building.

2.13 CURING

Appropriate protection and provision of suitable environmental conditions have a major contribution to both the short-term and long-term performance of lime mortars. Appropriate curing conditions involve a process of gradual drying and should, ideally, result in no shrinkage. Rapid drying, whether by wind, sun or artificial heat will have a detrimental effect on a lime mortar. Added to the problem of shrinkage cracking, rapid drying can result in separation of mortar from adjoining stones or backing, and in a crumbly or powdery mortar.

Early shrinkage may also be caused by too much water in the mix or by failure to compact the mortar as it starts to stiffen up. If initial shrinkage occurs in non-hydraulic lime mortar, it can be reworked and pressed back, providing the material has not been allowed to dry out. Drying shrinkage in mortars, which rely on a hydraulic set, should not be reworked and unsound work will need to be cut out and replaced.

Rapid surface drying can also lead to the pores becoming blocked with fine material transported to the surface by the movement of water, which in turn will inhibit the passage of moisture vapour through the outer skin of the mortar and inhibit carbonation of the underlying material. A dense surface skin will also be vulnerable to spalling when moisture trapped behind it was subject to freezing.

The excessive whiteness often seen in new lime mortars was frequently caused by over rapid drying which results in lime being drawn to the face of the mortar.

Appropriate conditions of curing can usually be achieved by the use of fine debris netting on the scaffold to provide shade and protection from drying winds, supplemented in hotter windy conditions by additional protection in the form of framed panels with hessian and polythene coverings (Gibbons and Leslie 1998; Van Balen and Van Gemert 1994)

All new lime mortars need to dry out slowly from within the depth of the material and to be maintained in a moist but not wet condition for a week to ten days. In very dry conditions intermittent fine mist spraying with clean water may be necessary to prevent premature drying of the surface. It may also be necessary to keep the hessian covers wet in hot or windy conditions. Protection against frost over the first winter was normally essential for any lime mortar. Lime mortar will generally be vulnerable to frost damage for a period of at least three months after placing and non-hydraulic lime mortars will always be vulnerable to frost damage when in a saturated condition (Gibbons and Leslie 1998; Van Balen and Van Gemert 1994)

2.14 MATURING

The quality and hence the potential performance of traditional lime mortars is improved by maturing before use. Where possible mortar should be mixed at least three months before required on site. Freshly made mortars, even when they incorporate mature lime putty, will not have had time to develop the necessary close bond between lime and aggregate and could prove less durable in use than well matured lime mortars.

Mortars made up directly from quicklime or unmatured lime putty should generally be matured for a period of at least three months, both to ensure complete slaking of the lime and to allow a close contact to develop between lime and sand.

2.14.1 Quicklime and sand mixtures for maturing

There are long established traditions of making mortars by laying down quicklime and sand pits or heaps. This can be done either in alternating layers of material or by covering a quantity of quicklime with a layer of damp sand. Suitably protected from the elements this would be left to slake and mature over the winter then thoroughly mixed and knocked up before use.

2.14.2 Hot mixing for maturing

Sand and lime may be combined and well beaten while the lime putty was still hot. Mortars made by this method are normally matured for about three months to ensure full slaking of the lime and to develop a close bond between sand grains and lime particles. The action of the hot caustic lime and silica sand can potentially etch the surface of otherwise unreactive silica grains. This was thought to improve the bond between lime and sand and perhaps to create some mild pozzolanic activity in suitable sands.

2.14.3 Cold mixing for maturing

Currently the most frequently used method of mortar production was cold mixing. Mature lime putty was combined with aggregate. The resulting mix should be matured before use to encourage closer contact between lime and sand and further reduction in the size of lime particles. The mix was thoroughly knocked up again for use. Traditionally maturing of lime mortars was carried out in earth or timber lined pits or timber vats or in covered heaps all of which allowed excess moisture to drain from the mortar but preventing drying out.

2.15 POZZOLONIC ADDITIVES

Known as 'pozzolans' after the volcanic additives used by the Romans, these materials are widely found in the lime mortars used in old buildings and monuments. Where conservation work was required, new mortars ought to match these mortars, not only to ensure continuity with the past, but also to ensure that the new work was both visually and physically compatible with the old. Therefore it would be important to know more about the performance of these additives (Gibbons 1997).

The addition of compounds can have the effect to allow a lime mortar to mimic the setting action of a natural hydraulic lime. This can be achieved using powdered additives with a high silica and aluminium content, such as natural pozzolans which were used in the past, such as finely ground brick dust, volcanic ash and pulverised fuel ash. The adding of a pozzolan to any lime mortar, hydraulic or non-hydraulic, will modify its characteristics. Pozzolanic materials can combine with uncarbonated lime (calcium hydroxide) to form stable compounds, thus reducing the risk of early leaching or frost damage and increasing the potential durability of the mortar. Depending on the pozzolan chosen, the density and compressive strength of the mortar may be increased and porosity reduced. (Aggelakopoulou et. al. 2004).

A simple everyday definition of 'pozzolan' could be a finely powdered material which can be added to lime mortar (or to Portland cement mortar) to increase durability and, in the case of lime mortars, to provide a positive set. A more formal definition was given by the American Society for the Testing of Materials (ASTM) as a siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (Gibbons 1997).

Laboratory tests on harden lime mortar can give conflicting results due to the way the samples are prepared and cured. A good quality manufactured lime and a high porosity mortar are essential to obtaining a durable mortar. Smeaton, particularly, was instrumental in developing specifications incorporating natural pozzolans with natural hydraulic lime to achieve exceptionally durable mortars for marine and other engineering works.

The curing of a lime mortar was decisive to its final characteristic. A fast carbonation must be promoted as this improves the durability. Carbonation would be accelerated when there was air circulation over the face of the mortar to allow continuos replenishment of used CO_2. (Jager and Pohle 1999).

It has been shown by Teutonico (1997) that brick dust in the lower size particle range (particles < 75 microns) can act as a reactive pozzolans assisting initial set and increasing durability while larger particles (>300 microns) of brick in mortars seem to behave more as porous particulates or air-entraining additives which improve resistance to frost and salt crystallisation. The most commonly used modern additive was the crushed brick which was ground down until the particle size is no more than fifty microns.

The addition of cement would increase the strength, durability and setting time of lime mortar. This would naturally appeal to the contractor due to the slow setting times of lime mortar.

2.16 THE RELATIVE MERITS OF ADDING CEMENT TO HYDRAULIC LIME

Since Roman times builders have used a lime-based mortar for the construction of masonry structures. The use of these mortars lasted up until the discovery of Portland cement by Joseph Aspdin, a Leeds builder, in 1824 (www.inventors.about.com 2000-2005). Since this time their use has died out. Ancient monuments, which have been restored within the last few decades, have been repaired using cement based mortar. Unwittingly this has caused great damage to many of these structures as discussed previously. This damage has been estimated at many millions of pounds over the last few decades.

For many years those specialisied in historic building repairs have known the dangers of using hard, cementbased mortars. But the specialist world has been split between those who advocated the use of small amounts of Portland cement as an additive to a lime mortar and those who rejected all cement additives. Various organisations which promote the use of hydraulic limes are accusing contractors and each other of adding cement to the lime in order to improve its properties. The addition of cement to hydraulic lime mortars was widespread, almost traditional practice, but few consider why it was used or the consequences.

In Sweden it was discovered that small percentages of cement if added to the lime will shorten the setting time of the lime mortar but decreases its strength. There are both advantages and disadvantages in adding cement to hydraulic limes:

Advantages:

- Imparts a chemical set which occurs before full shrinkage occurs, thereby reducing the risk of cracking.
- Layers may be built up more rapidly, without the need to wait a long time for one to set fully before applying the next.
- Provides protection from rain before carbonation has been completed due to its rapid hardening. This helps to beat the inclement British weather.
- Reliable and predictable in use as it was a artificial substance manufactured under closely controlled conditions.
- Available in a choice of colours, useful when it was necessary to match the colour of an existing mortar or render.

Disadvantages:

- Rapid setting time. This limits the time available to the user in which to work with the mortar.
- Some cements contain appreciable amounts of soluble salts, in particular potassium sulphate, which may become a source of salt damage to stonework.
- The use of cement tends to lead to the user treating the lime mortar as if it were cement. Too much reliance on the initial chemical set leads to neglect of the importance of the longer term carbonation of the lime component present.
- Danger that segregation occurs, whereby the cement separates from the lime as the mortar dries and hardens.

Segregation was a major hazard of gauging lime mortars with cement. As the mortar sets, the cement colloid tends to migrate into the pores of the lime mortar as they form, clogging them and leading to a greatly reduced porosity. If the proportion of cement was high enough, segregation was much less likely to occur, but the resulting mortar will be hard. If the cement proportion was low, the mortar will be less hard, but segregation was more likely to occur. The resulting mortar would be seriously weakened, with a poorly formed pore structure leaving it very susceptible to frost damage and deterioration, even after carbonation of the hydraulic lime present has taken place (O'Hare 1995).

The Smeaton Project, a research programme commenced by English Heritage indicates that a 1:1:6 mix, containing a 50% cement binder, was unlikely to segregate, while a 1:2:9 mix, containing a 33% cement binder, was almost certainly at risk. Until recently it was considered good practice to gauge lime mortars with as little as 5% cement, just enough to impart a chemical set but not enough to make the mortar appreciably harder. However all of the Smeaton Project test samples containing less than 25% cement failed (O'Hare 1995).

Given the possible hazards of segregation, an un-gauged lime mortar relying solely on carbonation and hydration was likely to be more resilient in the long run than one gauged with a small amount of cement. This will require care in its application and careful nurturing to ensure that it carbonates and hydrates properly. Cement was not in itself harmful, but insensitive and indiscriminate use of it was a problem. It can be used as a useful pozzolanic additive to mortars, but those specifying and using it should be clear why they are doing so and what its effects are likely to be. Given that it was now widely accepted that mortar should be weaker and more porous than the material that it was jointing or repairing.

2.17 POROSITY AND WATER ABSORPTION

The porosity of a mortar, its permeability and absorption are very important factors in influencing such properties of mortar as the bond between it and the brick, the resistance of the mortar to freezing and thawing, as well as its chemical stability and resistance to abrasion.

There was no test at present in the British or European Standards to measure the porosity of lime mortars. Porosity was defined as the volume of the pores within a mortar, expressed as a percentage of the total volume of the mortar. The porosity of lime mortar, as stated, influences its compressive strength, water absorption and permeability (Handisyde and Haseltine 1976; Butlin and Ross 1989; BRE 1997; Hendry and Khalaf 2000). The degree of porosity depends on the type of lime and aggregate used to manufacture the mortar and the duration and temperature of curing. In stones, it was most convenient to measure porosity by saturation with water under vacuum (Butlin and Ross 1989). The present investigation was to employ a similar test procedure to be carried out on lime cubes, sandstone and brick.

A major factor influencing the durability of masonry was the degree to which it becomes saturated with water. Saturation can occur directly through rainfall or indirectly by water moving upwards from foundations or laterally from retained material as in a retaining wall. Therefore, an accurate value for water absorption and saturation coefficient was required because water penetration was the main ingredient that leads to the degradation of masonry. Once a substantial amount of water has been absorbed, masonry was prone to degradation by the action of freezing and thawing. It was also important to know the value for absorption because water can act as a transport mechanism for salts, acids and other harmful chemicals (Coppola et. al. 2002).

2.18 MASONRY TENSILE BOND STRENGTH

The tensile bond strength between masonry units and mortar have been of considerable interest to researchers for some time. This thesis presents a test method to determine the tensile bond strength by bending. Many factors are known to influence the strength of the bond between units and mortar, this includes brick/block properties such as suction rate and surface roughness. Sand particle size distribution and mortar moisture content also have an influence whilst in practise the workmanship of the brick layer was often crucial (Hendry and Khalaf 2001; De Vekey et al. 1990; De Groot 1987; Held and Anderson 1983; Sinha 1967; Kamf 1963). The bond between brick and mortar was derived from penetration of mortar and hydration products such as calcium silicate hydrate and ettringinte, into the brick surface voids and pores (Cao and Lawrence 1987; Grandet 1975). The relative amount of lime in the mix was thought to be important in determining bond strength.

Jukes and Riddington (1994) used direct pull tests, bending tests on stacks and wrench tests to determine and compare results of bond tensile strength. Various brick and mortar combinations were used. For the direct tensile test, the authors used bolts through the brick thickness to apply the load (Fig. 2.8). The authors concluded that a direct tensile test was more likely to produce a representative value for tensile strength than a bending or wrench test providing a stress multiplication factor was applied to the average failure stress value obtained. The factor accounts for the difference between the average and maximum stress across the joint as indicated by a finite element analysis for the particular loading arrangement (Jukes 1997). The disadvantage of the direct pull test was the difficulty in applying the load to produce a completely uniform stress distribution across the bed joint.

The UK Building Research Establishment (BRE) in Digest 360 (1991) covered the technical background of results for bond wrench test called "Brench" (Fig. 2.9). The Brench was a BRE development of the bond wrench, an in-situ tool for testing the tensile strength of masonry units (brick and block) to mortar. BRE claimed that the Brench could be used for investigating suspect masonry, for quality control and for laboratory investigation of tensile bond strength. The Brench was based on an Australian test the bond wrench, which was developed mainly as a site test. The method was specified in the Australian Code of Practice AS 3700 (AS 1998). In the USA, the use of bond wrenches in the laboratory was now covered by ASTM Standard C 1072 (ASTM 2000) and ASTM Standard C 1357 (ASTM 2002).

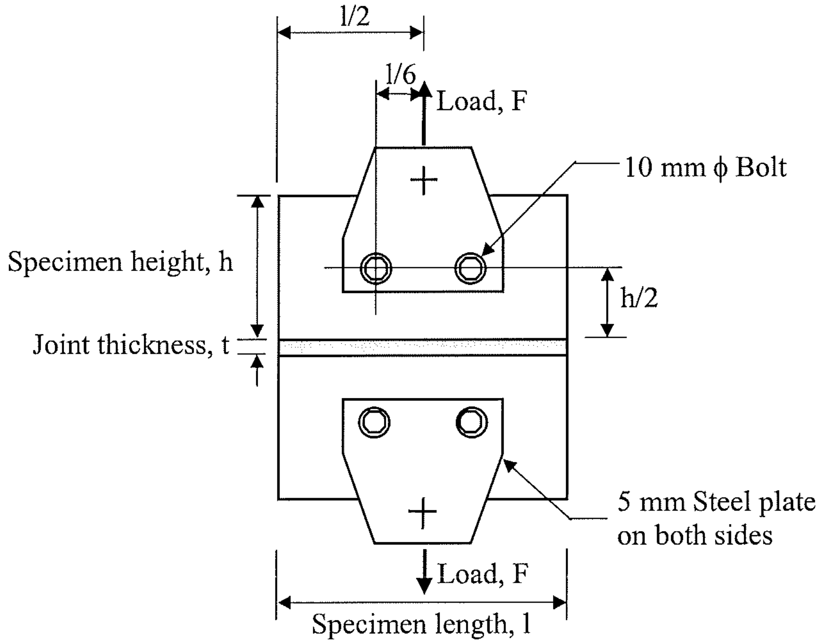


Fig. 2.8 - Direct tensile test

The Brench consists of a lever about 800 mm long which weighs about 9 Kg. At one end are jaws, which can be adjusted to fit the commoner thickness of masonry. The jaws are tightened on the masonry by a screw mechanism. At the other end was a crossbar handle, mounted on a load cell. Load was applied manually by putting body weight on to the crossbar handle; that ensures that all operatives press down on the Brench at the same distance from the masonry. Partway along the body was a combined battery container and LCD type display monitored unit. The display indicates the maximum reading until reset. BRE also claims that the Brench was safe to use because, as the brick/block comes free, the handle moves away from the operative and towards the wall.

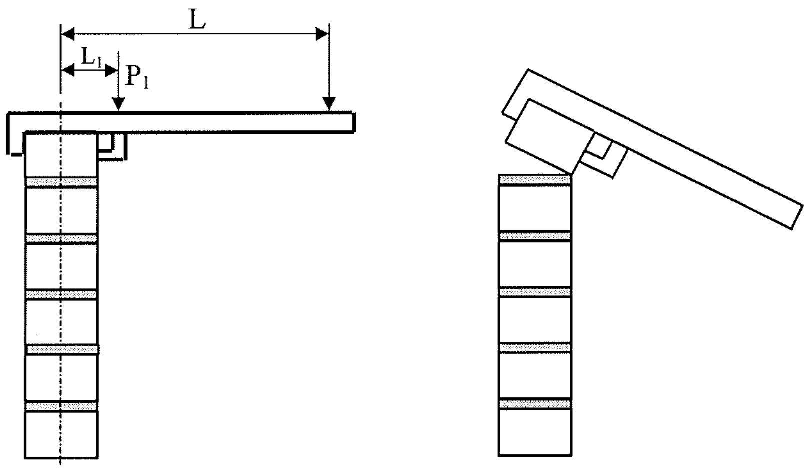


Fig. 2.9 - Brench test

Held and Andersen (1994) used crossed couplet specimens to establish bond strength. Failure was induced without pulling the sample (Fig. 2.10). Adams and Hobbs (1994) and De Vekey et al. (1990) compared results from several crossed couplet tests with those found from wallettes (Fig. 2.11). In general those from the wallettes were higher than those from the crossed couplet tests.

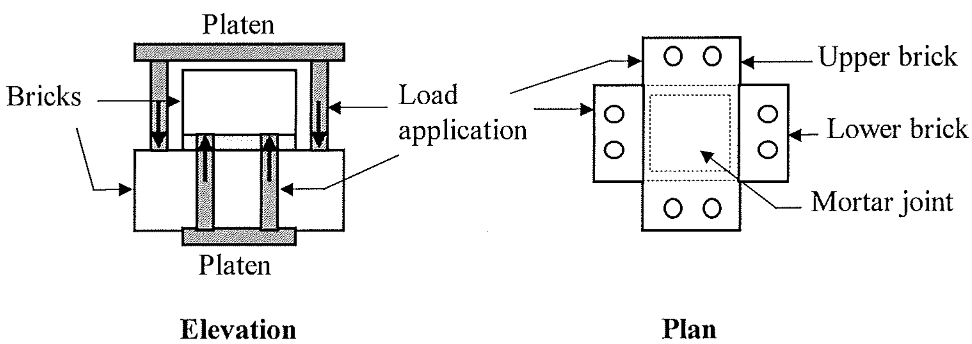


Fig. 2.10 - Held and Anderson crossed couplet specimens

Sinha (1967) conducted direct tensile tests to determine bond strength. Sinha's results, whilst suffering from a high degree of variability, show a general trend for tensile bond strength as moisture content varies. The bond strength tends to increase for wetter mortars, until the saturation moisture content was approached when strength falls off rapidly.

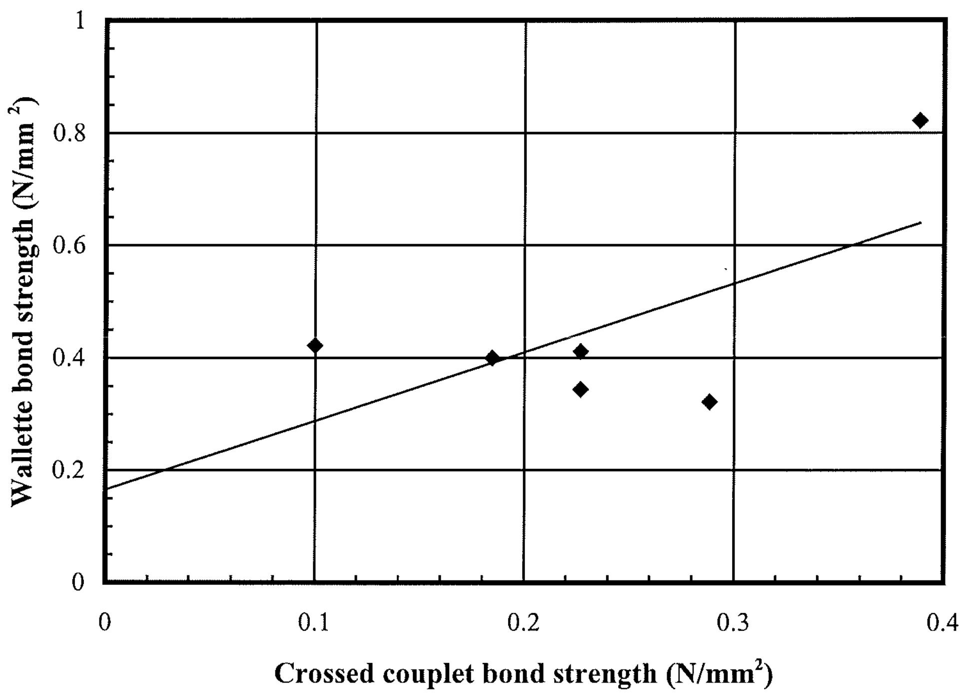


Fig. 2.11 - Cross couplets test compared to wallettes

The test method presented in this thesis was based upon some of the principles given above. The sample was constructed from two units in a Z-shaped configuration (Fig. 2.12) and failure was induced by bending under three-point loading. The Z-shaped test specimens were found to be easy to construct and results had a good degree of consistency.

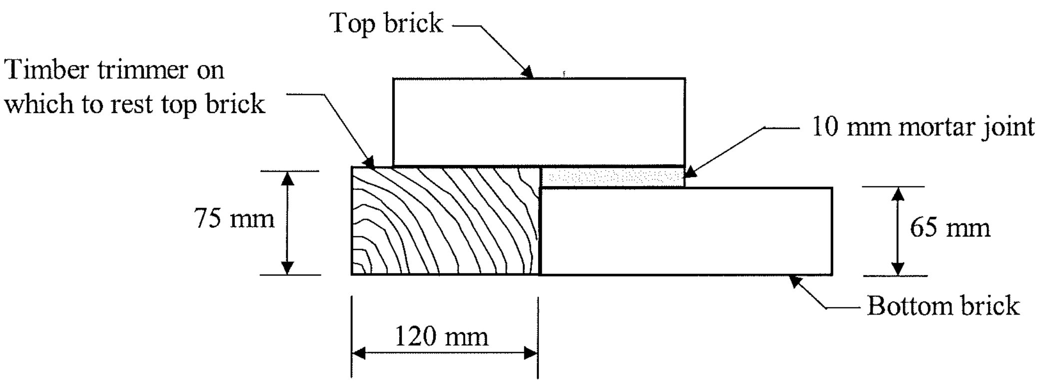


Fig. 2.12 - Z-shaped configuration

The method presented assumes that the brick-mortar bond remains intact up to the point of failure, when a hinge occurs, at the right-hand side of the mortar joint, under the loading point. The external forces on the Z-shaped specimen are shown in Fig. 2.13.

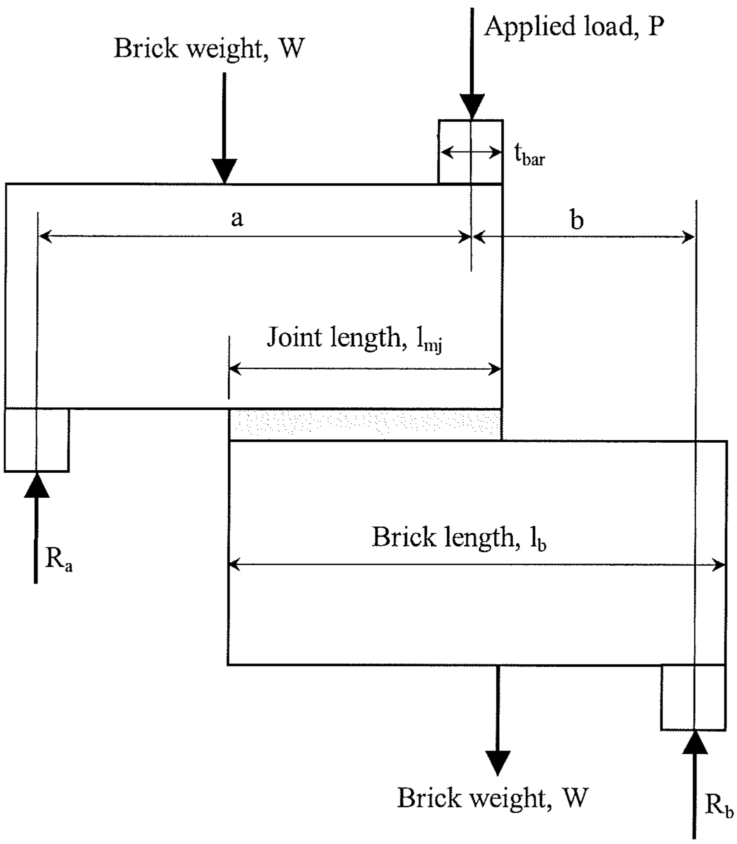


Fig. 2.13 - External forces on Z-shaped specimen

Thus the reaction at the left-hand support can be calculated by taking moments about the right-hand support, which was assumed to be simply supported:

$$R_a = \frac{P \times b + W\left(b + l_b - t_{bar}\right)}{(a + b)} \tag{2.1}$$

At failure, the free body diagram of the top brick forces, which was shown in Fig. 2.14 applies.

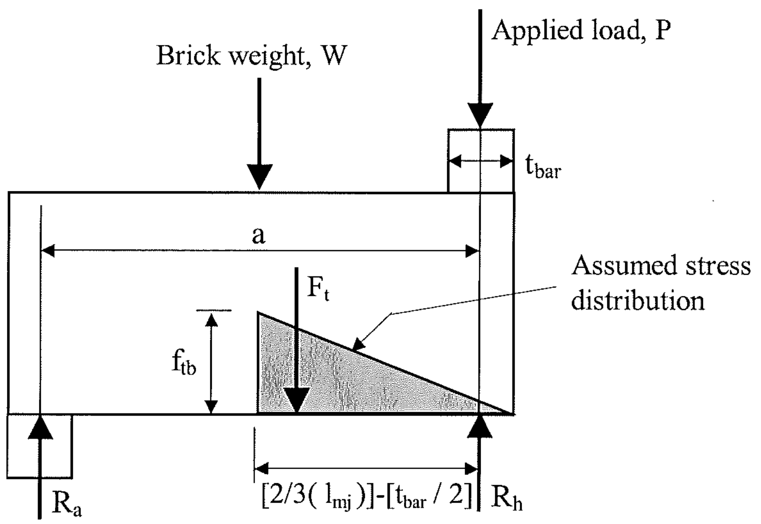


Fig. 2.14 - Free body diagram of the top brick forces

F_t the total force represented by the stress distribution was calculated from the area of a triangle:

$$F_t = \frac{1}{2} \times \left(l_{mj} \times f_{tb} \times w_b\right) \tag{2.2}$$

By taking moments about the loaded point (Fig. 2.14), assuming that the resultant moment was zero the tensile bond strength can be calculated as follows:

$$a \times R_a = \frac{1}{2} \times \left(l_{mj} \times f_{tb} \times w_b\right) \times \left(\frac{2l_{mj}}{3} - \frac{t_{bar}}{2}\right) + W\left(\frac{l_b}{2} - \frac{t_{bar}}{2}\right) \qquad (2.3)$$

By substituting for R_a using Eq. (2.1) and solving for f_{tb}, the tensile bond strength was obtained using the following expression:

$$f_{tb} = \left[\frac{1}{l_{mj} \times w_b \times \left(\frac{l_{mj}}{3} - \frac{t_{bar}}{4}\right)}\right] \times \left[\frac{Pba + Wa\left(b + l_b - t_{bar}\right)}{a + b} - W\left(\frac{l_b}{2} - \frac{t_{bar}}{2}\right)\right] \qquad (2.4)$$

2.19 MASONRY SHEAR BOND STRENGTH

Masonry walls are frequently subjected to racking shear in addition to compressive loads (Hendry 1998). A study has been made by Hamid and Drysdale (1980) using masonry prisms with angled joints to study shear behaviour. The whole specimen can be tested at an angle relative to the loads or a smaller specimen can be cut from a specimen constructed with horizontal bed joints so as to produce the effect of angled bed joints. Typical specimens are shown in Fig. 2.15. In general the behavior of walls under shear loading was a compound of failure events and so the basic shear behavior of mortar joints was obscured.

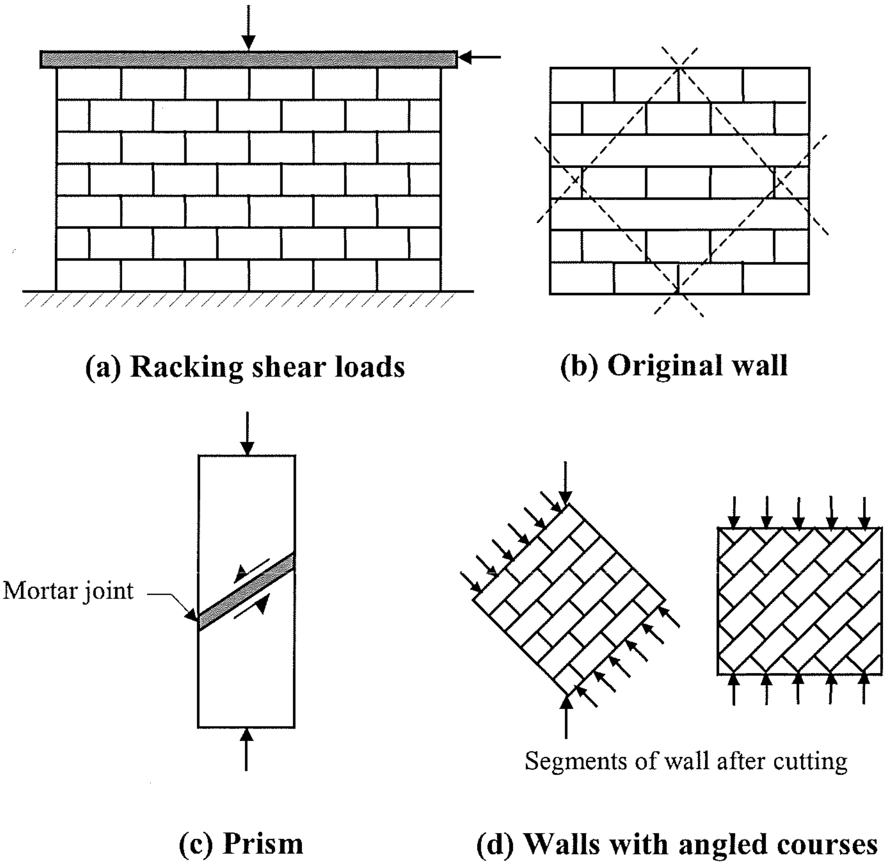


Fig. 2.15 - Typical specimens

The shear strength of masonry, τ_u has been shown to be a function of a large number of factors, including brick or block type, mortar mix and the normal pre-compression stress acting across the bed joint. It has also been shown (Hendry 1998; British Standard BS5628 1992; CEC 1996) that at pre-compression stress levels below approximately 2 N/mm^2, the relationship between shear strength τ_u and pre-compression σ_c can be adequately expressed by a Coulomb type equation:

$$\tau_u = \tau_o + \mu \, \sigma_c \tag{2.5}$$

Despite the fact (Hendry 1998; Stöckl and Hofmann 1988) that the shear strength of masonry varies considerably with different brick/mortar or block/mortar combinations, BS 5628 (1992) specifies single values of 0.35 N/mm^2 for τ_o and 0.6 for μ for all walls built with mortars of designation (i), (ii) or (iii) subject to an upper limit on the characteristic shear strength of 1.75 N/mm^2.

Similarly, the American Building Code ACI 530.1 (1995) specifies a single value for the masonry shear strength and states that the in-plane shear stresses shall not exceed the lesser of:

(a) $1.5\sqrt{f'_m}$

(b) 0.83 N/mm^2

(c) $\nu + 0.45\, N_v / A_n$

Where:

ν = 0.26 N/mm^2 for masonry in running bond that was not grouted solid, or

= 0.26 N/mm^2 for masonry in other than running bond with open end units that are grouted solid, or

= 0.41 N/mm^2 for masonry in running bond that was grouted solid,

= 0.10 N/mm^2 for masonry in other than running bond with other than open end units that are grouted solid.

The draft Eurocode EC 6: Design of Masonry Structures (EC 1996), proposed different methods to determine the value of the characteristic shear strength of unreinforced masonry, f_{vk}, for different ways of laying of masonry units. The standard proposed finding the value of f_{vk} from the results of tests on masonry specimens. However, where test data was not available, it can be assumed that the characteristic shear strength of unreinforced masonry, for an example filled mortar bed joints, will not fall below the least of the values described below:

$$f_{vk} = f_{vko} + \mu \, \sigma_d \qquad (2.6)$$

or $= 0.065\, f_b$ but not less than f_{vko}

or $=$ the limiting value given in a table.

Eq. (2.6) was similar to Eq. (2.5) (Coulomb equation) the only differences are the notations used. The proposed value for μ was 0.4 for all kinds of masonry unit and types of mortar used. The European code suggests determining the values of shear strength without pre-compression, f_{vko} or τ_o, and the coefficient of internal friction μ for bed joints from triplet test with pre-compression (Fig. 2.16) in accordance with BS EN 1052: Part 3 (British 2002). However, if test data was not available the value of f_{vko} or τ_o for different brick/mortar and block/mortar combinations can be obtained from specified values provided in a table. The triplet test with pre-compression does, however, require the use of highly specialised equipment since a load has to be applied and monitored simultaneously in two directions.

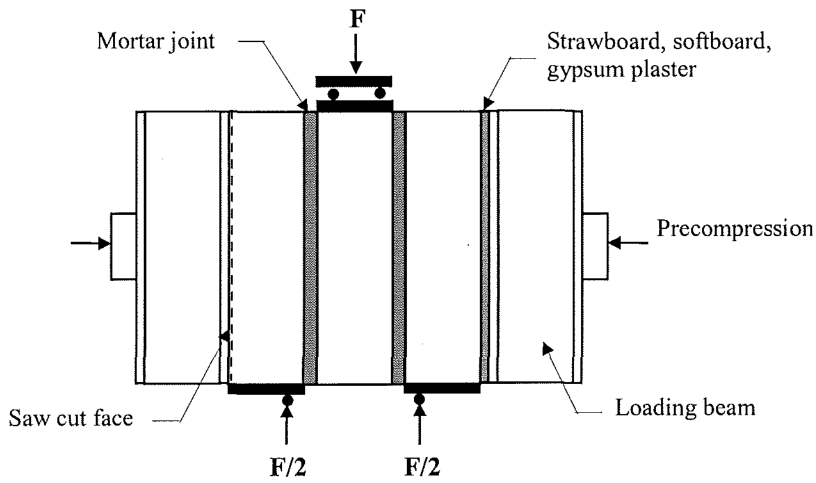


Fig. 2.16 - Triplet test with pre-compression

Riddington and Jukes (1994) conducted a number of tests on triplet samples without pre-compression to determine τ_o, using similar samples to the ones suggested by BS EN 1052: Part 3 (British 2002), that the triplet test method without pre-compression does not provide reliable results for certain types of perforated brick. The reason was the triplets formed from these bricks tended to spring apart at failure rather than to slide against each other. When these samples were then reassembled for testing on the inclined plane apparatus, protrusions on one side of the failure surface, key into indentations on the other side, and this prevents a representative value of the coefficient of friction, μ from being obtained. To overcome this problem the authors proposed the testing of two sets of triplets, one to obtain the τ_o value, and the other for the μ tests. To obtain the τ_o value a first set of triplets was tested without pre-compression and to obtain the μ value a second set of triplets was tested with the samples lightly clamped between steel plates using threaded rods to prevent them from springing apart at failure. Although this doubles the number of triplet specimens required, the authors believed that the total requirement was still less than that needed to conduct triplet tests with pre-compression.

The testing of triplet specimens requires careful set-up of heavy specimens and shearing of two unit/mortar interfaces. Since triplet specimens are loaded at four points, it was not clear how many unit/mortar interfaces will fail simultaneously. It was assumed in the triplet test that two interfaces will fail at the same time. This was not the case since usually only one interface fails by shear first, followed by complete disintegration of the specimen. This was due to the inherent variations in workmanship and materials. Additionally the setting up and loading of a triplet specimen certainly induces eccentricity in the specimen resulting in an uneven type of failure. It was, therefore, more conservative to derive the value of τ_0 by dividing the failure load by the area of two unit/mortar interfaces. Clearly, if the values for τ_0 and μ used in design were more closely related to the actual shear strength of masonry, more economical designs would be produced in the cases where the τ_0 and μ values exceed the Codes and Standards values and where shear strength was a critical factor in the design process of masonry elements.

Khalaf (1995) proposed a new test method for establishing the shear strength of brickwork masonry with zero pre-compression stress, τ_0. In this method, a horizontal two-brick sample was supported in such a manner as to cause torsion at the joint. He used a circular mortar joint and the shear strength was derived from the theory of torsion for solid circular shaft. He reported that the test method produced consistent results and was easy to perform.

Several researchers proposed a test method to measure μ using relatively simple sliding apparatus device (Ghazali and Riddington 1988; Jukes and Riddington 1994; Khalaf 1995).

The test described in this thesis made use of Khalaf (1995) previous test method for testing blockwork samples. Fig. 2.17 shows the loading and support arrangements used for testing the specimens.

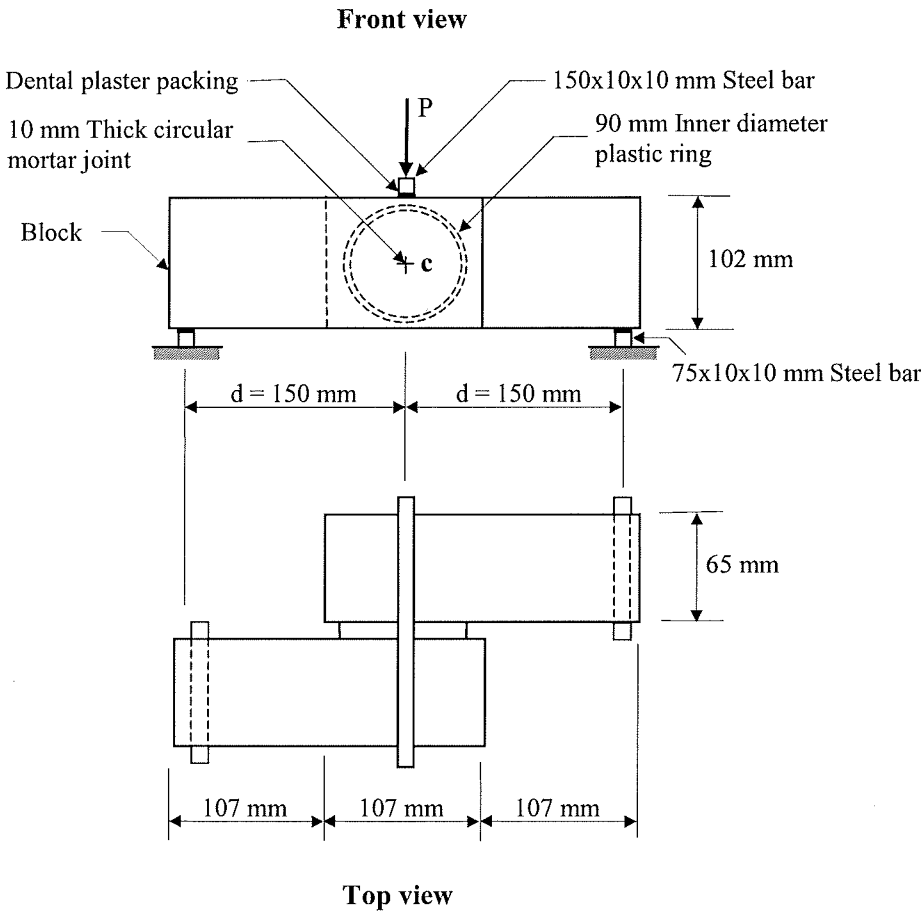


Fig. 2.17 - Loading and support arrangements for specimens

Dental plaster was used as a packing material and 10 mm square steel bars were used at all loading and supporting points. The reason of using dental plaster was to eliminate the uneven surfaces of block at these points. Once the dental plaster was hardened, the specimens were loaded to failure by applying the load at standard displacement rate of 1 mm/min. The samples loaded in such away that they experienced failure by torsion.

Fig. 2.18 represents a free body diagram for the top block with all the applied and reaction forces. The figure shows the state of the forces at low loads whereby the torque T rotates around Point c, but as the load increases the torque T starts shifting upward and it was assumed that at failure the centre of rotation will be around Point t at the extreme top fibre of the mortar joint. Based on this assumption and by ignoring the weight of the bricks, due to their marginal effect on results and also to simplify the calculations, the value of initial shear strength was calculated using the theory of torsion for a circular shaft (Stephens 1982) as shown in Eqs (2.7-2.11) below:

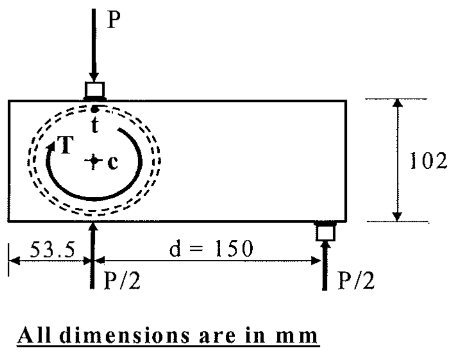


Fig. 2.18 - Free body diagram of top of block surfaces

The torsional moment T about the centre of the circular mortar joint (Point c) or the extreme top fibre of the circular mortar joint (Point t) is given by:

$$T = \left[\frac{P}{2}\right] d \tag{2.7}$$

The polar second moment of area about Point c was given by:

$$J_c = \left[\frac{\pi R^4}{2}\right] \tag{2.8}$$

Since at failure, the torsional moment moves to the extreme top fibre of the mortar joint (Point t), the polar second moment of area has to be transferred from Point c to Point t using the following equation:

$$J_t = J_c + \pi R^2 (R^2) = \left[\frac{3\pi R^4}{2}\right] \tag{2.9}$$

Since, the section modulus of a circular area about its extreme top fibre (Point t) was given by:

$$Z_t = \frac{J_t}{R} = \left[\frac{3\pi R^4 / 2}{R}\right] = \left[\frac{3\pi R^3}{2}\right] \tag{2.10}$$

Therefore, the initial shear strength with zero pre-compression was given as:

$$\tau_o = \left[\frac{T}{Z_t}\right] = \left[\frac{\frac{Pd}{2}}{\frac{3\pi R^3}{2}}\right] = \left[\frac{Pd}{3\pi R^3}\right] \tag{2.11}$$

2.20 CONCLUSIONS

Lime was one of the oldest building materials recorded. The Romans made the biggest contribution to the development of lime by mixing quicklime with pozzolans and aggregate. In 1756, James Smeaton developed the first hydraulic lime product by calcining Blue Lias limestone containing clay with Italian pozzolanic earth to provide additional strength. The discovery of cement, by Joseph Aspdin in 1824, and the desire for speed of construction, the employment of less knowledgeable craftsmen and aggressive marketing by the cement companies, contributed to the decline in the use of lime as a mortar and its relevant traditional techniques.

The type of lime available in the market nowadays was dependant on the composition of limestone from which it was produced and on the techniques of production. The characteristics of lime will be defined by the geological beds, and impurities such as sand, clay, iron oxides, hydroxides and organic materials.

Hydraulic lime covers materials that vary in properties such as setting times and strength development, but they are never to be thought of or used as a cement substitute. Hydraulic limes are characterised by good workability, low shrinkage, salt and frost resistance, adequate compressive and good flexural strength.

The properties of hydraulic lime are influenced by the existence of certain impurities and by the methods of burning and slaking. If clays or other suitably reactive forms of silicates and aluminates are present in the original limestone the resulting lime will have hydraulic properties. The strength of hydraulic lime mortar is developed by two processes, hydration and carbonation.

Modern buildings were made of hard, impermeable materials, so hard and impermeable mortars, renders and plasters were well suited. Problems arise when using modern materials and techniques for the restoration of old buildings. Lime mortars absorbs the water mostly through the joint, the moisture also evaporates through the joint. Cement mortars are impermeable and so the moisture circulates and evaporates through the stone causing severe stone decay. The material used for the restoration should be compatible with the original material and masonry used in the past.

CHAPTER 3

NATURAL BUILDING STONE

3.1 GENERAL

One of the attractions of natural building stone was the wide variety of colours and textures available to the designer. The problem associated with such a wide range was to choose the best stone for a specific purpose. The variety of stone was not restricted to colour or texture. Wide variations in durability and other properties may also be encountered.

A study of the geological map of Great Britain (Fig. 3.1) shows that the country has a great variety of rocks, but not every rock may be used successfully in construction. Some stones may be unaffected by centuries of exposure to the weather; others, if used in the wrong environment, may have to be replaced after a few years. Unlike colour and texture, durability was difficult to define and even more difficult to measure.

This chapter gives a brief introduction to the origin of stones, their nature and their basic classification.

3.2 ROCK FORMATION AND KINDS

Stones are natural materials and their colour, strength, weathering resistance and other physical properties are controlled by the method of formation and the geological history. Natural building stones used in constructions are classified according to the way in which their parent rock has been formed. Within each class there are variations of mineral content, both in proportion and type (BRE 1997). Stones can be placed geologically into one of three groups:

Fig. 3.1 – Geological map of Great Britain

3.2.1 Igneous rocks

Igneous rocks were formed from molten materials after cooling and solidification. The final texture of the rock depends on the rate of cooling which determines the size and form of the crystals. Those, which resulted from slow cooling and gradual crystallisation, are composed of larger, more perfect, crystals and have the coarser texture. When solidified beneath the surface of the earth from magma, as the molten material was called, they are termed intrusive rocks, while extrusive rocks are those formed on the surface from lava or volcanic fragments. Their nature will depend also on the chemical composition (Morgan and Walker 1971). Many have been found in Great Britain but only one kind (granite) has been commonly used in construction on a large scale (Fig. 3.2). The South-west of England and Scotland are the great granite producing areas of this kind of rock for buildings. Consideration of the igneous rocks for buildings was simplified if they are divided into three groups:

Fig. 3.2 – Edinburgh building made of granite stone

Plutonic rocks: The plutonic rocks were formed from magma buried at great depths below the surface of the earth and consequently crystallised very slowly to give them coarse texture. Outcrops occur wherever erosion has removed the top strata. The most common examples are the granites which are found in Cornwall and Devon and Aberdeen the 'Granite City'. Quartz, a form of silica, was the main constituent of the plutonic rocks, together with varying amounts of feldspar, a form of aluminium silicate. Other constituents include biotite, which was a black form of mica, an iron or magnesium silicate and hornblende, calcium, magnesium or iron silicate (Morgan and Walker 1971). The large crystal size of these rocks can be recognised by the naked eye and since feldspar itself may be coloured, the spotted appearance and colour of some granites was visually recognisable (Fig. 3.3).

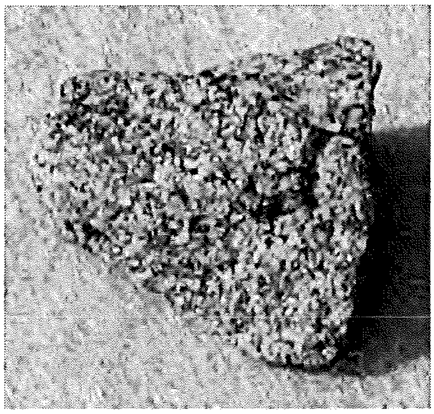


Fig. 3.3 – Granite rock

Hypabyssal rocks: These are formed by the injection of the molten material into crevices in the surrounding rocks where it cools more rapidly resulting in rocks of finer texture than plutonic rocks. An example was dolerite, which occurs in sills sheets that have intruded under a thin layer of other rocks. The Great Whin Sill has been formed in this way. It runs from the Pennines above the Vale of Eden through Teesdale and then north-eastwards to Bamburgh and the Farne Islands. It was valuable as a road making aggregate but it was not favoured for buildings because of its dark colour (Morgan and Walker 1971).

Volcanic rocks: The volcanic rocks were formed from the molten material, which was forced up to the Earth's surface and extruded as lava. Rapid cooling produced a rock which was composed of very fine crystals or was even non-crystalline. The most common example was basalt, a green or dark blue, heavy grained rock consisting largely of feldspar and containing iron and magnesium. The grains can only be distinguished under a microscope. Its main use was in road construction and not for buildings because of its dark colour, difficulty of cutting and shaping which makes its use in buildings complicated (Morgan and Walker 1971).

3.2.2 Sedimentary rocks

The sedimentary rocks are formed as a result of the erosion and disintegration of older rocks, the collection and layering of organic remains and the precipitation of salts from solution. Those composed of fragments of older rocks are called 'Clastic' and 'Detrital' rocks. Sandstone and shale rocks are one of these kinds. They consist of grains of sand and mud cemented together by a binder (Fig. 3.4).

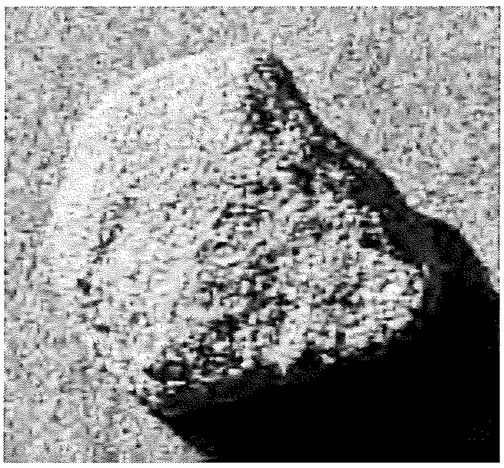


Fig. 3.4 – Sandstone rock

Water was an extremely powerful solvent and as the streams and rivers make their way to the sea they are constantly searching out and dissolving any salts which lie in their path. The sea itself performs similar action by eroding soluble salts. All kinds of salt are soluble to some extent which makes the sea a source of immense material wealth.

Sandstone and limestone are converted into rock by lithification, which involves compaction and then cementation in which the water was squeezed from between the particles and replaced by some material capable of binding the solid particles together. The most common binding materials are calcium carbonate, silica and iron oxide. Sedimentary rocks are the most common kind of rock which underly most of the earth's surface, metamorphic rocks are the most common in order of occurrence, whilst the igneous rocks are restricted to peculiar geological environments. As would be expected from the way in which the sediments accumulate in layers the sedimentary rocks have marked stratification with frequent changes in colour, texture and mineral content (Morgan and Walker 1971).

Most of the sedimentary rocks are not suitable for use as building stones. The nature of the grains, the type of mortar holding them together and the extent to which the cementing action has progressed all play part in deciding the properties of the rock and its suitability for use in construction. However, sandstone and limestone are two of the most important sedimentary rocks commonly used in buildings (Fig. 3.5).

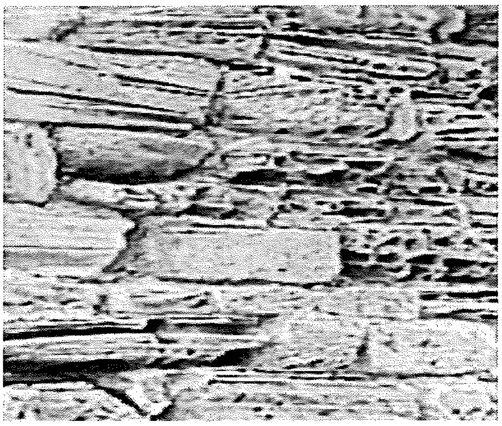


Fig. 3.5 – Sandstone wall

3.2.3 Metamorphic rocks

Metamorphic rocks are formed from pre-existing igneous and sedimentary rocks that have undergone changes below the Earth's surface caused either by pressure, heat, or both. The pressure and heat work simultaneously to produce a rock that was significantly different from its parents.

A good example is the effect of pressure and heat on feldspar which was an igneous rocks consisting of crystalline silicates and aluminium together with sodium, potassium or barium. When feldspar was exposed at the Earth's surface it readily weathers to clay and ends up as a fine textured sedimentary deposit. But if this clay becomes buried under layers of sediment and subjected over a lengthy period of time, to a high pressure and temperature, it changes to metamorphic rocks such as garnet or a semi-precious stone. Some of the species are so attractive they rival rubies (Morgan and Walker 1971).

One of the characteristics of metamorphic rocks was its foliated structure, being arranged as leaves or flat plates, in which the foliation planes grow at right angles to the direction of the pressure. In some metamorphic rocks these planes correspond to the original bedding planes but this was not always the case. Most metamorphic rocks have a good resistant to erosion than most sedimentary rocks. One of the most widely used in construction in Britain was slate (Fig. 3.6). Slate was found chiefly in Scotland, the Lake District, North Wales and Cornwall. Other forms of metamorphic rocks have little use in buildings such as marble.

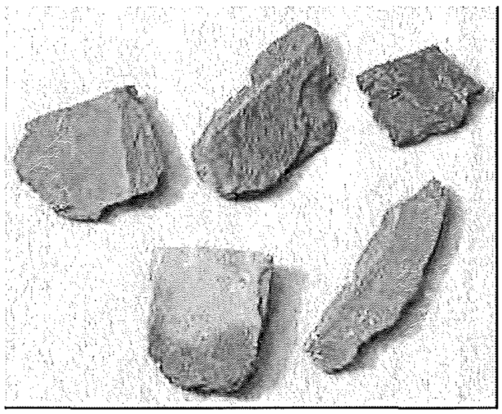


Fig. 3.6 – Slate rock

3.3 STONES FOR BUILDINGS

Some constraints inherited in stones limit their suitability for use in buildings. Igneous rocks may contain minerals which on exposure to the atmosphere may results in disintegration of the rock. Rising ground water with salt may cause spalling to some types of stones (Fig. 3.7). Sedimentary rocks should be placed in a wall in such a way that the load was applied normal to the natural bedding planes. Metamorphic rocks may have harmful minerals which limits their use. The greatest restraint in the use of stone was that of the jointing. All rocks are naturally jointed and this controls the size of the block that can be wrought from a quarry.

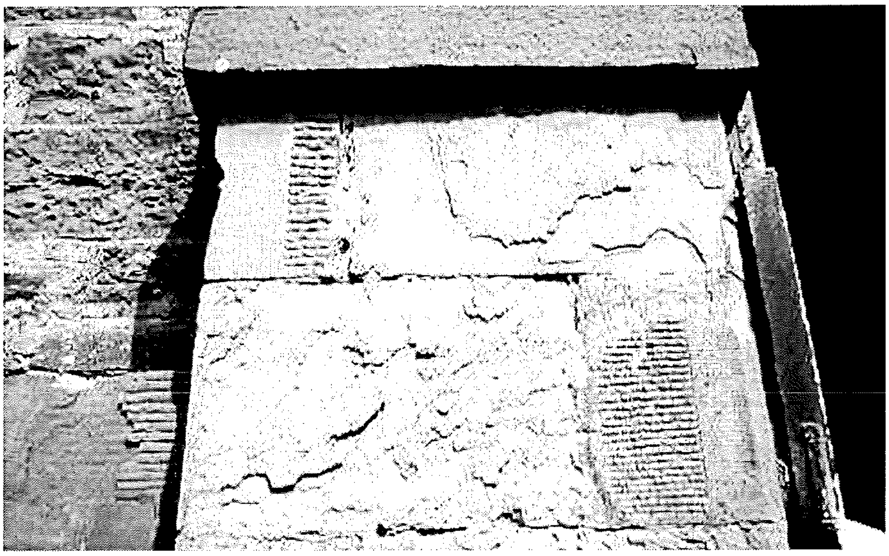


Fig. 3.7 – Stone wall showing spalling

Such constraints are minor compared with the benefits of using stones in construction. Stone from all the above groups, whether used in classical idiom or in contemporary form, will have durability other materials cannot match or provide. The identification of the type of stone was important when planning a new stone building in the vicinity of existing one or for repair and restoration work. The importance arises from matching materials for compatibility.

Despite their great variety, relatively few types of stones are suitable for masonry construction. In addition to accessibility and ease of quarrying, the stone must satisfy the requirements of strength, hardness, workability, porosity, durability and appearance. Some of the stones that satisfy these requirements are granite, limestone, sandstone, marble and slate.

3.3.1 Granite

In geological terms, granite was an intrusive igneous rock composed of crystals of quartz and of potassium and sodium feldspars, with a minor content of biotite and muscovite mica. Colours vary depending on the amount and type of secondary minerals. The mineral present in the greatest quantity was feldspar. Granite was classified as fine, medium or coarse grained texture.

Granites are well known for their durability and hardwearing qualities in many types of environment. They are generally very resistant to weathering and have high strength. The hardness of the stone lends itself to a finely polished surface which makes sawing and cutting very difficult.

3.3.2 Limestone

Limestone was a sedimentary rock, which was widely distributed throughout the Earth's crust as described in Section 2.2. The rock was durable, easily cut and worked with.

3.3.3 Sandstone

Sandstone was a sedimentary rock formed of sand or quartz grains cemented together by matrices of different compositions. The most common mineral grains are quartz, micas, feldspars and clays. The cementing medium holds the grain together but does not necessarily completely fill the voids between the grains. The stone porosity will be found both between and within the grains.

Sandstones are classified according to their texture and nature of the cementing materials which largely governs their resistance to erosion. The cementing materials which are holding the sand grains together may be calcareous, dolomitic, siliceous or ferruginous. The sandstone rocks can be classified as follows:

- Siliceous sandstones are lighter and harder than those cemented by carbonate. This makes them harder, difficult to work with and are considered to be the strongest sandstones.
- Ferruginous sandstones: Grains are cemented with iron oxides, either red oxides or brown hydrated oxide. The stones are soft, easy to cut and work with.
- Calcareous sandstones: Grains are cemented by calcium carbonate (lime) which formed as calcite. A small amount of this in the stone makes it easy to cut and work with but reduces its resistance to weathering. The calcite as a material was subject to attack from airborne acids and calcareous sandstone are therefore prone to deterioration in urban and industrial environments.
- Dolomitic sandstones: Grains are cemented by dolomite. They have better resistant to acid-based rain, compared with calcareous sandstone.
- Argillaceous sandstones: Grains are cemented by clay. They are soft and easy to work with but have low durability and disintegrate by weathering (Morgan and Walker 1971).

Sandstones in general are considered to have better resistant to chemicals in humid environments. They are available in a wide range of colours compared to limestone. Highly coloured varieties have dominated the building sandstone trade at various times and places. (RILEM/UNESCO 1997).

3.3.4 Slate

Slate was metamorphic rock, formed from clay deposits which have been subjected to high pressure and heat over a long period. The heat produces shells which are weak to be used as a building stone but have been used as a retarder for Portland cement. The pressure on the other hand, not only hardens the clay, but also realign the flakes of mica and other minerals into planes of cleavage at right angles to the applied pressure. It was along these plains that the slate could easily be split into sheets. Some slates are formed not from clays but from volcanic ash. Like sandstone, the durability of slate was affected by their chemical composition. Slate was very susceptible to physical weathering. Exposed slate appears grey or grey-black although other colour varieties can exist.

3.3.5 Marble

Geologically, marble (Fig. 3.8) was a metamorphic rock formed by re-crystallisation of limestone or dolomite through some combination of heat and pressure. Various rocks of other origin are classified as trade marbles. Pure calcium carbonate yields a white marble, while the presence of other minerals gives a colour or figured marble. Of all the building stones, marble presents the widest variety of colours. The colours are due to impurities in the original sedimentary rock. During the formation of marble the heat drives some of the carbon dioxide from the limestone and the remaining calcium oxide combines with any silica and other impurities such as iron to give the coloured veined and mottled effects (Morgan and Walker 1971).

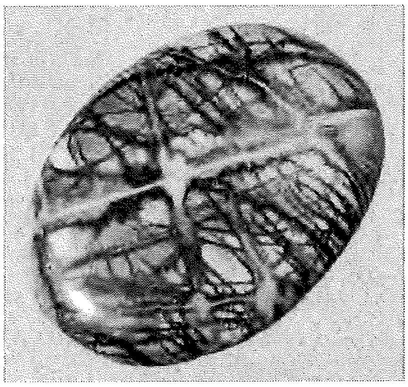


Fig. 3.8 – Marble stone

Marble does not have the parallel structure possessed by many of the metamorphic rocks but has a compact or massive structures, the crystalline grains are so small that they cannot be distinguished except under a microscope. Slate and marble therefore require different working techniques. Their low porosity and water absorption gives marble a good resistant to weathering. However, they erode by acidic rain and are affected by acidic gases.

3.4 TYPES OF STONE WALLING

3.4.1 Ashlar

Ashlar (Fig. 3.9) has defined and carefully worked beds and joints. Jointed in no more than 4.5mm joints and set in horizontal courses. The stones within each course should be of the same height, although successive courses may be of different heights. Ashlar was described according to its final surface finish.

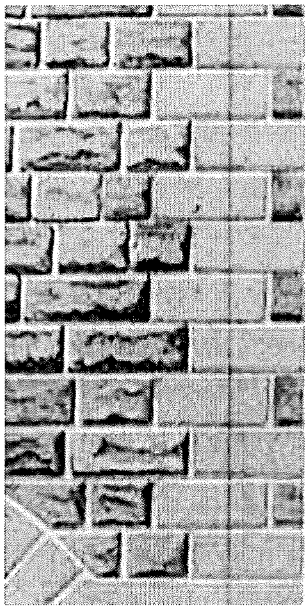


Fig. 3.9 – Ashlar walling

3.4.2 Block-in-course

This was rather an old-fashioned term to describe the large blocks of masonry walls seen in dock and railway engineering. The blocks are squared and brought to fair joints, and the faces are usually rock-faced. Massive solidity rather than sophistication was the keynote of this class of work.

3.4.3 Rubble

The majority of ancient buildings in this country are built in coursed or random rubble, and many have stood for centuries without any maintenance. Rubble was much more cost effective than ashlar. Rubble depends more on the hold of the mortar than ashlar.

3.5 STONE WEATHERING

Decay and disintegration of building stone was due mainly to chemical attack by gases present in the atmosphere and by temperature fluctuations, especially in the presence of water. Atmospheric carbon dioxide (CO_2) dissolves in water to form carbonic acid, which attacks the calcium carbonate present in limestone and calcareous sandstone (Morgan and Walker 1971). The calcium bicarbonate was then washed away, and in the case of sandstone, the individual grains of sand are no longer cemented together to stand washing out by rain (Fig. 3.10).

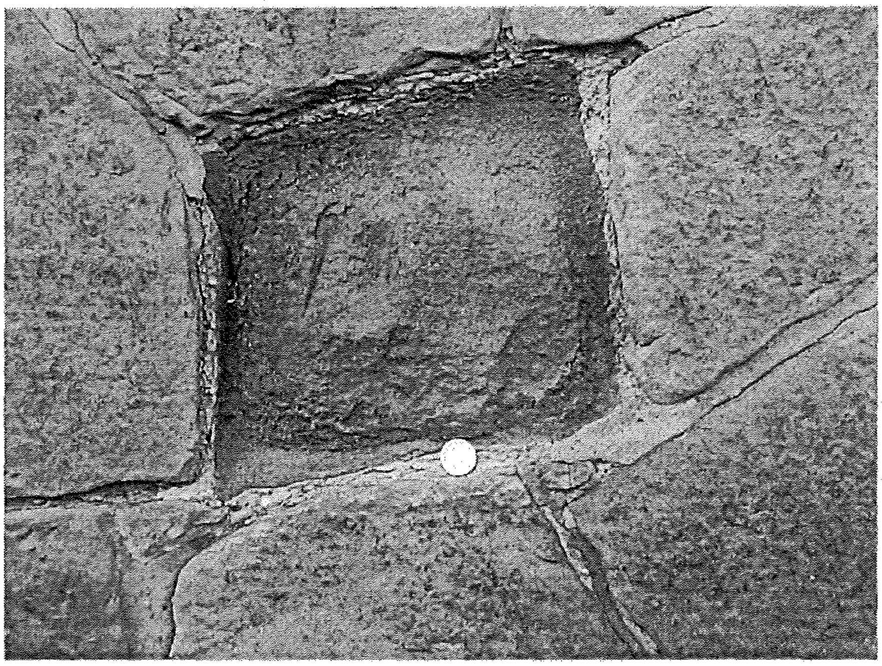


Fig. 3.10 – Weathering of a stonewall

Atmospheric sulphur dioxide (SO_2) likewise dissolves in water and attacks calcium carbonate to form calcium sulphite. The calcium sulphite then combines with atmospheric oxygen to form calcium sulphate, which crystallises from solution as gypsum. In addition the carbonic acid released from the chemical reaction continues to attack the stone.

Sulphur trioxide (SO_3) when present in the atmosphere, dissolves in water to form sulphuric acid, which produces calcium sulphate directly from calcium carbonate. The sulphur gases are present to serious extent in large towns, cities and industrial areas (Morgan and Walker 1971).

Stone walls in a building are liable to attack by physical forces, which cause some erosion. Temperature variations cause the stone to expand and contract, the action of frost also weakens the stone. The movement of water by capillary action allows salts in solution to be transferred within the structure. The salts may then crystallise as water evaporates. Sandstone was particularly prone to this sort of damage. There are three main categories which speed up the rate of stone weathering and decay. These are: natural defects in the material, faulty craftsmanship and errors in the choice of materials.

3.5.1 Natural defects in material and human errors in construction

Soft beds: It was mentioned earlier that sedimentary rocks form in layers. The weathering characteristics will therefore vary, depending on the layer from where the stone has been taken. Sedimentary stone quarried from rocks containing several layers may yield different qualities of stone. Frequently the various layers are distinguishable and soft beds susceptible to weathering and decay can be avoided.

Vents and shakes: A more serious defect was the presence of fissures in the stone arising mainly from geological movements. The fissures may be so small that they cannot be noticed until the stone was worked or weathered. Sometimes calcite has been deposited in the fissures, which have a cementing effect. The term vent was applied to a fissure which were prone to weathering and their presence may have serious consequences especially if the stone was used for decorative purposes. The term shake was used for a type of fissure which has been sealed by calcite. The presence of shakes does not have a serious effect on the durability of stone. Shakes in limestone walls can often be seen quite easily where they have weathered more slowly than the host stone.

Bedding: It was recommended that stones with laminated structure, which originally quarried from sedimentary rocks, should be laid with the laminate in a horizontal position to the applied load. This inhibits any tendency for the laminate to separate when exposed to the weather and was called 'natural bedding'. In special situations, such as cornices, parapets and string courses, placing the stone with the laminate in a vertical position was preferred to avoid the loss of mouldings and throattings. This 'edge bedding' (alternatively termed joint bedding) introduces no loss of weathering resistance provided it was not used at corners. Care should be taken to ensure that the stone was bedded evenly. If it was cut inaccurately, carelessly set or there are pebbles in the mortar, the stone will be unevenly stressed and liable to spall.

Seasoning: Freshly quarried stone contains certain amount of moisture, known as 'quarry sap', which should be allowed to dry out before the stone was used. There are a number of reasons to dry the stone before use. These are: (a) to avoid frost damage: if unseasoned stone was used the water it contained may freeze and cause disintegration of the stone, (b) to avoid flaking: it has been discovered that if the stone was carved while it was still green the surface may flake away in use, (c) to avoid decay: during seasoning most of the salts present in quarry sap concentrate at the surface and can be removed during construction. This reduces decay, which was attributed to the crystallisation of salts within the stone (Morgan and Walker 1971).

Quarrying and dressing: The selection of good quality stone was a measure of experience of the quarry men but even when this has been done it may be marred if the quarrying and subsequent dressing are not executed with care. The major points with regard to this are: (a) blasting: it was important that only moderate charges of powder be used to avoid cracking the stone. Even minute cracks will take in water and reduce the useful life of the stone, (b) bruising: hammer dressing, careless machine dressing, the use of blunt tools, or rough treatment of the stone after working, gave the stone a bruise which was likely to spall off in time.

Iron dowels: Dowels and cramps should be made from non-corrosive metals such as alloy steels or alloys of copper or nickel. If iron fittings are used the expansion arising from corrosion causes vents to appear in the stone and increases the rate of weathering.

Pointing: Excessive deterioration of stonework was caused by the application of dense Portland cement mortars.

Incompatible materials: Care must be taken to avoid the possibility of interaction of different types of stone. Sandstone and limestone must be kept separate. As limestone weathers calcium sulphate was produced which may be washed into the pores of the sandstone where it crystallises out of solution causing disintegration. Likewise limestone and magnesian limestone should not be used together since magnesium sulphate causes accelerated disintegration of the limestone.

3.6 CONCLUSIONS

Natural building stone have a wide variety of colours and textures available to the designers and engineers to use. Great Britain has a wide range of rocks but not every rock may be used successfully in construction. Some stones may be unaffected by centuries of exposure to the weather, others, may have to be replaced after a few years.

Despite their great variety, relatively few types of stones are suitable for masonry construction. In addition to accessibility and ease of quarrying, the stone must satisfy the requirements of strength, hardness, porosity, durability and appearance.

Stones are natural materials and their colour, strength, weathering resistance and other physical properties are controlled by the method of formation and the geological history. Stones can be placed geologically into one of three groups: igneous rocks, sedimentary rocks and metamorphic rocks.

Igneous rocks are formed from molten materials after cooling and solidification. Granite is the only kind of igneous rock commonly used in construction on large scale. Sedimentary rocks are formed as a result of the erosion and disintegration of older rocks, the collection and layering of organic remains and the precipitation of salts from solution. Sandstone and limestone are two of the most important sedimentary rocks commonly used in buildings. Metamorphic rocks are formed from pre-existing igneous and sedimentary rocks that have undergone changes below the Earth's surface caused either by pressure, heat or both. Slate is one of the metamorphic rocks which have little use in buildings because of the presence of some harmful minerals.

CHAPTER 4

STONE CLEANING

4.1 GENERAL

Cleaning of buildings facades has been a major activity for the construction industry, both in terms of financial outlay and the effect on the built heritage of our cities. Removal of the soiling layer has been perceived by the general public and building owners as a "good thing" because of the simplistic notion that a clean, bright facade reflects well on the urban environment in general and on the image of the building occupier in particular.

However, the inappropriate cleaning and waterproofing of masonry buildings was a major cause of deterioration of buildings. While both treatments may be appropriate in some cases, they may cause serious deterioration in others. The purpose of this chapter was to provide background information on the techniques used in cleaning and waterproofing of masonry buildings and to explain the consequences of their inappropriate use.

4.2 REASONS FOR STONE CLEANING

The reasons for cleaning any building must be considered carefully before arriving at a decision to clean. Some questions have to be answered before taking a decision, these were: (a) was there any evidence that the soiling and pollutants are having a harmful effect on the masonry? Improper cleaning can accelerate the deteriorating effect of pollutants, (b) was the cleaning being done to improve the appearance of the building or to make it look new? (Fig. 4.1) The "soiling" could be weathered masonry and not accumulated deposits, so a portion of the masonry itself may be removed if a "clean" appearance was desired (Fig. 4.1). These concerns may lead to the conclusion that cleaning was not desirable at least not until further study was made of the building, its environment and possible cleaning methods.

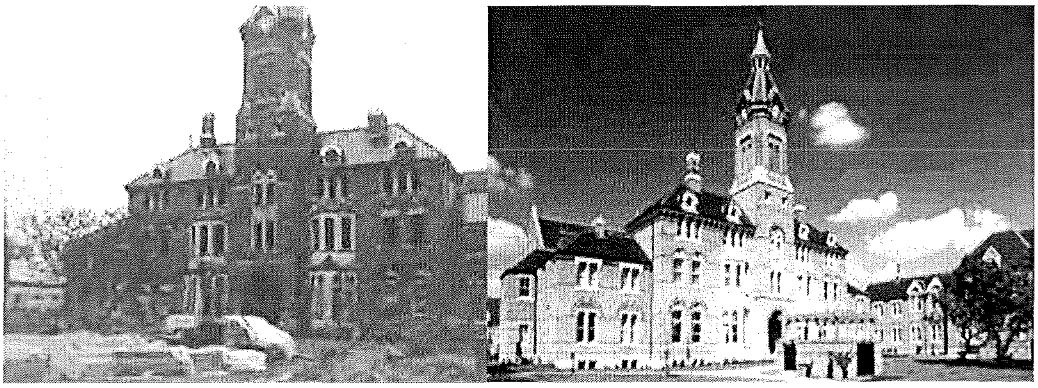


Fig. 4.1 – Building before and after cleaning

4.3 THE SOURCE OF SOILING

The soiling of building facades was a complex phenomenon that takes place at or near the surface of the stone and leads to a change in the appearance of the facade. The soiling can, for convenience, be sub-divided into two main groups (Verhoef 1988):

Non-biological soiling: This was caused by airborne particles (atmospheric constituents and pollutants, aerosols, soots, paint, aerosol-paint (graffiti) and iron staining of sandstone) (Fig. 4.2).

Biological soiling: This was due to the presence of microscopic flora (algae, fungi, bacteria and lichen) (Fig. 4.3).

Both types of soiling are likely to be present on stone surfaces. It was well recognised that soiling may be one cause of stone decay, leading to a loss of surface material. Alternatively, the soiling may take the form of surface discoloration.

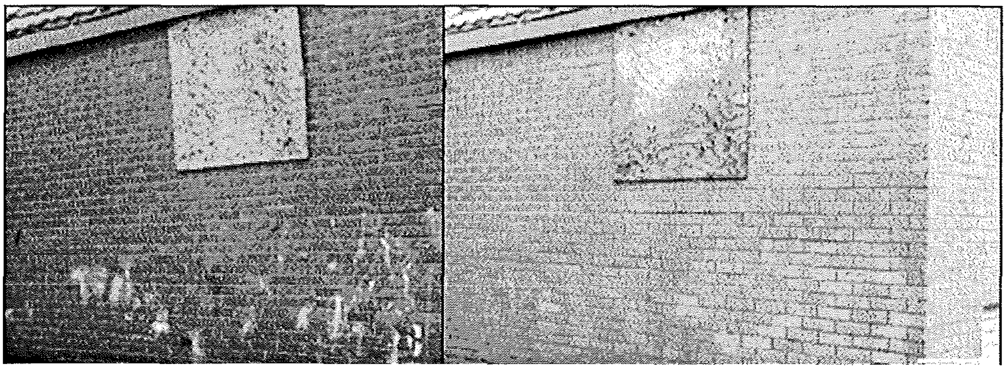


Fig. 4.2 – Non-biological soiling caused by graffiti before and after cleaning

Fig. 4.3 – Biological soiling

Non-biological soiling was influenced by atmospheric factors such as water, temperature, wind and microclimate effects and rainwater run-off. The conditions needed for the colonisation of biological soiling are water, light, temperature, pH and nutrition (Verhoef 1988).

Black soiling on older buildings, especially in urban areas, contains a high proportion of soot, tar and sulphur compounds from the coal burnt in domestic fires and factory boilers. Fine particles from petrol and diesel engines, black dust from vehicle tyres, fine dust from building sites, factories and open spaces, organic growths and bird fouling.

As well as giving a dark coating, soluble components of the soiling such as salts, acids and tarry liquids can be absorbed into the masonry and they may react with the mortar or masonry and become fixed. They may penetrate into the material to a depth of several millimetres. Sometimes they form a protective patina that reduces the risk of further deterioration. Alternatively, the surface can crumble or spall because of crystallisation effects. Bird fouling and organic growths can also cause chemical or physical damage (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005).

Urban soiling since the Clean Air Act can contain the above components with a higher proportion of deposits from oil-fired boilers and diesel exhausts, but less from the burning of coal. Recent soiling generally contains more organic growths. Soiling in rural areas was mainly composed of organic growths and wind-blown particles (Leynaud 2001).

The general nature and source of soiling on a building must be determined in order to remove it in the most effective, yet least harmful, manner. Soot and smoke (Fig. 4.4), for example, may require a different method of cleaning than oil stains or bird droppings. The soiling may weather or discolour a portion of the masonry itself rather than extraneous materials. Removal of part of the masonry thus would be required to obtain a clean appearance, leading to loss of detail and gradual erosion of the masonry (Fig. 4.5). Other common cleaning problems include metal stains such as rust or copper stains and organic matter such as the tendrils left on the masonry after removal of ivy. The source of soiling, such as coal soot, may no longer be a factor in planning longer-term maintenance, or it may be a continuing source of problems. Full evaluation of soiling and its effect on the building may require one or several kinds of expertise, consultants of soiling and its effect on the building, the conservators, the geologists, the chemists and the preservation architects. Other sources of local experience or information may include building owners in the area, local universities, Historic Scotland and the English Heritage.

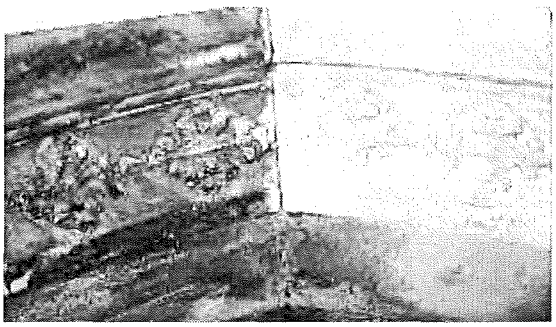


Fig. 4.4 – Stonework starting to be cleaned up from soot and smoke

If the proposed cleaning was to remove paint, it was important in each case to learn whether or not exposed stone was historically appropriate. Many buildings were painted at the time of construction or shortly thereafter, retention of paint, therefore, may be more appropriate historically than exposing the stone. Even in cases where unpainted masonry was appropriate, the retention of the paint may be more practical than removal in terms of long-term preservation of the masonry. In some cases removal of the paint may be desirable, for example, the old paint layers may have built up to such an extent that removal was necessary prior to repainting. It was essential that research on the paint type, colour and layering be completed on the entire building before removal of any subject matter (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005).

Fig. 4.5 – Eventual erosion of stone from cleaning

4.4 MATERIALS USED IN CONSTRUCTION

Advance knowledge of the materials used in construction of a building must be considered in developing a cleaning program because inappropriate cleaning can have a corrosive effect on both the masonry and the other building materials.

Incorrectly chosen cleaning products can cause damage due to chemical reactions with the masonry. For example, the effect of acidic cleaners on marble and limestone was well recognised. Understanding of the physical and chemical properties of the masonry can help avoid the inadvertent selection of damaging cleaning materials.

Other adjacent building materials may also be affected by the cleaning process. Some chemicals used in cleaning have a corrosive effect on paint or glass. The portions of building elements most vulnerable to deterioration may not be visible, such as embedded ends of iron window bars. Other totally unseen items, such as iron cramps or ties, which hold the masonry to the structural frame, may also be subject to corrosion from the use of chemicals or even from plain water. The only way to prevent problems in these cases was to study the buildings construction in detail and evaluate proposed cleaning methods with this information in mind (Leynaud 2001).

Previous treatments of the building and its surroundings should be evaluated first, if known. Earlier waterproofing applications may make cleaning difficult. Previous repairs may have stained the building and any cleaning may make these differences apparent. Salts or slow removal chemicals used on other parts of the building may have dissolved and been absorbed into the masonry, causing potentially serious problems of spalling or efflorescence. Techniques for overcoming each of these problems should be considered prior to the selection of a cleaning method.

4.5 METHODS USED IN CLEANING

Cleaning methods generally are divided into three major groups: water, chemical and mechanical (abrasive). Water cleaning softens the soiling and rinses the deposits from the surface. Chemical cleaners react with the dirt and/or masonry to hasten the removal process. The deposits, reaction products and excess chemicals were rinsed away with water (Fig. 4.6). Mechanical methods include: sand blasting, grinders and sand discs, which remove the dirt by abrasion, are usually followed by a water rinse (Verhoef 1988).

The potential effect of each proposed method of cleaning should be evaluated carefully. Chemical cleaners, even though diluted, may damage trees, plants and grass. Animal life, ranging from domestic pets to birds to earth worms, may be affected by runoff. In addition, mechanical methods can produce hazards through the creation of airborne dust. The chemical and mechanical cleaning methods may cause property damage. Wind drift may carry cleaning chemicals onto nearby vehicles, causing etching of the glass or spotting of the paint finish. Similarly, airborne dust can enter surrounding buildings and excess water can collect in nearby gardens and cellars. The potential health dangers of each method proposed must be considered and the dangers avoided. Both acidic and alkaline chemical cleaners can cause serious injury to the cleaner and passers by, injuries can be caused by chemicals in both liquid and vapour forms. Mechanical methods cause dust, which can pose a serious health hazard, particularly if the abrasive or the masonry contains silica. Steam cleaning has serious hazards because of the high temperatures.

Several potentially useful cleaning methods should be tested prior to selecting the one for use on the building. The simplest and least dangerous methods should be included as well as those more complicated. Often simple methods such as low-pressure water wash are not even considered, yet they frequently are effective, safe and the least expensive.

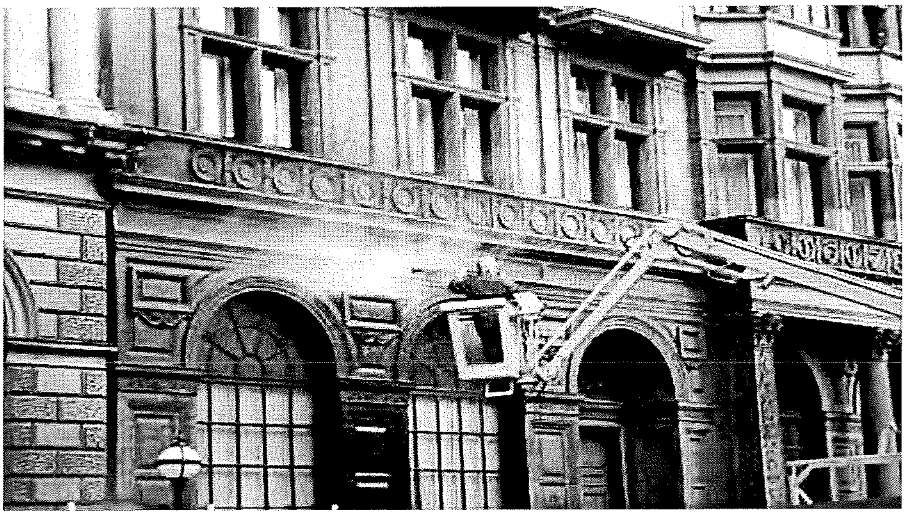


Fig. 4.6 – Rinsing away of chemical cleaners

Water of slightly higher pressure or with a mild non-ionic detergent additive may also be effective. These methods are safer for the building, safer for the environment and less expensive. Cleaning tests, whether using simple or complex methods, should be applied to an area of sufficient size to give a true indication of effectiveness (Verhoef 1988). It should be remembered that a single building may have several types of masonry materials and similar materials may have different surface finishes, each of these differing areas should be tested separately. The results of the tests may well indicate that several methods of cleaning should be used on a single building. When feasible, test areas should be allowed to weather for an extended period of time prior to evaluation (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005). A waiting period of a full year was not unreasonable in order to expose the masonry to a full range of seasons. For any building, which was considered historically important, the delay was insignificant to the potential damage and disfigurement which may arise from using an inappropriate method of cleaning.

The final level of cleanliness desired should be determined prior to selection of a cleaning method. Obviously, the intent of cleaning was to remove most of the soiling. A brand new appearance may be inappropriate for an older building. It may be wise, therefore, to determine a lower level of acceptable cleaning. The precise amount of residual soiling considered acceptable would depend upon the type of masonry and local conditions.

4.5.1 Water washing

Pressurised water was used to create a low-pressure fine mist over the surface of the stone for long periods of time (often days) (www.cr.nps.gov/tps/briefs/htm 2000-2004). The water dissolves or softens soiling which was then easier to brush off or rinse off at low-pressure. Water washing has some side effects, these are as follows:

- Using soft bristle brushes may still cause abrasive damage. If a brush was applied forcefully against the masonry surface, loose masonry and particles act as additional abrasives between the brush and the masonry.

- Washing with water under low pressure can lead to saturation of the masonry and penetration to the internal fabric of a building.

Water washing was not normally used on granites and sandstone where it was generally ineffective and could lead to efflorescence. Water washing was effective to clean limestone where the dirt, which was generally bound to calcium sulphate, was easily softened and washed away. High-pressure washing can be physically damaging to stone, particularly decaying stone.

Deposits on sandstone are not water-soluble and water can only remove a small amount of surface dirt. Sandstone buildings are typically cleanest in those parts sheltered from rain, where water-borne pollutants do not reach. Most of the pollutants on limestone, on the other hand, are water-soluble. Which explains why those areas, regularly washed by rain, stay cleaner than the sheltered areas where deposits were allowed to build up.

Washing with clean water will not only remove the visible dirt, but will also remove some of the damaging salts and extend the life of the stone (Verhoef 1988). Soaking the surface was liable to give rise to staining, as dirts and salts are drawn to the face. The ideal solution was an intermittent spray, which softens the dirt without either soaking the stone or causing heavy run-off.

Water jets and lances: Many cleaning products and systems involve high-pressure water to rinse away cleaning residues (Fig. 4.7). However, unscrupulous operators may use high-pressure jets to remove the soiling itself and to improve the effectiveness of other cleaning systems (www.rgu.ac.uk/schools/mcrg.htm 1995-2005). The jets are very powerful and can destroy many building materials at close range. Trial cleaning will determine the correct pressure and distance for achieving a rinsing effect without risking a cutting action. There are two side effects associated with water jets and lances methods. Frost may damage water soaked surfaces, and loose or soft mortars may be washed out of joints.

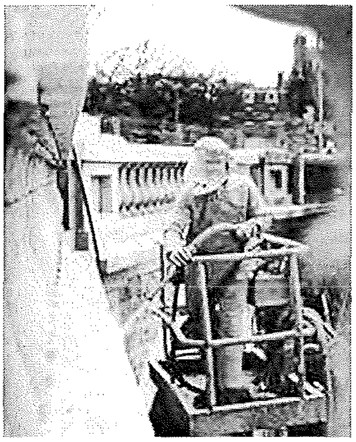


Fig. 4.7 – Water lances

High-pressure jets and lances are used from a stand-off position, as a rinse to remove dust or cleaning residues. The water from a jet or lance, used at a distance from the building, loses much of its pressure between the nozzle and treatment surface. The speed of the spray at the masonry surface was just sufficient to remove residues without damaging the surface.

At closer distances and at high pressures, water jetting was also used as primary abrasive method of removal. Water from high-pressure lances was capable of cutting some masonry materials and so there was risk of damaging the wall surface. This method was suitable for use on impact-resistant surfaces (www.cr.nps.gov/tps/briefs.htm 2000-2004). It was rarely suited to any heritage masonry. Chemicals should not be introduced into the water stream, as they will be forced deeply into the stone for removal by rinsing.

Low-pressure water lances: Low-pressure water lance from a stand off position (i.e. not at close range), was used for wetting down walls prior to chemical treatments, removing loosely attached soiling, softened soiling, organic growths and for rinsing after wet-grit blasting or chemical cleaning where it rinses off dirt or chemicals remaining on the stone surface (www.cr.nps.gov/tps/briefs.htm 2000-2004).

Steam or hot water: Steam cleaning uses super heated water vapour and water particles with the jetting method in order to aid the removal of alkaline cleaners, solvent-based graffiti removers and some modern paints. However, this method was only considered if cold washing was ineffective as heating complicates the process.

Steam cleaning has been used with alkalis, which can lead to efflorescence, and humidity stains in more porous stones so it was important to test its effect on the stone before hand. It was also important to test the effects of the high temperatures on the stone.

Pre-soaking of stone to be steam cleaned can improve performance. It was effective at getting rid of organic growth but it was slow and expensive and potentially dangerous to the operator.

4.5.2 Chemical cleaning

Chemical cleaning methods work by chemical reaction between the cleaning agent and the soiling on the surface of masonry. The stone must be thoroughly wetted before the acid/alkali was applied. This was necessary to prevent the acid/alkali being drawn deeply into the stone. The stone should be allowed to dry out prior to rinsing (Verhoef 1988).

A liquid acid cleaning regime might involve the following steps:

1. Pre-wet the stone.
2. Apply alkaline degreaser and allow dwelling for an appropriate length of time.
3. Thoroughly wash off with high-pressure water spray.
4. Apply acid cleaner and allow dwelling for the correct length of time.
5. Wash off with high-pressure water spray.

An alkaline poultice cleaning programme might involve:

1. Application of poultice to dry stone.
2. Cover with plastic sheet to prevent drying.
3. Leave for stated time.
4. Unwrap and scrape off poultice.
5. Rinse off with water.
6. Apply neutralising wash and allow dwelling for stated time.
7. Wash with high-pressure water spray.

Alkali treatments often include a neutralisation stage after application to avoid surface salts appearing. Neutralisation fixes the salts so that they remain below the masonry surface but not in a form, which allows them to crystallise on the surface. Weak acid may be specified to neutralise any alkalis remaining after cleaning (www.cr.nps.gov/tps/briefs.htm 2000-2004).

Chemical cleaning agents can include acid and alkali cleaners, caustic and solvent cleaners, hypochlorites, amines and biocides. The cleaners range from strong acids (low pH) through near-neutral detergent (pH 6 to 8) to strong alkalis (high pH). There are two basic types of chemical cleaner, acid and alkaline (www.cr.nps.gov/tps/briefs.htm 2000-2004).

Acidic cleaners: Acidic cleaners can work either by dissolving some of the masonry material to release the soiling, or by dissolving the iron or calcium component of the staining.

Hydrofluoric acid (HF) was capable of dissolving all minerals in stone and can be very damaging if improperly used. HF was commonly used to clean sandstone. Suitably diluted, it was very useful because it leaves no soluble salts in the stone. It was often used in conjunction with orthophosphoric acid, which reduces the risk of any iron staining. If HF alone was used, it will dissolve small quantities of iron, which are often present in the stone and leads to unsightly rusty stains (Verhoef 1988).

HF works by dissolving the silica in the stone. This breaks the bond between the dirt and the stone and allows the dirt to be washed away along with the silica. The acid was brushed or sprayed at low-pressure onto the stone. It should not be left on for too long before washing as it may cause blooms of silica on the surface. These are formed by redeposition of silica, dissolved out of the stone by the acid. Hydrofluoric acid can also cause bleaching of the stone (Verhoef 1988). Acid cleaners are generally unsuitable for limestone, calcareous sandstone and polished stone, and they can etch mortar joints. Calcareous sandstone was very easily damaged by hydrofluoric acid which dissolves the calcite cement leaving the sand grains loose.

Alkaline cleaners: Alkalis (sodium hydroxide) are used as degreasers prior to application of acidic cleaners. These are not recommended for use on sandstone due to its high porosity. Severe damage can result from crystal growth of sodium salts from alkali left in the stone. The alkali may be deeply absorbed into a porous stone or gain access through defective mortar joints. Alkalis soften dirt deposits and allow easier washing off of surface stains. Alkaline cleaners should not be used on stones with relative high iron content as treatment can result in staining by ferric hydroxides (Verhoef 1998).

Chemicals can be applied to masonry surfaces by brushes or sprays where they dissolve, bleach or soften soiling. They can be combined with specially designed thickeners, gels or poultices to provide a safer medium for applying potentially harmful substances.

Table 4.1 - Common active components of chemical cleaning agents

Alkalis	Acids
Ammonia Sodium bicarbonate Sodium carbonate Sodium hydroxide	Ammonium hydrogen fluoride Hydrochloric acid Hydrofluoric acid Phosphoric acid Sulphuric acid

Thickeners, poultice and gels: The physical nature of cleaning agents was usually modified by the addition of relatively inert materials which control the viscosity. The same chemical applied with different thickeners, gels or poultices may have different cleaning effects (www.cr.nps.gov/tps/briefs.htm 2000-2004).

Chemicals can be prepared with a thickener which allows small amounts of chemical to be maintained on the surface longer. This can reduce waste and increase effectiveness, but lead to over applications.

Poultice or pack materials can contain absorbent clays, paper pulp or methylcellulose. They are used for cleaning and for drawing out salts and stains from within building materials. They can be mixed with chemicals for controlled coverage of treatment areas. This method was developed for cleaning statuary and marble but has been extended to cleaning other stones including sandstone (Leynaud 2001). The poulticing material should be inert and porous with a large surface area and be able to absorb large volumes of water or other solvents.

4.5.3 Mechanical (abrasive) cleaning

Mechanical (abrasive) techniques can include air abrasives (i.e. sand blasting, soft media abrasives, and micro-air abrasives), grinders and sand discs (Fig. 4.8).

These can be sub-divided into water systems carrying abrasives and dry air abrasives.

Air abrasives: Abrasive particles, commonly sand or flint, are blown through nozzles by compressed air against the masonry surface to scour away the dirt. Abrasive cleaning can be difficult to specify accurately because of the range of services and systems, nozzles, particles sizes, flow rates and pressures that can be produced for very different rates and sensitivities of cleaning.

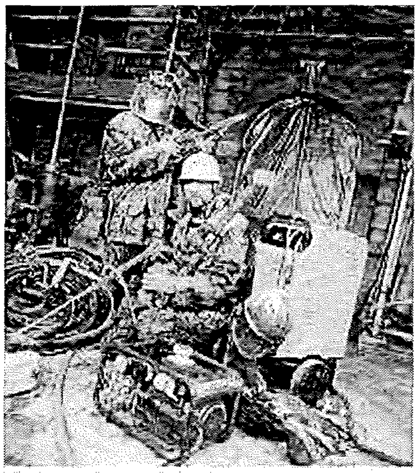


Fig. 4.8 – Equipment used for air abrasion

The effects of abrasive cleaning can change substantially at different distances from the stonework. In practice, this technique was difficult to control and it was easy to cause severe damage to a building.

During cleaning, abrasive particles knock or cut off particles of soiling and often particles of masonry. Abrasive cleaning methods cannot remove deeply penetrated stains without removal of the masonry to an equivalent depth.

For best results, abrasion should be followed by washing with a high-pressure water lance to remove all loose dust since otherwise any dirt left on the surface of the stone will be washed back into the pores by the next heavy rain shower and staining may result (www.cr.nps.gov/tps/briefs.htm 2000-2004). This method should not be used on smooth or polished surfaces or on areas of delicate architectural details or carvings (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005). The advantages of air abrasion are:

- Air abrasion techniques will lead to an even finish if operative was skilled in the use of a widespread nozzle.
- Removal of heavy soiling was relatively quick.
- Absence of the use of water washing, there was no risk of water penetration, staining and efflorescence from soluble salts or frost damage.
- Removal of soiling from irregular surfaces and pores in masonry.

The disadvantages of air abrasion are:

- The disadvantages of the air abrasion method can take the form of erosion of material from bedding planes or inclusions within stone, or uneven erosion due to nozzle design or operative technique.
- Pitting and patina, and the softer part of joints can be removed from masonry.
- The definition of arises, features and textures may also be removed or reduced.

Techniques used in air abrasion:

Low-pressure air abrasive: Low-pressure air abrasion uses fine abrasives at a low pressure. It was capable of removing soiling and organic growths but caution was required to avoid destruction of the natural patina or undue erosion of the surface. It was suitable for use on tooled stonework. This method was designed to reduce the type of damage caused by high-pressure blast methods.

Micro-air abrasion: Micro-air abrasion uses very fine particles of abrasive ejected in a narrow air stream from pencil guns (Verhoef 1988). The technique can achieve very controlled cleaning of complex surfaces with minimum damage to the original surface. Because it was very time-consuming, it was only used for cleaning surfaces or features of heritage value.

Wet-air abrasion: Wet-air abrasion introduces a small amount of water into an airflow containing abrasive particles to make slurry (Verhoef 1988). The process uses a minimal amount of water, produces much less dust and uses less abrasive materials than the dry method. It was also less harsh than dry blasting. This technique has some of the disadvantages of both water and dry air abrasive systems. These include risk of damage to the surface and risk of staining from tarry deposits washed out of pores.

After cleaning, the stone should be rinsed down to remove any dirt and grit adhering to the stone. This method should not be used on smooth or polished stone.

High-pressure water abrasion (hydroblasting): This method was similar to wet air abrasion but uses more water at higher pressures (Fig. 4.9). Less abrasive materials are used than in wet air abrasion. The effect of the water was supposed to be a reduction in the impact of the abrasion due to the cushioning effect of the water.

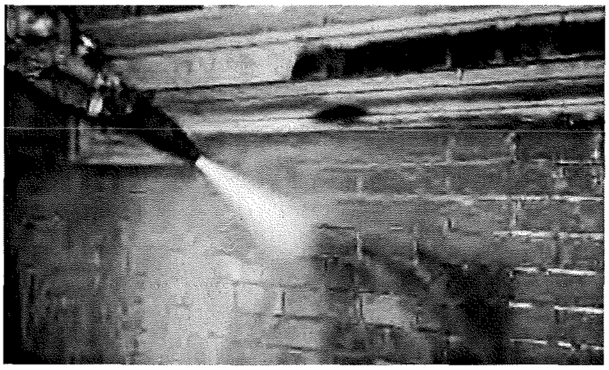


Fig. 4.9 – High- pressure water abrasion

Brushes, scrubbing and direct abrasion: Abrasion was used directly to remove soiling from surfaces. The tools used are:

- Soft, fine wired phosphorous brushes may be used on loose moss and some lichens.
- Brushes with soft but very short fibers can produce a substantial degree of abrasion.

Even with soft fibers, brushes may exert a substantial amount of abrasive force in cleaning. The loose masonry grains act as an abrasive material under the brush as it was moved backwards and forwards.

Using a scrubbing brush was the simplest form of mechanical cleaning but this would remove only loose dirt from the surface including efflorescence and lime bloom. If used with a bucket of water, a certain amount of ingrained dirt may be loosened. Steel wire brushes must never be used, only natural or synthetic bristle, or soft bronze wire, because of the risk of rust staining masonry and other surfaces (Verhoef 1988). Any brush can damage the surface of a soft or decaying stone, so care must be used in their selection.

4.6 POTENTIAL PROBLEMS WITH STONE CLEANING

A limited preliminary study by Roberts and Urquart (from the Masonry Conservation Research Group in 1995) investigated the incidence of decay as a result of stone cleaning at four terraces in Edinburgh and Glasgow. Whilst the results of this study were inconclusive due to the small sample size there was nevertheless clear evidence that stone cleaning increased the incidence of granular disintegration on these terraces by 15-20% when compared to uncleaned facades (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005).

In general, facades that had undergone stone cleaning have been found to have a significantly higher incidence of stone decay and repair compared to uncleaned facades as investigated by Roberts and Urquart. On average, the amount of decay and repair on cleaned facades was approximately twice that found on uncleaned facades. The biggest difference between cleaned and uncleaned facades was in the amount of repair that had been carried out, with substantially more repairs on cleaned facades (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005).

All joints, including mortar and sealant, must be sound in order to minimise water penetration to the interior. Porous masonry may absorb excess amounts of water during the cleaning process and cause damage within the wall or on interior surfaces. Normally, however, water penetrates only part way through even moderately absorbent masonry materials.

Excess water can bring soluble salts from within the masonry to the surface, forming efflorescences. In dry climates the water may evaporate inside the masonry, leaving the salts slightly behind the surface, which may cause detrimental damage to the masonry exterior. Another source of surface disfigurement was chemicals such as iron and copper in the water supply.

Water methods cannot be used during periods of cold weather because water within the masonry can freeze, causing spalling and cracking. In spite of these potential problems, water methods generally are the simplest to carry out, the safest for the building and the environment and the least expensive.

Since most chemical cleaners are water based, they have many of the potential problems of plain water plus chemical aspects. Some types of masonry are subject to direct attack by cleaning methods. Acidic cleaners, even in diluted forms, as discussed earlier, dissolve marble and limestone, easily. Another problem may be a change in the colour of the masonry caused by the chemicals, not by removal of dirt, but by the cleaner leaving a hazy residue in spite of heavy rinsing. In addition, chemicals can react with components of the mortar and stone to create soluble salts, which can form efflorescences as mentioned earlier.

Historic stone buildings are particularly susceptible to damage from hydrochloric acid.

Results indicate that stone decay was most accelerated in the years immediately following cleaning. The effects of stone cleaning on decay rates appear to approach the normal background levels after about 20 years. However, this significant amount of "extra" decay can occur during this 20 year period (www.rgu.ac.uk/schools/mcrg/milong.htm 1995-2005).

Sand blasting, grinders and sanding discs all operate by abrading the dirt off the surface of the masonry, rather than reacting with the dirt and masonry as in water and chemical methods. Since the abrasive method does not differentiate between the dirt and the masonry, some erosion of the masonry surface was inevitable with mechanical methods, especially blasting. Although a skilled operator can minimise this erosion, some erosion will take place. In the case of brick, stone, detailed carvings or polished surfaces even the minimal erosion was unacceptable. Brick, a fired product, was hardest on the outside where the temperatures were highest; the loss of skin of the brick, exposes the softer inner portion to more rapid deterioration. Abrasion of intricate details causes a rounding of sharp corners and other loss of delicate features, while abrasion of polished surfaces removes the polished quality of stone. Mechanical methods, therefore, should never be used on these surfaces and should be used with extreme caution on others.

Sand blasting, unfortunately, was still widely used in spite of the above serious effects. In most cases, blasting will leave minute pits on the surface of the masonry. This additional roughness actually increases the surface area on which new dirt can settle and pollutants can react. Mechanical cleaning can erode mortar joints, especially those with lime mortar. In some cases, the damage may be visual, such as loss of joint detail or increased joint shadows. Joints constitute a significant portion of the masonry surface (up to 20% in a brick wall) so this change should not be considered insignificant. In other cases, the erosion of the mortar joint may permit increased water penetration, leading to the necessity for complete repointing.

Many practitioners have changed their methods of cleaning in the past decade in response to planning department guidelines, information and experience with respect to the potential damage, which may be caused to facades. Harsher forms of chemical cleaning and higher pressure abrasive methods are increasingly avoided. The overwhelming majority of practitioners have observed some detrimental effects of stone cleaning including erosion, increased biological growth, discoloration, spalling and efflorescences. Those avoiding stone cleaning often cited how earlier witness to the effects of stone cleaning has led them to believe that the risks outweigh the benefits.

4.7 WATERPROOFING

Is waterproofing necessary? Coatings frequently are applied to historic buildings without concern for the requirement or the consequences of the coating. Most historic buildings have survived for years without coatings, so why are they needed now? Water penetration to the interior usually was not caused by porous masonry but by deteriorated gutters and down spouts, deteriorated mortar, capillary moisture from the ground (rising damp) or condensation. Coatings will not solve these problems. In the case of rising damp, in fact, the coatings will allow the water to go even higher because of the retarded rate of evaporation. The claim also was made that coatings keep dirt and pollutants from collecting on the surface of the building thus reducing the requirement for future cleaning. While this at times may be true, at other times the coatings actually retain the dirt more than uncoated masonry. More important was the fact that these coatings can cause greater deterioration of the masonry than that caused by pollution, so the treatment may be worse than the problem that it was attempting to solve.

Masonry coatings are of two types, waterproof coatings and water repellent coatings. Waterproof coatings seal the surface from liquid water and from water vapour; they usually are opaque, such as bituminous coatings and some paints. Water repellents keep liquid water penetrating the surface but allow water vapour to enter and leave through the pores of the masonry. They usually are transparent, such as silicone coatings, although they may change the reflective property of the masonry, thus changing the appearance (www.cr.nps.gov/tps/briefs.htm 2000-2004).

Waterproof coatings usually do not cause problems as long as they exclude all water from the masonry. If water does enter the wall, the coating can intensify the damage because the water will not be able to escape. During cold weather this water in the wall can freeze, causing serious mechanical disruption, such as spalling. In addition, the water will eventually get out by the path of least resistance. If this path was towards the interior, damage to interior finishes can result, if it was towards the exterior cracks in the coating, it can lead to damage from the build up of salts.

Water repellent coatings also can cause serious damage, but by somewhat different mechanism (Leynaud 2001). As water repellent coatings do not seal the surface to water vapour, it can enter the wall as well as leave the wall. Once inside the wall, the vapour can condense at cold spots, producing liquid water. Water within the wall, whether condensation, leaking gutters or other sources can do damage as explained earlier. Soluble salts can do further damage. Salts frequently are present in the masonry, either from the mortar or from the masonry units themselves. Liquid water can dissolve these salts and carry them towards the surface. If the water was permitted to come to the surface, efflorescences can again appear upon evaporation. These are unsightly but usually are easily removed; they often are washed away by the simple action of rain. The presence of a water repellent coating prevents the water and dissolved salts from coming completely to the surface. The salts then are deposited slightly behind the surface of the masonry as the water evaporates through the pores. Over time, the salt crystals will grow and will develop substantial pressure, which will spall the masonry, detaching it at the depth of crystal growth. This build up may take several years to cause damage.

Test patches for coatings generally do not allow an adequate evaluation of the treatment because water may enter and leave through the surrounding untreated areas, thus flushing away the salt build up. In addition, salt deposits may not cause visible damage for several years, well after the patch has been evaluated. This was not to suggest that there was no use for water repellents and waterproofings. Sandblasted brick may have become so porous that paint or some type of coating was essential. In other cases, the damage being caused by local pollution may be greater than the potential damage from the coatings. Generally, coatings are not necessary, unless there was a specific problem, which they will help to solve. If the problem occurs on only a portion of the masonry, it was probably best to treat only the problem area rather than the entire building. Extreme exposures such as parapets or portions of the building subject to driving rain can be treated more effectively and less expensively than the entire building.

4.8 CONCLUSIONS

Cleaning of building facades has been a major activity for the construction industry, both in terms of financial outlay and the effect on the built heritage of our cities. However, the inappropriate cleaning and waterproofing of masonry buildings was a major cause of deterioration of buildings and should never be considered without suitable investigations.

Stone cleaning can be divided into three methods; water, chemical and mechanical (abrasive). Water cleaning softens the soiling and rinses the deposits from the surface, but water penetration, soluble salt movement, spalling and cracking are problems involved with this application. Chemical cleaners react with the dirt and/or masonry to hasten the removal process and are rinsed away with water. Since most chemical cleaners are water based, they have many of the potential problems of water cleaning plus the attacking aspects from the chemicals. Mechanical methods include sand blasting, grinders and sand discs, which remove the dirt by abrasion and are usually followed by a water rinse. The mechanical methods suffer from the potential problems from water cleaning, plus, the inevitable, the erosion of the masonry.

Buildings are constructed of many materials and tests should be conducted on each, to compare their compatibility. The results may show that several methods of cleaning should be used on a single building.

Most historic buildings have survived for years without waterproof coatings. Water penetration to the interior usually was not caused by porous masonry but by deteriorated gutters and down spouts, deteriorated mortar, rising damp or condensation and waterproofing will not solve these problems. Coatings may actually exaggerate the problems because of the retarded rate of evaporation.

CHAPTER 5

MATERIALS AND TESTING

5.1 GENERAL

The materials used and testing procedures described in this chapter were performed in order to establish the physical and mechanical properties of different lime mortars for various applications. The first section of the testing programme was determines the compressive strength of three hydraulic lime mortars and OPC cement mortars. The second section was carried out to determine the followings: merits of adding different percentages of cement to St. Astier hydraulic lime, effect of sand grading, mortar mix ratios, types of mould used for casting and methods of curing. The materials and mortar mixes for preparing the cubes, prisms and specimens were made in accordance with relevant British and European Standards. Table 5.1 provides list of all the materials and some of the experiments conducted in the present investigation. The table provides information on the types of mortar, types of sand used, mix ratios, testing procedure, number of samples, other material used in the investigation and the reason for carrying out the experiments.

Table 5.1 - Materials used and experiments carried out

Mortar/stone /brick type	Sand type	Ratio	Testing procedure	No. of sample	Reason for carrying out the experiment
Three types of lime and OPC mortar	Coarse	1:3	Compressive strength	48	Compare results of different hydraulic limes and OPC and to choose mid ranged hydraulic lime for use in other experiments
Fen-X and OPC cured in air	Coarse Fine	1:3	Compressive strength	48	To determine the effect of sand grading on a mortar
Fen-X and OPC cured in air	Coarse Fine	1:3	Splitting strength	48	To determine the effect of sand grading on a mortar

Table 5.1 - Continue					
Mortar/stone /brick type	**Sand type**	**Ratio**	**Testing procedure**	**No. of sample**	**Reason for carrying out the experiment**
Fen-X cured in air	Coarse	1:1 1:2 1:3 1:4	Compressive strength	48	To determine the strength of different ratios so a designer can choose a mix to match the specification
Fen-X cured in water	Coarse	1:1 1:2 1:3	Compressive strength	36	To determine the effect of curing lime mortar in water
Fen-X cured under different regimes	Coarse	1:1 1:2 1:3	Compressive strength	144	To determine the effect of curing lime mortar under different kinds of cover
Fen-X cured at different temperatures	Coarse	1:1 1:2 1:3	Compressive strength	54	To determine the effect of curing lime mortar at different temperatures
St. Astier made with different % of cement	Coarse	1:3	Compressive strength	72	To determine the effect of adding different percentages of cement to lime mortar
Fen-X cured in different moulds	Coarse	1:3	Flexural strength	18	To determine the effect of using different moulds on lime mortars
Fen-X cured in different moulds	Coarse	1:3	Compressive strength	36	To determine the effect of using different moulds on lime mortars
Fen-X and OPC cured in air	Coarse Fine	1:3	Flexural tensile bond strength	24	To determine the effect of sand grading on bond strength and to compare results with OPC
Fen-X and OPC cured in air	Coarse Fine	1:3	Flexural shear bond strength	24	To determine the effect of sand grading on bond strength and to compare results with OPC
Fen-X cured in air	Irish coarse sand	1:3	Porosity and water absorption	3	To determine the porosity and water absorption of the lime mortar
Fen-X cured in air	Coarse	1:1 1:2 1:3	Porosity and water absorption	9	To determine the porosity and water absorption of the lime mortar
Fen-X cured in water	Coarse	1:1 1:2 1:3	Porosity and water absorption	9	To determine the porosity and water absorption of the lime mortar
Red sandstone	N/A	N/A	Porosity and water absorption	2	To determine the porosity and water absorption of the stone
White sandstone	N/A	N/A	Porosity water absorption	2	To determine the porosity and water absorption of the stone
Common clay solid-frogged brick	N/A	N/A	Porosity and water absorption	2	To determine the porosity and water absorption of the brick
Type B engineering brick	N/A	N/A	Porosity and water absorption	2	To determine the porosity and water absorption of the brick
Granite	N/A	N/A	Porosity and water absorption	2	To determine the porosity and water absorption of the granite

5.2 HYDRAULIC LIME

At present there are no standards which cover the types of hydraulic lime and its use in construction. However, for the purpose of this investigation and in order to determine the properties, three types of pre-packaged hydraulic lime from three different sources were used. These are as follows: St. Astier (French), Fen-X (Italian), Jura Cement Fabriken (JCF) (Swiss). The main hydraulic lime used for most of the tests was Fen-X, which was a pre-packaged inorganic binder based on natural hydraulic lime, supplied by Telling Lime Ltd (www.telling.co.uk).

BS EN 459: Part 1 (British 2001) defines natural hydraulic limes (NHL) as: Limes produced by burning of more or less agrillaceous of siliceous limestones with reduction to powder by slaking with or without grinding. All NHL have the property of setting and hardening in contact with moisture (hydration) and by atmospheric carbon dioxide (carbonation).

Fen-X was used mainly in the present investigation because the supplier guaranteed that it has good physical properties and setting time. The properties of Fen-X as provided by the manufacturer are:

Density of binder = 1.00Kg/m^3

Compressive Strength = 9N/mm^2 after 90 days (Type NHL 5 according to BS EN 459: Part 1 British 2001).

Tensile strength = 0.6N/mm^2 after 60 days.

Modulus of elasticity = 6130N/mm^2.

The above properties were determined by tests in accordance with BS EN 459: Part 2 (British 2001).

The composition of hydraulic limes was complex, although a satisfactory lime may show a wide range of proportions in their basic chemical composition. Varying relative proportions of lime, silica, alumina and iron oxide can result in a satisfactory cementation index. Fen-X shows from previous x-ray analysis that it does contain these chemical compounds (Turnball 1996).

5.3 CEMENT

The cement used in all mixes was ordinary Portland cement (OPC) to BS EN 197: Part 1 (British 2000). The basic raw material used in the manufacture of Portland cements are calcium carbonate found in calcareous rocks such as limestone or chalk and silica, alumina and iron oxide found in argillaceous rock such as clay or shale. Cement has important properties that when mixed with water, a chemical reaction (hydration) takes place, which in time, produces a very hard and strong binding medium.

For comparative reasons OPC mortar cubes were cast and tested to determine their compressive and splitting strengths along with lime mortar cubes.

5.4 WATER

Water from sources likely to introduce salts into the mortar, such as sea water, should not be used. For this reason all water used for the experiments was ordinary tap water. As the water source was fit for human consumption it can be considered acceptable for use as mixing water.

5.5 SAND

Sand comprises a high percentage of the volume of a mortar mix. The type of sand chosen was critical to the characteristics and performance of the mortar (BS 1199 (British 1995) and 1200 (British 1976).

Sand in lime/cement mortar performs a number of functions:

- Act as filler, thereby reducing the amount of lime/cement needed and reducing drying shrinkage of the mortar.
- Act as air entrains and thus contribute to some degree, to the frost resistance of the mortar.
- Their air entraining properties may influence carbonation and hardening of the mortar.
- They contribute to the compressive strength of the mortar.

5.5.1 Sieve analysis

The aim of sieve analysis was to determine the particle size distribution of the sand (BS 812: Part 103.1 (British 1985)). The data obtained from the sieve analysis can be seen in Table 5.2. Concrete sand with 5mm maximum size was used in the present investigation. The sand was sieved first and separated into coarse and fine building sand to investigate the effects of using sand of different sizes on the properties of lime/cement mortar.

Table 5.2 - Sieve analysis for concrete sand

BS sieve size	Mass retained (gm)	Mass passing (gm)	Percentage retained (%)	Cumulative passing (%)	Cumulative retained (%)
10.00mm	0	500.25	0	100	0
5.00mm	3.17	497.09	1	99	1
2.36mm	117.25	379.84	23	76	24
1.18mm	95.89	283.95	19	56	44
600μm	74.52	209.43	15	42	58
300μm	84.73	124.70	17	25	75
150μm	64.95	59.75	13	12	88
Tray	59.62	0	12	0	100

The 5mm maximum size concrete sand was separated into coarse and fine sand using the grading limits from BS 1199 and 1200 as given in Table 5.5. The coarse sand (Table 5.3) was classified by choosing limits of grading for coarse concrete sand from BS 1199 (British 1995) and 1200 (British 1976) (Table 5.5).

Table 5.3 - Sieve analysis for coarse sand

BS sieve size	Mass retained (gm)	Mass passing (gm)	Percentage retained (%)	Cumulative passing (%)	Cumulative retained (%)
10.00mm	0	500.25	0	100	0
5.00mm	55.03	445.22	11	89	11
2.36mm	145.07	300.15	29	60	40
1.18mm	150.08	150.08	30	30	70
600μm	75.04	75.04	15	15	85
300μm	50.03	25.01	10	50	95
150μm	25.01	0	5	0	100
Tray	0	0	0	0	100

The fine sand (Table 5.4) was also completed by choosing limits of grading for fine concrete sand from BS 1199 (British 1995) and 1200 (British 1976) (Table 5.5).

Table 5.4 - Sieve analysis for fine sand

BS sieve size	Mass retained (gm)	Mass passing (gm)	Percentage retained (%)	Cumulative passing (%)	Cumulative retained (%)
10.00mm	0	500.25	0	100	0
5.00mm	0	500.25	0	100	0
2.36mm	0	500.25	0	100	0
1.18mm	100.05	400.2	20	80	20
600μm	100.05	300.15	20	70	30
300μm	50.03	250.13	10	50	50
150μm	200.1	50.03	40	20	80
Tray	50.03	0	10	0	100

A large amount of sand was sieved, separated and stored in bags to sizes. The different sizes were then re-mixed with the appropriate percentage of each to make coarse and fine sand.

Table 5.5 - Limits of grading for concrete sand from BS 1199 and 1200

BS sieve size	Percentage by mass passing BS sieve Overall limits	Additional limits for grading Coarse	Medium	Fine
10.00mm	100	100	100	100
5.00mm	89-100	89-100	89-100	89-100
2.36mm	60-100	60-100	65-100	80-100
1.18mm	30-100	30-90	45-100	70-100
600μm	15-100	15-54	25-80	55-100
300μm	5-70	5-40	5-48	5-70
150μm	0-15	0-15	0-15	0-15

5.6 SANDSTONE

White and red sandstone were investigated. The white sandstone was a Darney sandstone from the Darney Quarry in West Woodburn, Northumberland. The red sandstone was a Red St. Bees sandstone from the Bank End Quarry in St Bees, Cumbria. They were tested for compressive strength, porosity and water absorption to compare results with other materials, used in the investigation.

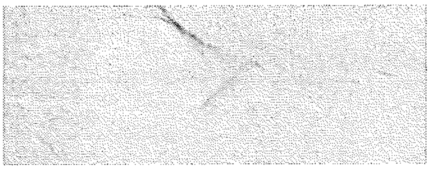
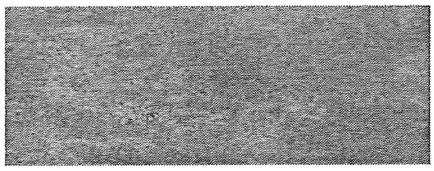



Fig. 5.1 – Darney (white) sandstone and Red St. Bees (red) sandstone.

5.7 CLAY BRICK

Two types of clay brick of different compressive strengths were tested for porosity and water absorption to compare results. (BS 3921 : 1985).

5.8 SAMPLES PREPARATION

A British Standard mixing procedure (BS 4551: Part 1 (British 1998)) was used to produce the batches of 70mm mortar cubes, prisms and specimens needed for the investigation.

5.8.1 Lime/cement mortar cubes

The lime/cement mortar mixes used in the investigation were proportioned by volume. The oven dry material was placed in the mixer and water slowly added until the workability of the mixture reached a desired level. The steel moulds were cleaned, coated with mould oil and placed on a vibrating table, unless otherwise stated. The moulds were then filled to approximately half height with mortar and vibrated until a surface sheen of water formed. A second layer was added and vibrated similarly; they were topped up until they were level with the top of the moulds. The mortar mixes were de-moulded after 2-4 days from casting.Thelime/cement mortar cubes were tested after 7, 14, 28 and 56 days following different curing methods: under ambient laboratory conditions (temperature of 17^0C with a relative humidity of 38% before testing), in air, in water, at different temperatures and covered in a combination of hessian and plastic bags. The lime/cement mortar cubes were tested to determine their compressive and tensile splitting strengths. The Fen-X lime/cement: sand ratio used for most of the cubes was 1:3 by volume unless otherwise stated. Three cubes were tested for each batch of mortar mixed and cast to give the mean value.

Test to determine the cubes compressive strength were carried out in accordance with British Standard BS 1881: Part 116 (British 1983) and the cube splitting strength were carried out in accordance with British Standard BS 1881: Part 117 (British 1983).

5.8.2 Lime mortar prisms

Mortar prisms were prepared in accordance with BS EN 196 (British 1995). The prisms were prepared in a similar way to the cubes apart from the casting moulds used. They were cured under ambient laboratory conditions (temperature of 17^0C with a relative humidity of 38%). The prisms were tested after 14 and 28 days following casting using different types of moulds (steel, scabbold and polystyrene) for flexural and compressive strength. The Fen-X lime: sand ratio used was 1:3 by volume and three prisms were tested for each test date. First for flexural strength and the resulting halves tested for compressive strength to give the mean value.

5.8.3 Tensile bond strength specimen

The lime/cement mortar was mixed in the same way as the cubes with Fen-X lime/cement: sand ratio of 1:3 by volume. Z-shaped tensile bond specimens (Fig. 5.2) were constructed with two bricks bonded together by a 10mm rectangular mortar joint in a staggered arrangement to try and reproduce the way in which brickwork was constructed in stretcher bonding. The first brick was placed on the ground and against a timber trimmer then a 10mm rectangular joint was created and filled with mortar followed by the second brick which was supported by the timber trimmer from one side and the mortar joint on the other side.

A 5kg weight was placed on each sample after construction in order to produce a pre-compression of 0.005 N/mm^3 and reduce cracking, achieve consistency and to simulate load from the top courses in actual construction. The timber trimmer and the 5 kg weight were left in place for 7 days to allow the mortar to gain in strength before removal. During these 7 days the specimens were cured under laboratory conditions (temperature 17°C with humidity 38%). The specimens were left for a further 21 and 49 days to cure under ambient conditions in the laboratory, before testing at 28 and 56 days. The specimens were made at the same time, from the same mortar, as the cubes

Three specimens of each brick/mortar combination were constructed, cured and tested. Three Z-shaped specimens were tested after 28 and 56 days from casting. Before testing the location and length of mortar joint were recorded. Fig. 5.3 shows the loading and support arrangements used for testing the Z-shaped specimens. Dental plaster was used as a packing material at all the loading and support 10 mm square steel bars. Once the dental plaster was hardened, the specimens were loaded to failure by applying the load at standard displacement rate.

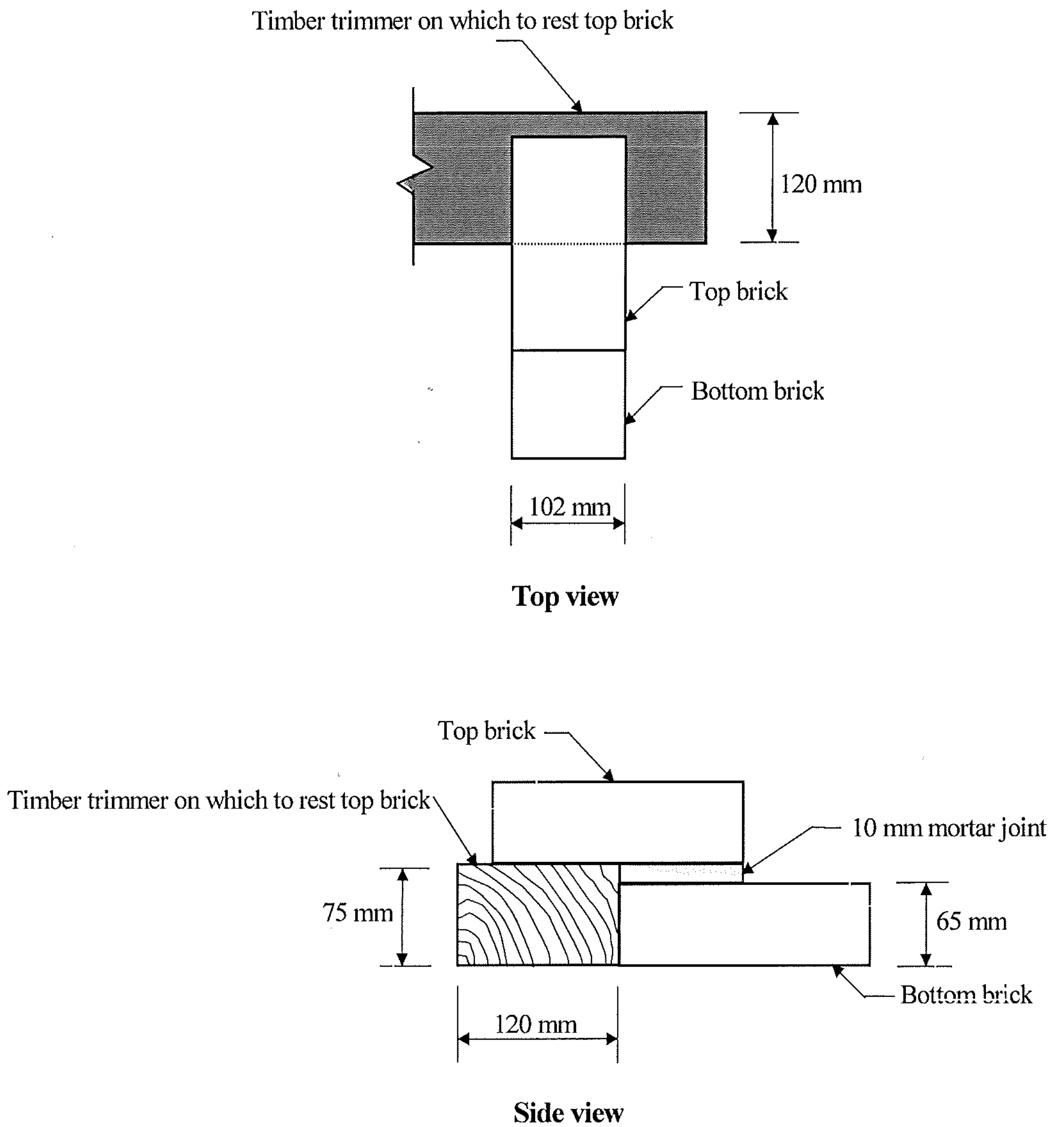


Fig. 5.2 - Construction of Z-shaped specimen

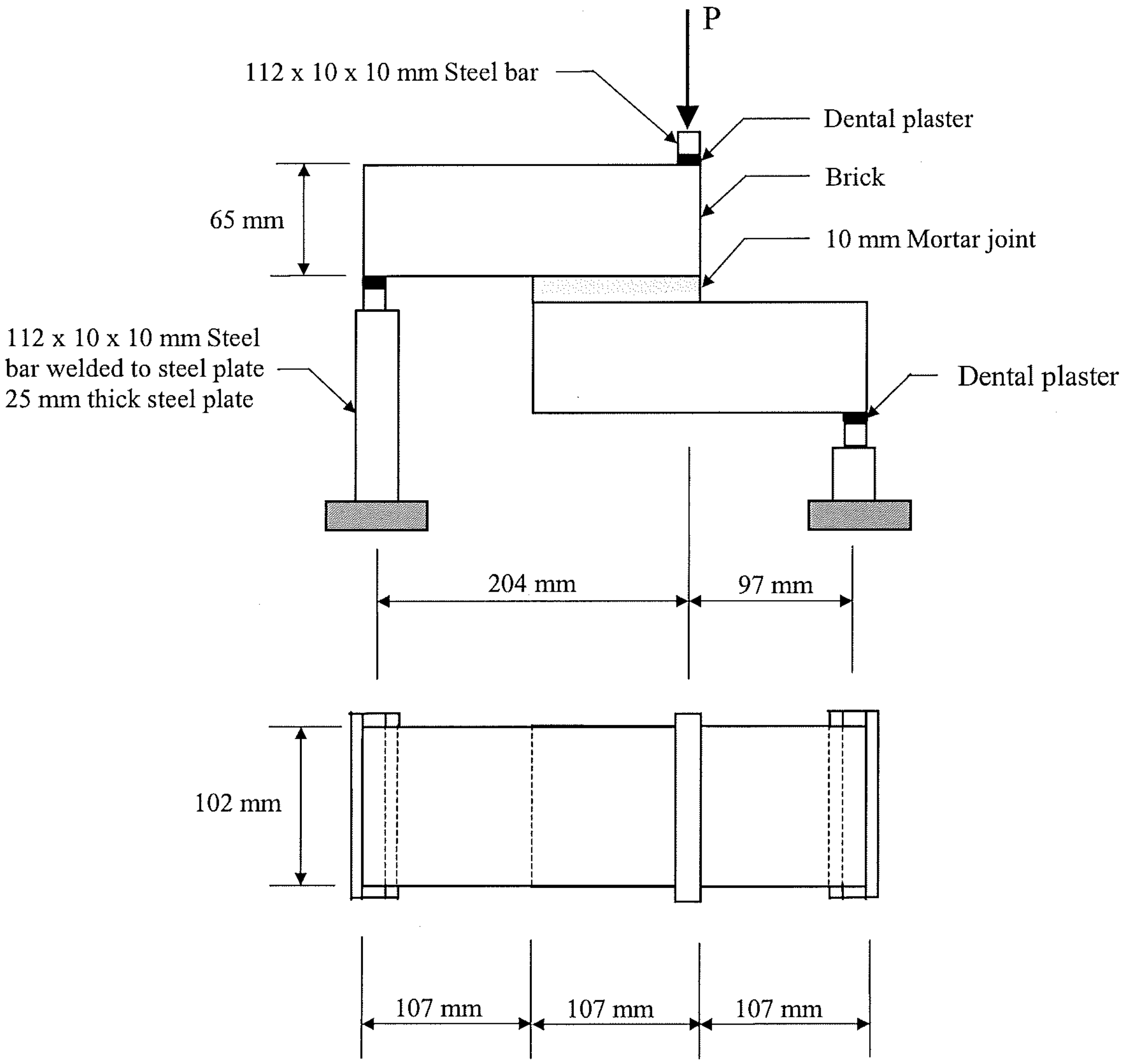


Fig. 5.3 - Test set-up for Z-shaped specimen

5.8.4 Shear bond strength specimen

The lime/cement mortar was mixed in the same way as the cubes with Fen-X lime/cement: sand ratio of 1:3 by volume. The Z-shaped shear bond specimens were constructed in a similar way to the tensile bond specimens. The test specimens were composed of two block units laid flat and connected by a mortar joint (Fig. 5.4). The circular mortar joints were constructed using a plastic ring 10mm thick, thus allowing a circular mortar bed joint of 90mm inner diameter and 10mm thick to be achieved. The plastic ring acts as a form whilst laying one block onto another (Fig. 5.4a). A piece of timber, as detailed in Fig. 5.4, was used to support the top block and to align the specimen during construction.

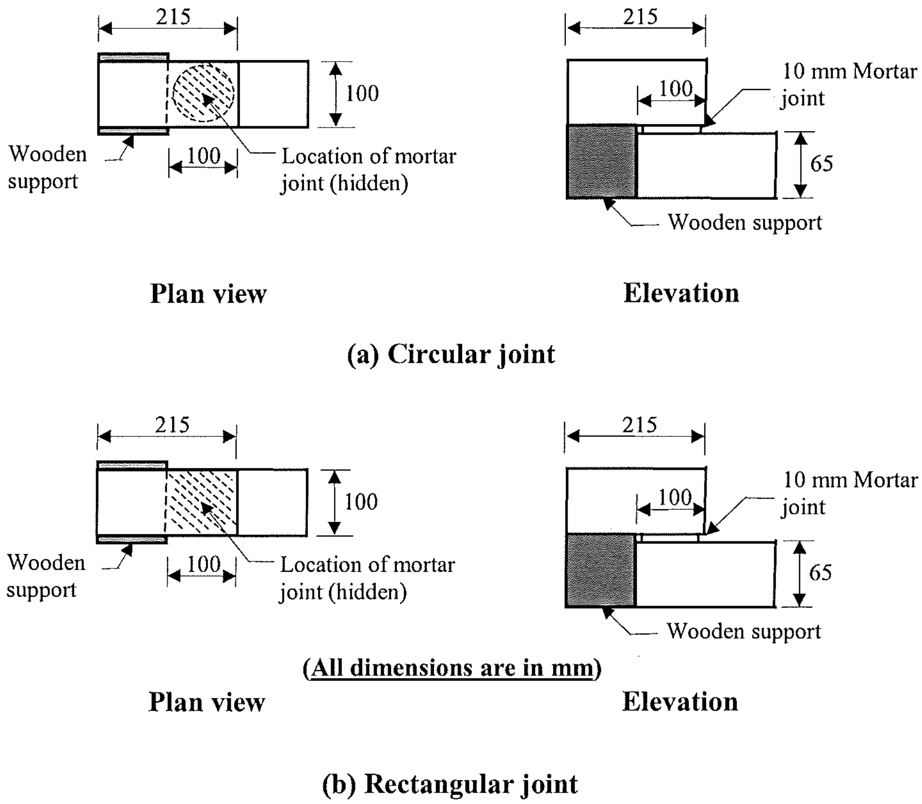


Fig. 5.4 – Construction of Z – Shaped shear specimens

5.9 TESTING

5.9.1 Compressive test

The compression test was carried out in accordance with BS 1881: Part 116 (British 1983). The testing machine used was the Lloyd Universal Instrument. All testing steel bearing surfaces were wiped clean from loose grit and other extraneous material before testing. The cube was centred on the lower platen ensuring that the load would be applied to two opposite cast faces of the cube. Without shock, a load was applied and increased until no greater load could be sustained. The maximum loads applied to the cubes were recorded and the average compressive strengths were calculated from three cubes for each test date. Table 5.6 shows the results of compressive strength for the four different types of mortar used in the investigation.

Table 5.6 - Compressive strength of three types of lime and cement mortar with lime/cement: sand ratio of 1:3 (strength was in N/mm^2)

Mortar type	Mix ratio	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
St. Astier	1:3	0.82	11.3	1.35	5.3	1.62	3.1	1.82	7.7
Fen-X	1:3	1.85	4.5	2.78	3.1	3.47	4.0	3.84	3.7
JCF	1:3	3.66	8.5	5.40	2.9	6.42	1.5	6.86	2.6
OPC	1:3	26.05	4.5	31.87	1.2	32.75	2.6	33.12	3.2

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.7 shows the results of compressive strength for Fen-X hydraulic lime and cement mortar mixed with coarse and fine sand.

Table 5.7 - Compressive strength of Fen-X hydraulic lime and cement mortar mixed with coarse and fine sand with lime/cement: sand ratio of 1:3 (strength was in N/mm^2)

Mortar type	Sand type	Mix ratio	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	coarse	1:3	1.99	2.7	1.94	6.4	1.97	6.7	1.68	6.1
Lime	fine	1:3	1.04	5.1	1.06	3.6	1.1	1.9	0.84	4.7
OPC	coarse	1:3	14.5	2.5	18.42	2.3	25.82	4	28.17	4
OPC	fine	1:3	13.49	4.4	14.62	4.5	16.82	9.6	17.11	2.9

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.8 shows the results of compressive strength for Fen-X hydraulic lime mortar made with coarse sand and different mix ratios.

Table 5.8 - Compressive strength of Fen-X lime mortars made with coarse sand, cured in air - Ratio 1:1, 1:2, 1:3 and 1:4 (lime/cement:sand) (N/mm^2)

Mortar type	Mix ratio	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	1:1	2.08	4.2	3.55	4.7	4.26	2.6	6.03	1.4
Lime	1:2	2.02	4.3	2.1	4.1	2.03	2.8	2.21	2.4
Lime	1:3	1.63	3	1.36	0.4	1.09	6.6	1.16	1.5
Lime	1:4	0.72	1.4	0.7	3.8	0.67	2.6	0.64	5.4

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.9 shows the results of compressive strength for Fen-X lime mortars made with coarse sand and cured in water.

Table 5.9 - Compressive strength of Fen-X lime mortars made with coarse sand and cured in water - Ratios 1:1, 1:2 and 1:3 (lime:sand) (N/mm^2)

Mortar type	Mix ratio	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	1:1	2.3	2.5	3.05	2.6	4.13	1.7	5.28	6.2
Lime	1:2	1.64	5.6	2.07	4.7	2.87	2.4	3.41	5.9
Lime	1:3	1.21	6.4	1.64	3.1	1.92	5.7	2.4	5.9

Cured in water under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.10 shows the results of compressive strength for Fen-X lime mortars made with coarse sand and cured under different regimes with a 1:1 mix ratio.

Table 5.10 - Compressive strength of Fen-X lime mortars made with coarse sand and cured under different regimes - Ratio 1:1 (lime/cement:sand) (N/mm^2)

Mortar type	Mix ratio	Method of curing	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	1:1	Hessian	4.27	3.9	3.65	4	4.97	5.2	7.43	3.5
Lime	1:1	Hessian plastic	4.6	7.9	3.48	7.1	5.28	2.6	7.75	6.9
Lime	1:1	Plastic	4.71	3.2	4.17	2.8	5.27	7	8.16	6.2
Lime	1:1	Air	2.08	4.2	3.55	4.7	4.26	2.6	6.03	1.4

Cured under laboratory conditions, hessian sacks were kept damp throughout 56 day period by checking twice a day and spraying with water, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.11 shows the results of compressive strength for Fen-X lime mortars made with coarse sand and cured under different regimes with a 1:2 mix ratio.

Table 5.11 - Compressive strength of lime mortars made with coarse sand and cured under different regimes - Ratio 1:2 (lime/cement: sand) (N/mm^2)

Mortar type	Mix ratio	Method of curing	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	1:2	Hessian	1.62	3.7	2.9	4.3	2.52	1.9	4.17	4
Lime	1:2	Hessian plastic	1.85	5.3	3.41	6	2.46	7.6	4.35	1.8
Lime	1:2	Plastic	2.39	3	3.29	4.4	3.62	1.9	4.44	2.4
Lime	1:2	Air	2.02	4.3	2.1	4.1	2.03	2.8	2.21	2.4

Cured under laboratory conditions, hessian sacks were kept damp throughout 56 day period by checking twice a day and spraying with water, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.12 shows the results of compressive strength for Fen-X lime mortars made with coarse sand and cured under different regimes with a 1:3 mix ratio.

Table 5.12 - Compressive strength of lime mortars made with coarse sand and cured under different regimes - Ratio 1:3 (lime/cement:sand) (N/mm^2)

Mortar type	Mix ratio	Method of curing	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	1:3	Hessian	0.88	2.6	1.15	3.8	2.26	5.3	2.29	4.9
Lime	1:3	Hessian plastic	0.86	5.3	1.11	2.7	1.56	6.7	2.04	7.8
Lime	1:3	Plastic	1.47	7.2	1.82	6.7	2.49	2.8	2.18	4
Lime	1:3	Air	1.63	3	1.36	0.4	1.09	6.6	1.16	1.5

Cured under laboratory conditions, hessian sacks were kept damp throughout 56 day period by checking twice a day and spraying with water, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.13 shows the results of compressive strength for Fen-X lime mortars made with coarse sand and cured at different temperatures with mix ratios 1:1, 1:2 & 1:3.

Table 5.13 – Compressive strength of Fen-X lime mortars made with coarse sand and cured at different temperatures – Ratios 1:1, 1:2 and 1:3 (lime:sand) (N/mm^2)

Temperature (°C)	Hydraulic lime Ratio 1:1 (N/mm^2)	Hydraulic lime Ratio 1:2 (N/mm^2)	Hydraulic lime Ratio 1:3 (N/mm^2)
-14	3.25	2.07	1.74
6	4.47	2.54	2.28
17	5.43	3.27	2.44
23	4.82	2.67	2.46
55	5.57	3.42	2.38
120	3.34	2.56	1.86

Cured under laboratory conditions, de- moulded after 2-4 days, the results in the table are the average of 3 cubes.

Table 5.14 shows the results of compressive strength for St. Astier lime with different percentages of cement added with a 1:3 mix ratio.

Table 5.14 - Compressive strength of St. Astier lime with different percentages of cement added - Ratio 1:3 (lime/cement:sand) (N/mm^2)

Mortar Type	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
100% St. Astier lime	0.87	5.2	1.42	4.3	1.68	3.3	1.88	2.7
87.5% Lime + 12.5% Cement	1.88	8.5	2.54	4.9	3.68	8.1	4.61	3.9
75%lime + 25% Cement	4.02	2.4	5.65	5.7	6.93	1.9	7.6	2.2
50% Lime + 50% Cement	8	5.5	14.93	6.7	15.99	7.2	17.46	1.8
25% Lime + 75% Cement	17.81	2.1	21.5	2.8	23.02	1.6	22.93	0.8
100% Cement	25.61	1.6	31.15	2.1	32.9	0.9	33.19	0.9

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

5.9.2 Splitting test

The tensile splitting test was carried out in accordance with BS 1881: Part 117 (British 1983). The testing machine used was the Lloyd Universal Instrument. All testing steel bearing surfaces were wiped clean so that any loose grit and other extraneous material were removed before testing. A device was used to position the jig correctly on the lower platen, with the cube central. Two cylindrical steel platens of 75mm radius were used to apply a line load on the opposite smooth sides of the cube to split it into two halves.

The maximum loads applied to the cubes were recorded and the average splitting strengths were calculated from three cubes on each test date using Equation 5.2.

$$\text{Splitting strength} = \frac{(2 \times \text{Failure load})}{(\Pi \times \text{Area})} \tag{5.2}$$

The following table shows the average splitting strength and C.V. values for mortars tested:

Table 5.15 - Tensile splitting strength of Fen-X lime/cement mortars made with coarse and fine sand - Ratio 1:3 (lime/cement:sand) (N/mm^2)

Mortar type	Sand type	Mix ratio	Average strength 7 days	C.V. (%)	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Lime	Coarse	1:3	0.18	11.1	0.17	0	0.15	0	0.13	11.7
Lime	Fine	1:3	0.13	13.3	0.12	8.3	0.10	5.7	0.08	7.2
OPC	Coarse	1:3	2.03	5.3	2.36	5.3	2.46	4.3	3.3	2.6
OPC	Fine	1:3	1.23	3.1	1.48	6.4	1.73	5.6	1.96	0.6

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 cubes.

5.9.3 BS EN 196 prism test

Mortar prisms were prepared in accordance with BS EN 196 (British 1995) using different types of casting moulds. The reason for using different types of moulds (steel, scabbold and polystyrene) was to investigate the effect of changing the materials used for casting the moulds on the process of carbonation. It was thought that the steel moulds restricted the carbonation of the lime mortar cubes by blocking the supply of CO_2 from the air during the first few days of curing. According to BS EN 196 the prisms first have to be tested for flexural strength and then the two resulting halves tested for compressive strength. The types of moulds used are:

Steel moulds: The moulds used (Fig. 5.5) consisted of three horizontal compartments in order to prepare three prismatic specimens of 40 × 40mm in cross section and 160mm in length. The moulds were positively and rigidly held together and fixed to the base.

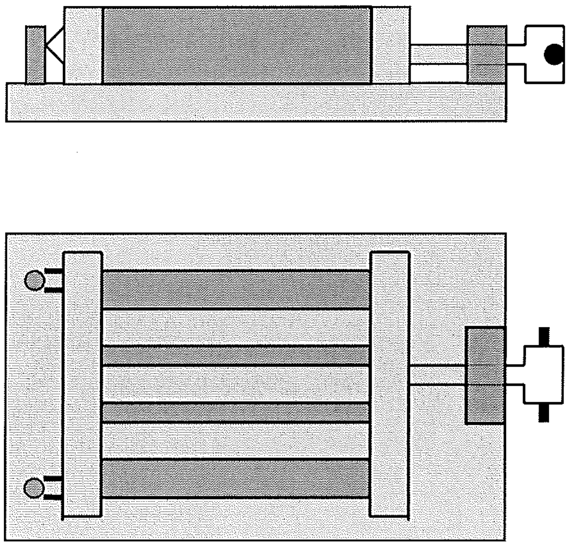


Fig. 5.5 - Steel mould

Polystyrene moulds: Polystyrene moulds were used so that air would be able to get through the sides to carbonate the lime mortar. The moulds were made of polystyrene with walls thick enough to withstand the vibration of the jolting table.

Scabbold prisms: It was first thought that the smoothness of the surface blocked the pores and prevented air with CO_2 to penetrate deeper into the cubes for better carbonation. Scabbolding the prisms smooth surfaces after casting in steel moulds maybe helps CO_2 penetration and improves carbonation. The scabbolding took place after the prisms were de-moulded using the wire end of a sieve brush and using a stabbing/brushing movement all over the specimens.

After the prisms were casted and cured they were first tested in flexure under three point loads. An increased load was applied at mid point until failure. Three prisms were tested for different ages. From failure loads the average flexural strengths and C.V. values were calculated and are shown in Table 5.16.

Table 5.16 - Flexural strength of lime mortars cast in different moulds made with coarse sand - Ratio 1:3 (lime/cement: sand) (N/mm^2)

Mortar type	Mix ratio	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)
Steel mould	1:3	0.33	1.8	0.45	0
Scabbold mould	1:3	0.31	9.8	0.43	3.6
Polystyrene mould	1:3	0.34	8.8	0.46	4.3

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 prisms.

After the prisms were broken into two halves by flexure, the halves were tested to determine their compressive strength in accordance with BS EN 196. The prism halves were centred laterally on the platens of the machine within ±0.5mm, and longitudinally such that the end face of the prism overhangs the platens or auxiliary plates by about 10mm. The load was increased at a smooth rate until failure. As there were three prisms for each age the total number of specimens tested in compression were six. Table 5.17 shows the average compressive strength for the prism halves tested for compression.

Table 5.17 - Compressive strength of Fen-X hydraulic lime mortar prisms with lime: sand ratio of 1:3 (lime:sand) by volume cured in different moulds (strength was in N/mm^2)

Mortar type	Mix ratio	Average strength 14 days	C.V. (%)	Average strength 28 days	C.V. (%)
Steel mould	1:3	1.57	4.6	1.65	3.2
Scabbold mould	1:3	1.15	5.2	1.48	2.7
Polystyrene mould	1:3	1.41	4.3	1.31	4.5

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 6 cubes.

5.9.4 Tensile bond test

The brick/mortar tensile bond strength was not a British Standard test but it was a new method devised by Khalaf (1995). The test has shown to give a good degree of consistency with previous works. The theory for the tensile bond strength was shown in Chapter 2; Section 2.18. The main equation is given as:

$$f_{tb} = \left[\frac{1}{l_{mj} \times w_b \times \left(\frac{l_{mj}}{3} - \frac{t_{bar}}{4} \right)} \right] \times \left[\frac{Pba + Wa\left(b + l_b - t_{bar}\right)}{a + b} - W\left(\frac{l_b}{2} - \frac{t_{bar}}{2} \right) \right] \quad (5.3)$$

By substituting the dimensions and weights of Type B Engineering brick used in this investigation into the equation:

$a = 205mm$

$b = 115mm$

$W = 30N$

$l_b = 215mm$

$l_{mj} = 100mm$

$t_{bar} = 10mm$

$w_b = 102mm$

Therefore:

$$f_{tb} = \frac{P}{4270} + 0.01 \tag{5.4}$$

This equation was used to calculate the tensile bond strength of lime/cement mortars. Table 5.18 shows the average tensile bond strength and the C.V. values for mortars tested:

Table 5.18 - Flexural bond strength of Fen-X lime/cement mortars made with coarse and fine sand – Ratio 1:3 (lime/cement:sand)

Mortar type	Sand type	Mix ratio	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Hydraulic lime	Coarse	1:3	0.35	11.4	0.3	0
Hydraulic lime	Fine	1:3	0.07	14.3	0.1	5.8
OPC	Coarse	1:3	0.55	4.6	0.35	10.8
OPC	Fine	1:3	0.76	9.2	0.61	8.4

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 specimens.

5.9.5 Shear bond test

The brick/mortar shear bond strength was not a British Standard test but was developed by Khalaf (1995). The theory for the shear bond strength was shown in Chapter 2; Section 2.19. The main equation is given as:

$$\tau_o = \left[\frac{T}{Z_t}\right] = \left[\frac{\frac{Pd}{2}}{\frac{3\pi R^3}{2}}\right] = \left[\frac{Pd}{3\pi R^3}\right] \tag{5.5}$$

This equation was used to calculate the shear bond strength of lime/cement mortars. Table 5.19 shows the average shear bond strength and the C.V. values for mortars tested.

Table 5.19 - Torsional bond strength of Fen-X lime/cement mortars made with coarse and fine sand - Ratio 1:3 (lime/cement:sand)

Mortar type	Sand type	Mix ratio	Average strength 28 days	C.V. (%)	Average strength 56 days	C.V. (%)
Hydraulic lime	Coarse	1:3	0.27	16.7	0.19	8
Hydraulic lime	Fine	1:3	0.13	13.3	0.1	5.8
OPC	Coarse	1:3	0.77	8.5	0.37	2.8
OPC	Fine	1:3	0.73	13	1.11	2.7

Cured in air under laboratory conditions, de-moulded after 2-4 days, the results in the table are the average of 3 specimens.

5.9.6 Porosity and water absorption tests

The test for determining porosity and water absorption of materials was a new test developed by Khalaf and DeVenny (1998). The test determines the porosity and water absorption using vacuum. To provide a wide range of results, the experimental work was carried out on lime mortar, sandstone, clay brick and granite aggregate. The lime mortars were made with fine, coarse and Irish sand. They were also tested for different ratios (lime:sand) and curing conditions. The sandstones tested for porosity were of different types, colours and strengths. The clay bricks were of 215 x 102.5 x 65mm working sizes and of varying compressive strength. The bricks strength and dimension were determined in accordance with BS 3921 (British 1985).

In order to measure the porosity and water absorption for the above materials, samples from each material were broken up by hand into 20mm lumps (fractions passing 20mm but retained on 14mm sieve). The 20mm lumps obtained were a representative sample as they were broken up from three different full size specimens. However, the lime/cement mortar cubes 70×70mm did not need to be broken up as they were small enough to be tested whole.

To calculate the porosity and water absorption for all the above materials, the 20mm lumps and mortar cubes were tested under vacuum using the new test procedure. A sample of granite aggregate was also tested so that a comparison could be made with the other materials. Table 5.20 shows the compressive strength, porosity and water absorption for different lime mortars and different engineering materials.

Table 5.20 - Compressive strength, porosity and water absorption of different Fen-X lime mortars and different materials

Sample type	**Compressive strength at 28 days (N/mm^2)**	**Porosity by vacuum (%)**	**Water absorption by vacuum (%)**
Hydraulic Lime mortar made with Irish sand Ratio 1:3	2.36	26.77	12.25
Hydraulic Lime mortar made with coarse sand Ratio 1:1 (cured in air)	6.03	33.75	15.95
Hydraulic Lime mortar made with coarse sand. Ratio 1:2 (cured in air)	2.21	30.95	14.41
Hydraulic Lime mortar made with coarse sand. Ratio 1:3 (a cured in air)	1.16	29.7	13.13
Hydraulic Lime mortar made with coarse sand. Ratio 1:1 (cured in water)	5.28	33.22	12.07
Hydraulic Lime mortar made with coarse sand. Ratio 1:2 (cured in water)	3.41	33.35	11.96
Hydraulic Lime mortar made with coarse sand. Ratio 1:3 (cured in water)	2.4	34.72	12.71
Red sandstone	24.58	28.38	15.12
White sandstone	54.68	13.96	6.22
Common clay solid-frogged brick	39	25	13.5
Type B engineering brick	92	15	7.2
Granite	-	6	2.3

Cured in air under laboratory conditions, unless otherwise stated, de-moulded after 2-4 days, the results in the table are the average of 3 specimens.

5.10 CONCLUSIONS

Chapter 5 presents the materials used, test procedures and test results for all the experiments carried out in this investigation. Table 5.1 summarises the materials used, mortar mix ratios, experiments carried out and reason for carrying out each individual experiment.

The materials used are: three types of hydraulic lime: St. Astier (French), Fen-X (Italian) and Jura Cement Fabriken (JCF) (Swiss), OPC cement, fine and coarse sand, red sand stone, white sand stone, common clay bricks, type B engineering bricks and granite

Different exterminates were designed and carried out, in accordance with the current British and European Standards, to determine the materials compressive strength, tensile strength, flexural tensile and shear bond strength with the clay bricks, porosity and water absorption. Other experiments were carried out to establish mortar mix ratios, effect of sand grading, types of mould used for casting, merits of adding different percentages of cement to St. Astier hydraulic lime and methods of curing.

Results of tests on mortar cubes made from hydraulic lime and OPC cement showed that the cement mortar was by far more superior in strength than all the other mortars made with hydraulic limes.

CHAPTER 6

DISCUSSION OF RESULTS

6.1 GENERAL

This chapter discusses the results derived from the testing programme and gives conclusions. As stated before the reason for carrying out the present investigation was to study the effects of several variables on the physical and mechanical properties of hydraulic lime mortars. Tests were also carried out on ordinary Portland cement mortar and presented along side for comparison reasons. Complete results of all strength tests can be found in Appendix A.

6.2 HYDRAULIC LIMES

This part of the investigation determines the compressive strength of three types of hydraulic lime (St. Astier, Fen-X and JCF) from three different sources with a lime/cement: coarse sand ratio of 1:3 by volume. The test was carried out to classify the above three types of hydraulic limes in relation to their compressive strength according. From this the middle hydraulic lime was chosen and used for the rest of the testing program.

6.2.1 Compressive strength of hydraulic limes

Fig. 6.1 gives the relationship between hydraulic lime/cement mortar compressive strength and age at testing for a mix of 1:3 lime/cement: coarse sand by volume. The figure shows that there was a great difference in compressive strength between the three types of lime tested. For example the 56 days compressive strength of Jura Cement Fabriken (JCF) lime was 1.79 and 3.77 times stronger than Fen-X and St. Astier lime respectively. The figure also shows that the compressive strength of all the lime mortars tested at different age fall below the compressive strength of the mortar made with ordinary Portland cement (OPC).

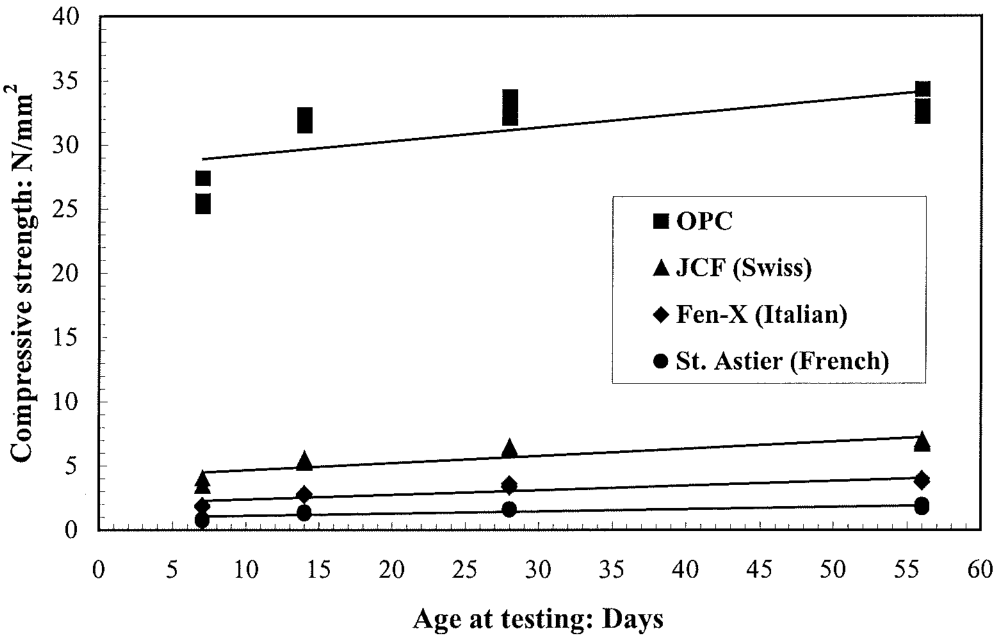


Fig. 6.1 - Compressive strength Vs age at testing for lime/cement mortars of 1:3 (lime/cement: coarse sand)

The values of compressive strength for lime mortars suggest that the hydraulic limes used in the investigation were from different origins. The compressive strength values suggest that the three pre-packaged hydraulic limes used in this part of the investigation were from different origins. The three types identified by the French: St. Astier (French) – low strength, Fen-X (Italian) – mid strength and Jura Cement Fabriken (Swiss) – high strength. The table shows that the Fen-X hydraulic lime from Italy was the medium hydraulic lime and it was used for most of the testing carried out in the present investigated.

6.3 EFFECTS OF USING DIFFERENT SAND ON STRENGTH

This section summarises the results of Fen-X lime/cement mortar cubes made with coarse and fine sands. As derived in the previous section Fen-X hydraulic lime was chosen for the experimental program considering it was "moderately" hydraulic lime. In this part of the investigation the ratio used for producing the mortar was 1:3 (lime/cement: sand by volume). The reason for choosing this mix ratio was the belief that in order to study the effect of sand grading on the strength of the mortar, a mix with a high percentage of sand would reflect and give a better indication to the effect of this factor on properties. It was also felt that this was the most acceptable with regards to cost. The mortars for this part were cast, de-moulded, cured in air and tested as stated previously. Other ratios (1:1 and 1:2 - lime/cement:sand) were also tested in the present investigation.

6.3.1 Compressive strength of mortar cubes

Fig. 6.2 shows the relationship between the cubes compressive strength and age at testing for Fen-X lime/cement mortars made with coarse and fine sands. The figure shows that the compressive strengths of OPC mortars are far above the compressive strength of the mortars made with Fen-X hydraulic lime.

The figure also shows that the cement mortar are sharply increasing in strength over time, whereas there was no great change in strength of lime mortars with time. Although, the lime used was hydraulic in nature the changes in strength with time for the different sands used was very small.

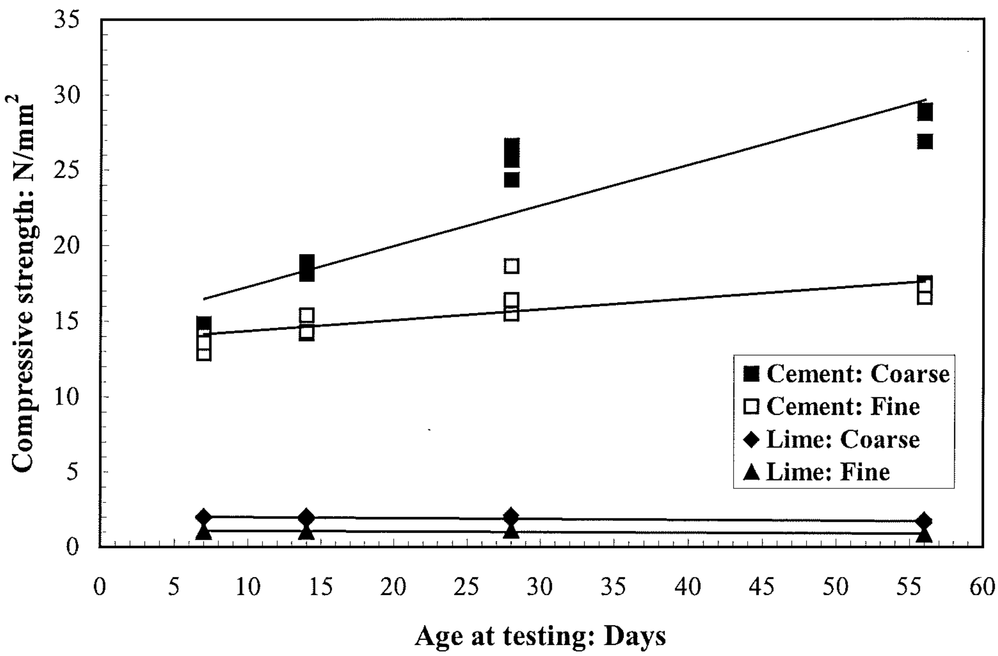


Fig. 6.2 - Compressive strength Vs age at testing for lime/cement mortars mixed with coarse and fine sands ratio of 1:3

The Fig. 6.2 also shows that Fen-X lime/cement mortars made with coarse sand are stronger than that made with fine sand. The compressive strength of lime mortar made with coarse sand for 7, 14, 28 and 56 day was 61, 83, 66 and 88% stronger than cubes made with fine sand respectively. Similarly, for the 7, 14, 28 and 56 day, cement mortar made with coarse sand showed an increase in compressive strength of 24, 27, 52 and 65% respectively compared to the cement mortar made with fine sand.

This was partially due to the contribution to strength resulting from the presence in a high percentage of rough, angular in shape and sharp large particles of sand, which are better bonded to the lime/cement paste than fine sand which contains higher percentage of smooth and rounded shaped particles. Coarse particles of sand when compacted produce a denser mortar as the particles are better interlocked. The larger particles are also rougher, tougher and stronger in nature, which when compacted together have a restraining and stiffening effect in mortar that indirectly increases the strength.

Fine sand contains a higher percentage of rounded particles, which has the tendency to roll easily over each other during mixing and compaction, producing a workable mortar but weaker in strength. Round particles when compacted leave air voids between them which produce less dense and weaker mortar.

Another reason was the number of solid particles of sand used in the mixes. It was true, since the amount of sand needed for a mix was batched by volume, that fine sand has more solid particles in a measured volume than coarse sand due to less air voids between the solid particles of sand during the batching process. This meant that the actual ratio of lime/cement binder to sand was higher for a mortar made with fine sand compared to a mortar produced using coarse sand. This was reflected clearly on the mortars compressive strength in Fig. 6.2. This problem could be eliminated if the constituents of the mortar mixes were batched by weight instead of volume, but BS 5628 (British 1992) recommends batching mortar mixes by volume for ease of construction on site.

The final conclusion derived from Fig 6.2 was that if lime/cement mortars are to be used for load bearing walls, where strength was required, coarse sand should be used instead of fine sand.

6.3.2 Tensile splitting strength of mortar cubes

Fig. 6.3 shows the relationship between cubes tensile splitting strength and age at testing for lime/cement mortars made with coarse and fine sands. The figure shows a similar relationship to the one shown in Fig. 6.2 for compressive strength. The only difference was that the tensile splitting strengths were found to be approximately equal to one tenth of the values of compressive strengths.

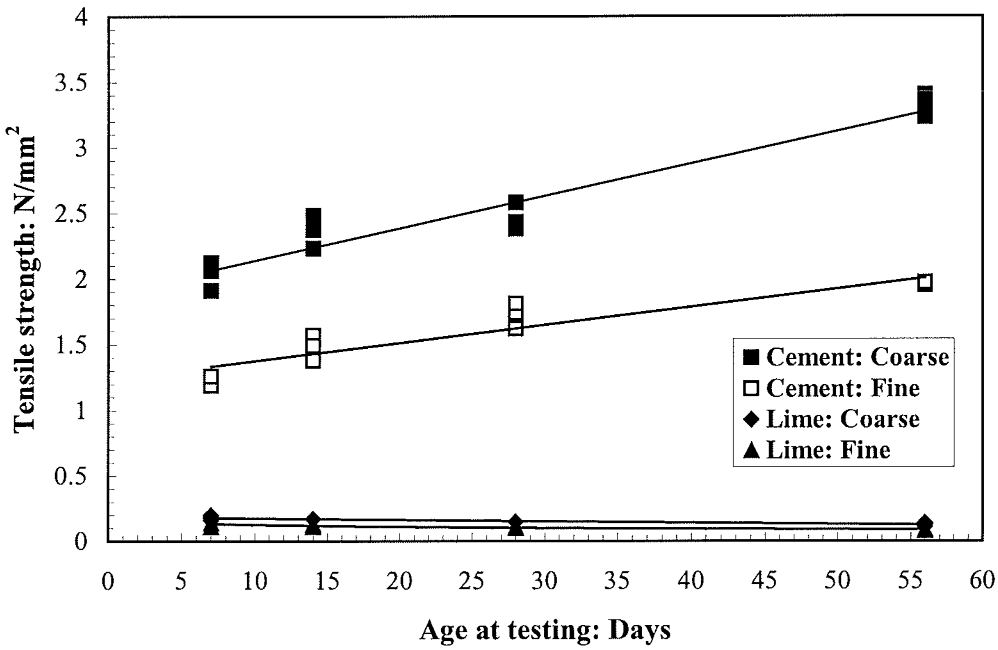


Fig. 6.3 - Tensile splitting strength Vs age at testing for Fen-X lime/cement mortars mixed with coarse and fine sands

The results show that the tensile splitting strengths of lime mortars made with coarse sand for 7, 14, 28 and 56 days are 25, 42, 50 and 63% respectively, stronger than the cubes made with hydraulic lime and fine sand. Similarly, for the 7, 14, 28 and 56 days, cement mortar made with coarse sand showed an increase in tensile splitting strength of 41, 53, 41 and 48% respectively, compared to cement mortar made with fine sand.

As a whole the previous figures show that the compressive and tensile splitting strengths of lime mortars don't change dramatically. The compressive strengths of lime mortar made with coarse and fine sands decrease by 20% over the 56 day test period, while the tensile splitting strengths of lime mortars made with coarse and fine sands decrease by 24% and 33% respectively over the 56 day test period. However, the compressive and tensile splitting strengths of cement mortars made with coarse and fine sands increased with age. The compressive strengths of cement mortar made with coarse and fine sands increase by 35% and 15% over the 56 day test period respectively, while the tensile splitting strengths of cement mortars made with coarse and fine sands increase by 22% and 25% over the 56 day test period respectively.

The figures show the cement mortars are by far the more superior in strength compared to lime mortars. This does not mean that strong cement mortars are better for construction and repair than weak mortars. Strong mortars usually have problems accommodating cracks caused by thermal, settlement and moisture movement. Using strong mortars result in large cracks concentrated in fewer mortar joints in the wall allowing an easy access of rainwater to the interior of buildings. Strong mortars usually have low porosity and permeability and they are not suitable for repair and conservation of historic masonry buildings. Strong mortars work as a barrier preventing the normal circulation and evaporation of rainwater in masonry walls. This results in speeding up the decay process and disintegration of stones.

6.3.3 Tensile bond strength

Fig. 6.4 shows the relationship between the tensile bond strength and age at testing for both Fen-X lime/cement mortars made with coarse and fine sands. The figure shows that the lime mortars are hydrating and carbonating to a greater extent, as the tensile bond strength of the lime mortars made with coarse sand are closer to that of the cement mortars. The figure also shows that the 28 and 56 days tensile bond strength of lime mortar made with coarse sand are approximately 2.5-3 times stronger than the lime mortar made with fine sand respectively. This suggest that coarse sand gives better tensile bond strength than fine sand due to the improvement in carbonation as a result of the presence of more air voids in the mortar between the large particles of coarse sand. The thickness of the mortar joint (10mm) between the two bricks did also help the tensile bond strength by improving the carbonation of lime compared to the thicker 70mm cubes which when split gave lower tensile splitting strength (Van Balen and Van Gemert 1994).

As stated in Chapter 2, lime was characterised by stickiness, which means it binds gently and sticks to give good adhesion to other surfaces. This shows another example of why the lime mortar produces good tensile bond strength. The lime mortar was sucked with the moisture into the bricks pores which when harden produces good bond.

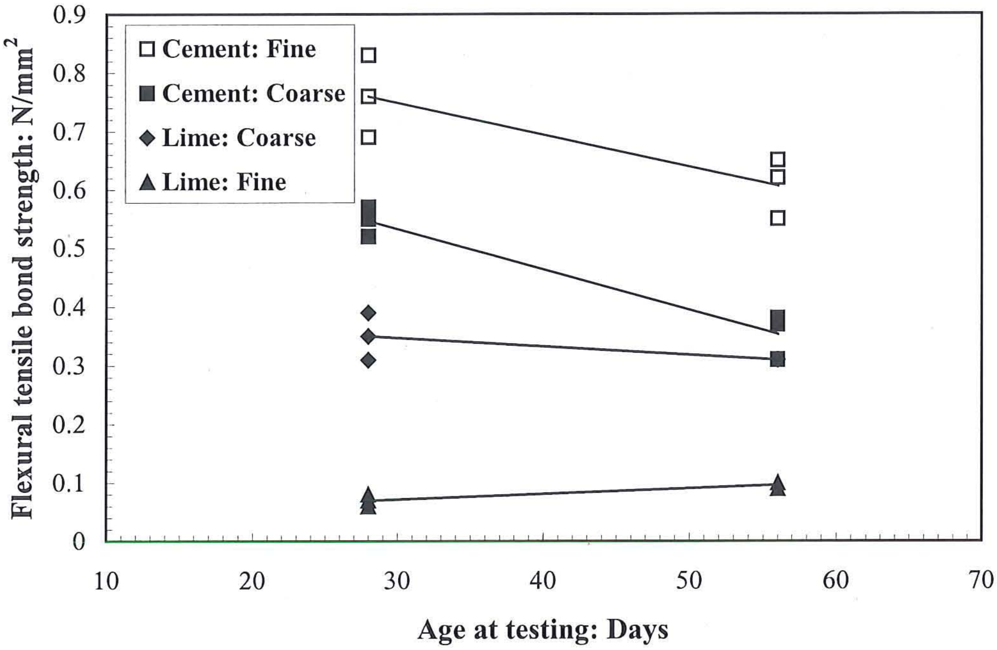


Fig. 6.4 - Tensile bond strength Vs age at testing for Fen-X lime/cement mortars mixed with coarse and fine sands

The figure shows completely different results for cement mortar whereby the mortar mixed with fine sand produces higher tensile bond strength than mortar mixed with coarse sand. The fine particles of sand and cement were able to penetrate and fill more pores on the bricks surface than the larger particles. As the cement strength development was hydration and not carbonation there was no need for air voids full with carbon dioxide to develop strength, as the case with lime mortar. Tensile bond strength was better for cement mortar containing fine sand and has less air voids.

Fig. 6.4 shows strangely that tensile bond strength for cement mortar decreases with time which dose not reflects the development in cement strength by hydration over the 28 days deference. This reduction in strength with time needs more investigation.

6.3.4 Shear bond strength

Fig. 6.5 shows the relationship between the shear bond strength and age at testing for both cement and lime mortars mixed with coarse and fine sands. The figure shows a similar relationship to Fig. 6.4 with the shear bond strength of lime mortar made with coarse sand are approximately 2.0-2.5 times stronger than lime mortar made with fine sand over the 56 day test period. Additionally, the cement mortar joint mixed with fine sand produced higher bond strength than the cement mortar mixed with coarse sand. The reason, once more was the fine particles of sand and cement filled more surface pores in the brick, which resulted in a stronger bond between the two materials.

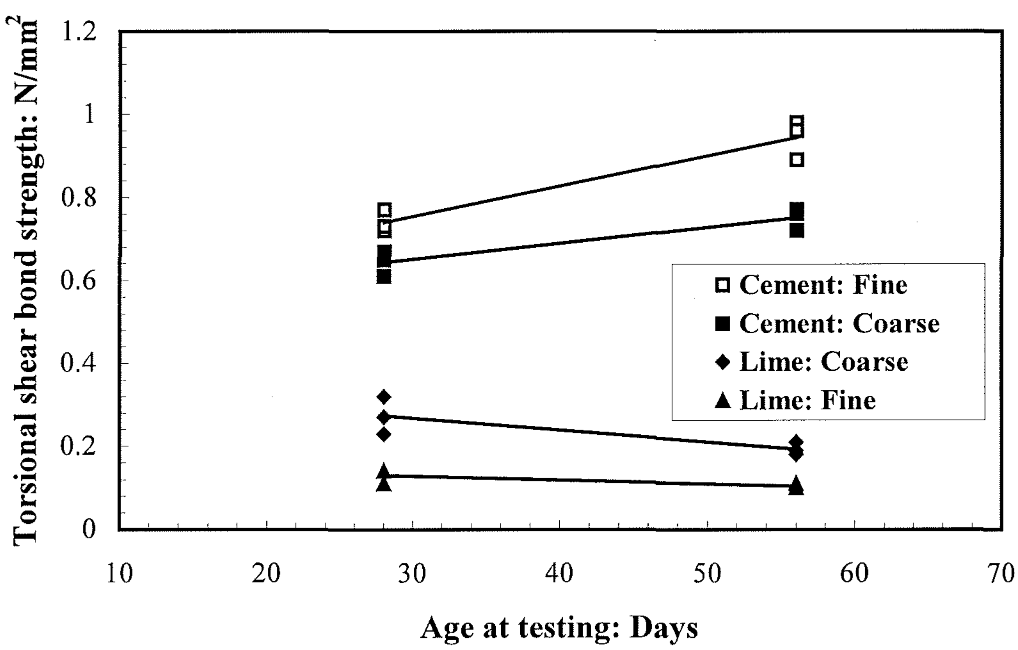


Fig. 6.5 - Shear strength Vs age at testing for Fen-X lime/cement mortars mixed with coarse and fine sands

The results in Figs. 6.4 and 6.5 show remarkably the lime mortars to have high values of tensile and shear bond strength. These values were achieved despite lime mortars low compressive and splitting strength compared to cement mortars. These important results give masonry walls constructed with hydraulic lime mortars a better bond strength and resistance to rainwater ingress through the masonry unit/mortar joint interface. Further research would be necessary to investigate the bond between hydraulic lime mortar and building stone i.e. sandstone and limestone.

The above findings give the answer to the outstanding durability of historic masonry building built with lime mortar under changing weather conditions for such a long time. Also, as a result of the findings derived for sand from the above parts of the investigation, all mortars produced for the forthcoming parts of the investigation were made with coarse sand.

6.4 FLEXURAL STRENGTH OF PRISMS

The next sets of results were investigated after noticing that the lime mortar was not carbonating fully in steel moulds for strength to reach optimum values. The Fen-X lime:coarse sand ratio used for the prisms was 1:3 by volume and they were de-moulded after 2-4 days. The prisms were cured normally in air under ambient laboratory conditions at a temperature of 17^0C with a relative humidity of 38% before testing.

Fig 6.6 shows the relationship between the flexural strength and age at testing for mortars cast and cured in three different moulds (steel, polystyrene and scabbold). The figure shows that there was no significant change in strength using the three different casting moulds. This was not what was expected, as it was thought by scabbolding the mortar prisms after de-moulding would result in an increase in strength due to better exposure and carbonation. It was also thought that the steel moulds, with the smooth sides, blocked the pores of the mortar and so inhibited the carbonation of the lime. However, the results show that the lime mortars made by the three methods have similar flexural strengths.

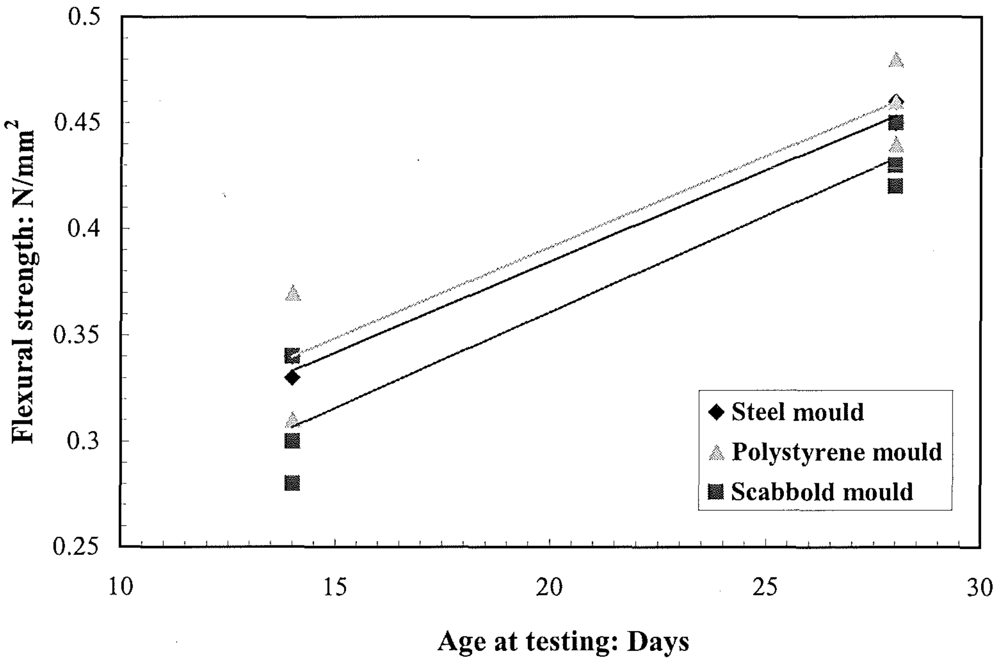


Fig. 6.6 – Flexural strength Vs age at testing of prisms cast in different moulds

However, Fig. 6.7 shows clearly that the percentage change in flexural strength between the three methods of preparation was different. The figure shows that the mortars scabbold after de-moulding have a higher increase in strength over time than both the polystyrene and the steel moulds. The scabbold mould has a 10% and 14% increase in flexural strength over the 56 day period than the polystyrene and steel moulds, respectively. The reason for this was that although the initial strength was low, as time proceeds the air can circulate easier around the mortar as the outer pores have been scabbolded off, and so carbonate the lime to a higher extent compared to the other two prisms.

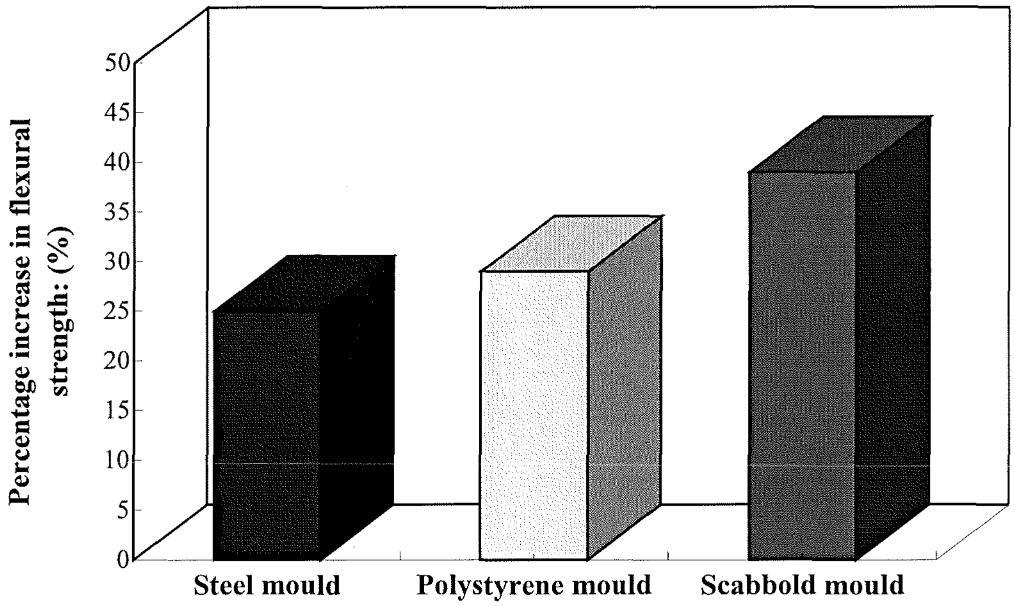


Fig. 6.7 - Percentage increase in flexural strength

Fig. 6.8 shows the relationship between compressive strength of the prisms, after flexural testing prepared by the three different methods. The figure shows that the prisms prepared using the steel and polystyrene moulds have a constant compressive strength over time while specimens scabbold after de-moulding increasing sharply. Thus proving what was discussed earlier that initially the specimens scabbold after de-moulding has poor flexural and compressive strength but by removing the smooth surfaces exposed the pores for air to penetrate to improve carbonation. The main outcome of this part of the investigation was that although the scabbling has the lowest strength at early age it will increase at a greater rate and will give a higher strength later.

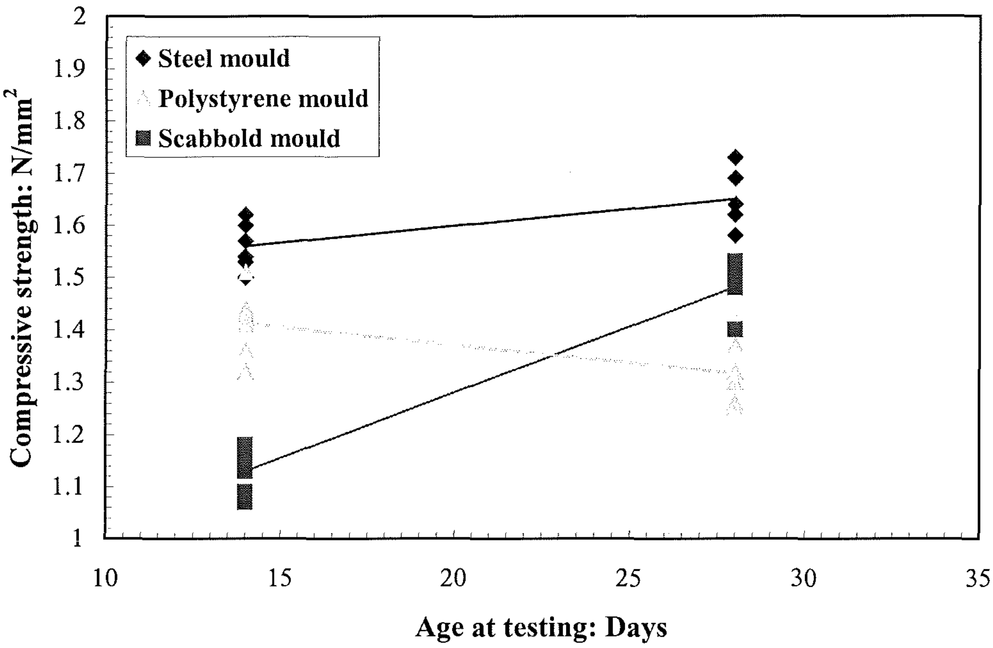


Fig. 6.8 – Compressive strength Vs age at testing of prisms cast in different moulds

6.5 EFFECTS OF DIFFERENT MIX RATIOS

Fig. 6.9 shows the relationship between the compressive strength and the age at testing for four different types of lime mortar mixes made with coarse sand. The objective of this part of the investigation was to determine the effect of changing the Fen-X lime: sand ratio (1:1, 1:2, 1:3 and 1:4) on the compressive strength of the mortar. This provides mortar mixes with different strengths for selection to be made in restoration, renovation of old masonry buildings or for the construction of new buildings. As before the specimens were de-moulded after 2-4 days and cured under ambient laboratory conditions normally in air.

Fig. 6.9 shows the relationship between the cubes compressive strength and age at testing for lime mortars made with different amounts of coarse sand. The figure shows as predicted that the mortar made with 1:1 mix ratio produced the highest compressive strength compared to the other mix ratios and was increasing in strength over age. This increase in strength with age for this type of mortar was a clear indication that the combined hydration and carbonation reactions of hydraulic lime were occurring in a faster rate for mortars with a low proportion of sand compared to mortars with high proportion. The other mix ratios did not increase in strength within the time scale presented in Fig. 6.9. This was an indication that the samples have not enough hydraulic lime to improve the strength within the time scale. Unfortunately, no tests were carried out to investigate the strength beyond 56 days. But previous investigations and researches showed that hydraulic limes do increase in strength over long periods of time due to the slow reaction with carbon dioxide (Historic Scotland 1996).

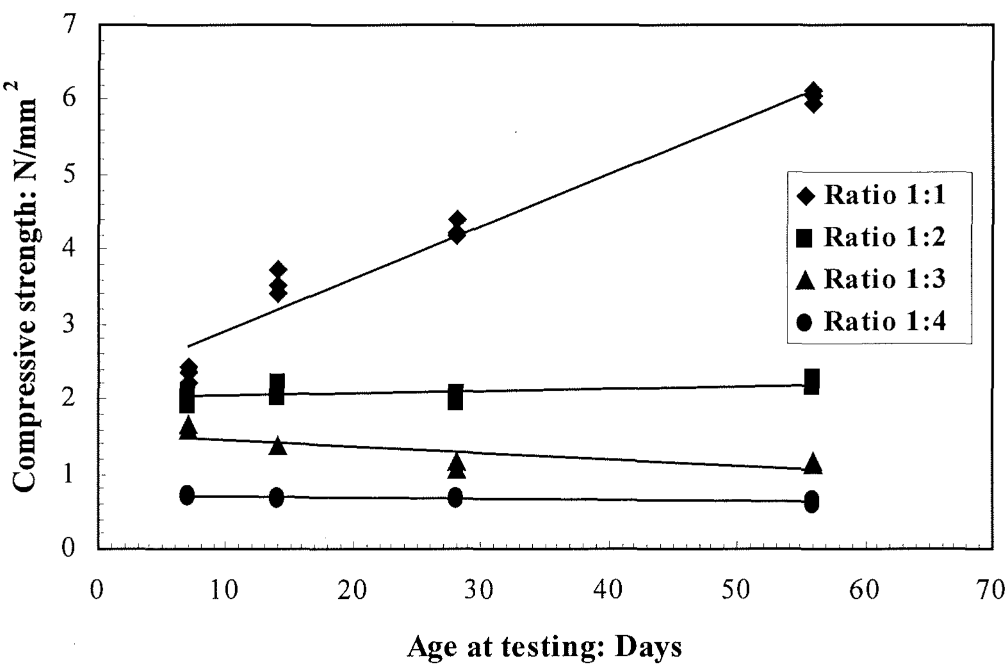


Fig. 6.9 - Compressive strength Vs age at testing of different mix ratios

As a clear conclusion from Fig. 6.9, hydraulic lime mortars show more hydraulic reaction for mortar mixes with a high proportion of lime. These types of mortars started the hydration process using the water added to the mix at early days, then the humidity in the air. When the specimens were dried out CO_2 gas was able to penetrate deeply inside the specimens to increase strength by carbonation.

The above conclusion promotes carrying out the next part of this experimental program, whereby the mortar specimens were stored under different curing regimes in order to investigate the effect on strength of containing moisture within the specimens.

6.6 DIFFERENT CURING REGIMES

Fig. 6.10 shows the relationship between the compressive strength and age at testing of Fen-X lime mortars made with 1:1, 1:2 and 1:3 lime: coarse sand ratios by volume. The mortar cubes were de-moulded after 2-4 days from casting and cured in water, in accordance with BS 1881: Part 111 (British 1983) for 56 days.

The figure shows that by curing the mortars in water the strength can be increased with time. All three ratios show at least an increase in strength of 50% over the 56-day curing period compared to their strengths after 14-days curing. The figure also shows the differences between the ratios with the 1:1 mix ratio having 36% higher strength than the 1:2 mix ratio and in turn the 1:2 mix ratio having 30% higher strength than the 1:3 mix ratio at 56 days curing. The carbonation process in lime mortar was influenced by the diffusion of carbon dioxide into the mortar pore system, by the kinetics of the lime carbonation reaction and by the drying and wetting process in the mortar. All these phenomena depend on the presence of water in the mortar (Van Balen and Van Gemert 1994). However, the mortar was submerged in water and the carbon dioxide could not penetrate to carbonate the lime. Thus by curing the mortars in water the lime present in the mortars will hydrate but will not carbonate. The strengths shown are due totally to the hydration process.

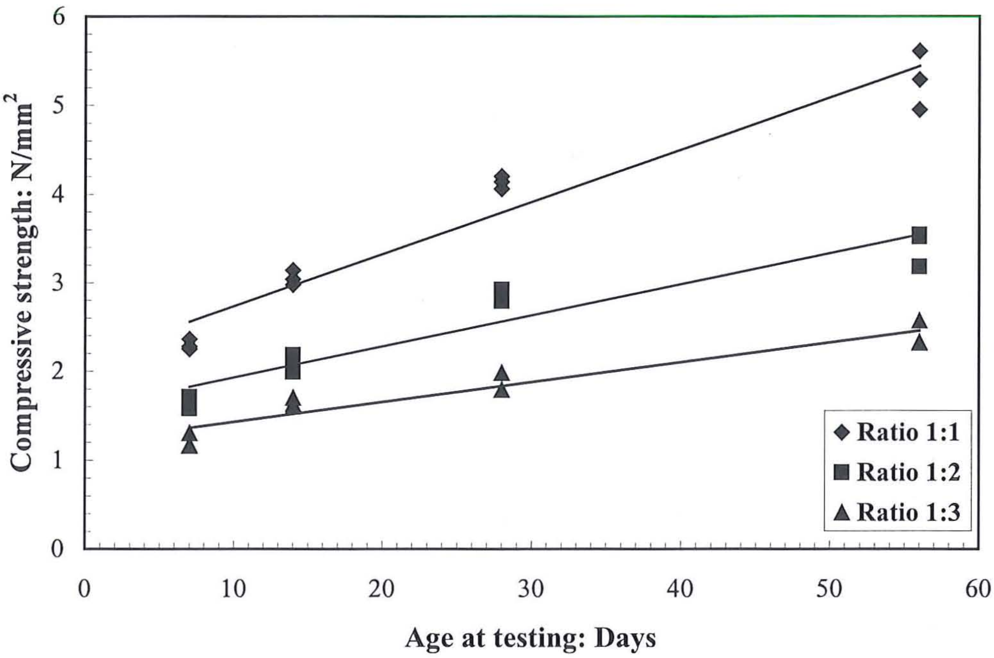


Fig. 6.10 – Compressive strength Vs age at testing of different mix ratios cured in water

Fig. 6.11 compares the results shown in Fig. 6.10 with the compressive strength and age at testing of Fen-X lime mortars made with 1:1, 1:2, and 1:3 lime: coarse sand ratios by volume cured in air under ambient laboratory conditions. The figure shows great improvements in compressive strength when the specimens were cured in water compared to the specimens cured in air. This proves that hydraulic lime mortar needs water for hydration due to the presence of hydraulically reactive natural or artificial pozzolanas.

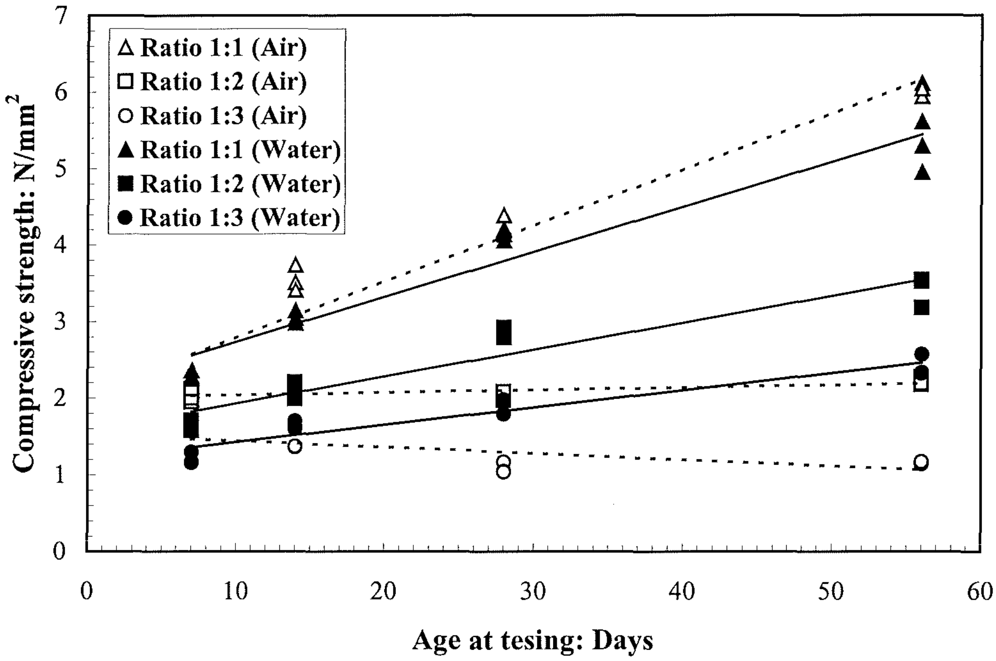


Fig. 6.11– Compressive strength Vs age at testing of mortars cured in air and in water

The 1:1 mix ratios are very similar, with only a 12% difference between the 56 day compressive strength. This was not the case with the 1:2 and 1:3 mix ratios. The 1:2 mix ratio cured in air starts of with a higher compressive strength than the 1:2 mix ratio cured in water yet its compressive strength increased by 4% over the 56 day test period. However, the 1:2 mix ratio cured in water starts of with 20% less strength but over the curing period increased by 52% and after an age of 56 days was 36% stronger than the 1:2 mix cured in air. The 1:3 mix ratios showed similar pattern to the 1:2 mix ratio, with the mix ratio cured in air decreasing in strength consistently over the test period. While the 1:3 mix ratio cured in water increases in strength consistently over the same test period, not only did it have 73% more strength than the 1:3 mix ratio cured in air, at the end of testing, but it was stronger than the 1:2 mix ratio cured in air.

The reduction in strength at the age of 7 days for all mortars cured in water was because the diffusion of carbon dioxide in water was much slower than in the air. Carbonation was thus retarded if not stopped when the material was saturated with water (Richardson 1988). This shows why the mortars cured in air start off with higher strengths than the mortars cured in water as the strength was only due to hydration rather than hydration and carbonation. However, as the mortars age, the hydration process increases in the mortars cured in water at a steady rate and the constant temperature increases the curing environments stability.

This part of the investigation proves that by curing the mortars in water the strength of the lime mortar can be increased steadily with age, however the actual practicality of this being used on-site was of little use due to the fact of keeping the mortar covered with water all the time. However, underwater construction will benefit from this finding.

The above findings promote the next testing programme, whereby the lime mortar cubes were cured using different types of covering to contain moisture within the cubes. Curing hydraulic lime mortar underwater for several days was not a practical option but using other materials that help prevent the evaporation of moisture was more practical.

For the purpose of this part of the investigation, Fen-X lime mortar cubes were prepared, de-moulded after 2-4 days from casting and cured under different regimes. The results of the cube crushing are presented in Figs. 6.12, 6.13 and 6.14. The subsequent figures show the relationship between the compressive strength and age at testing for mortar cubes made with 1:1, 1:2 and 1:3 mix ratios by volume. The regimes for curing were: hessian bag, hessian and plastic bag, plastic bag and in air under ambient laboratory conditions.

Fig. 6.12 shows the compressive strengths of the 1:1 ratio lime mortar cubes cured using hessian bags, hessian and plastic bags, plastic bags and cured in air. The figure shows that specimens cured in air produced the lowest values of strength compared to all the other specimens cured under cover. The reason was the loss of moisture by evaporation. This reveals that hydraulic lime mortars need to retain the moisture at early stage to cure due to the presence of some form of reactive cementious materials.

The other three regimes of curing show slight differences in the values of compressive strength with the mortar cured in plastic only having 3.8% less final strength than the mortar cured under hessian covered by plastic. The final compressive strength of every covered mortar cube increases by 80% over the 8-week period, showing a good consistency and good hydration due to the retention of moisture. Since the results of strength are so similar, the author recommends using the cheapest and most practical regime of curing on site, whereby the restored or newly built walls with lime mortar should be covered by plastic sheets for a period of 10-14 days after construction, depending on the surrounding temperature and humidity. In actual fact the longer the walls are covered the better the strength. The daily spraying of the walls with water would also help the hydration process. After the wet period of curing the walls should be uncovered to allow the lime mortar joints to dry out to increase the carbonation process.

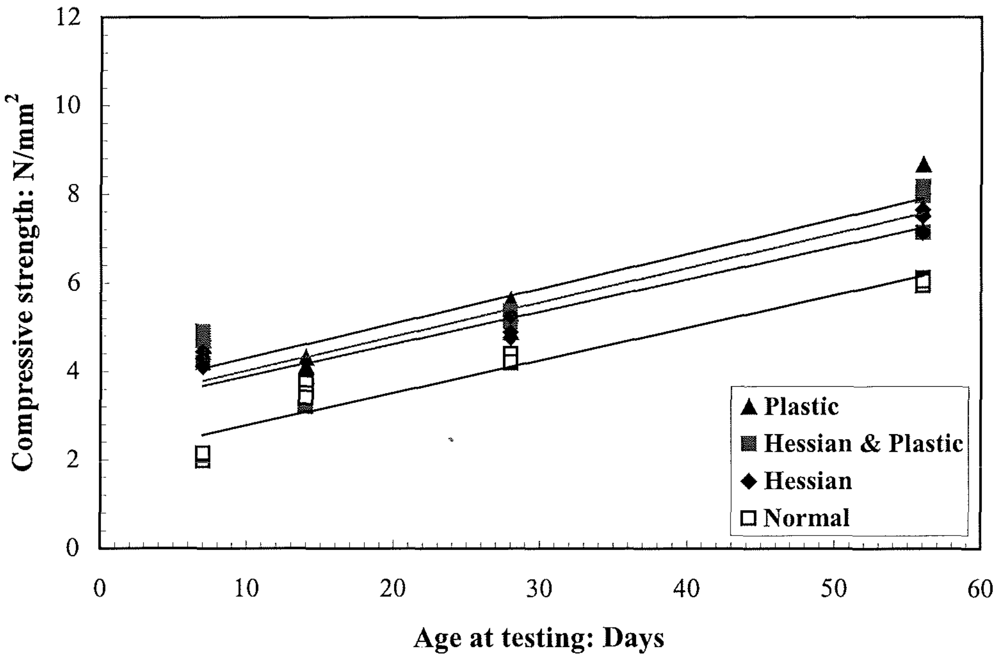


Fig. 6.12 - Compressive strength Vs age at testing of 1:1 ratio mortar cured under different regimes

Fig. 6.13 shows the compressive strengths of the 1:2 lime mortar ratio cubes cured using hessian bags, hessian and plastic bags, plastic bags and cured normally in air. The figure shows that all the mortars cured under some kind of cover achieved similar compressive strength of about 4.5N/mm^2 at 56 days, which was more than double the strength of the mortar cubes cured in air. The reason for this was again the presence of the hydraulically reactive cementious materials in hydraulic lime. The mortars wrapped in different materials are able to hold more of the water and so keep the mortars damp, this causes an increase in hydration and so increases the strength of the mortar. While the mortars cured undercover prohibits the evaporation of water, as the mortar cured in air has no protection the water can evaporate easily and so the compressive strength can not reach its full potential.

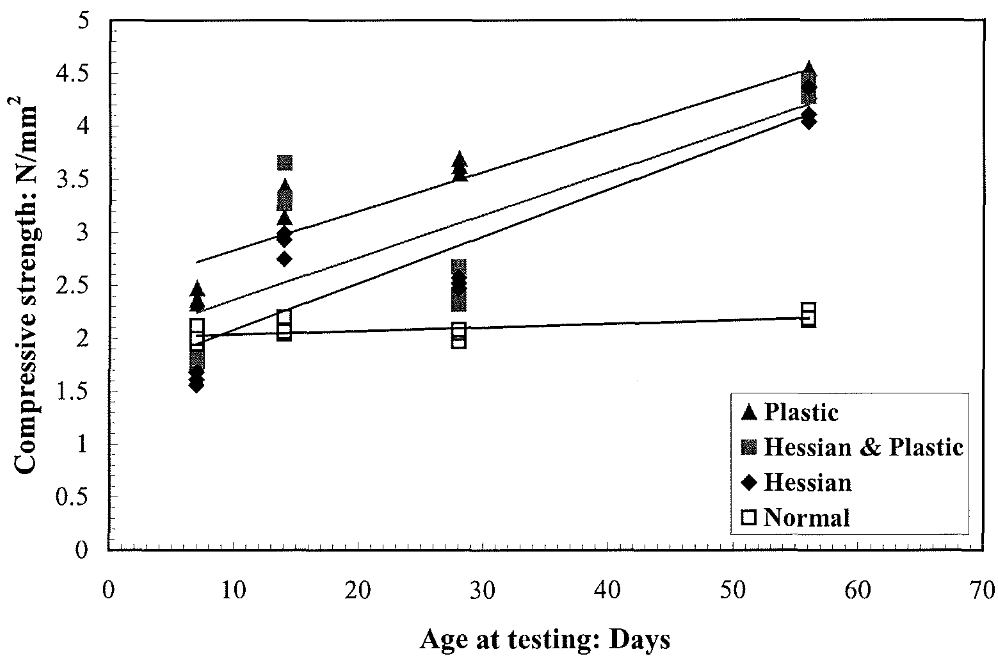


Fig. 6.13 – Compressive strength Vs age at testing of 1:2 ratio mortar cured under different regimes

Fig. 6.14 shows the compressive strengths of the 1:3 lime mortar ratio cubes cured using hessian bags, hessian and plastic bags, plastic bags and cured in air. Similarly, the results showed that the cubes cured undercover produced higher compressive strength than the ones cured in air, with the cubes cured in plastic bags producing the highest values of strength. This proves once again that all the mortars cured under some kind of sheet achieve higher compressive strength at 56 days, while the mortar cured in air reaches approximately half their strength. This was due to greater hydration in the mortar occurring under moist conditions.

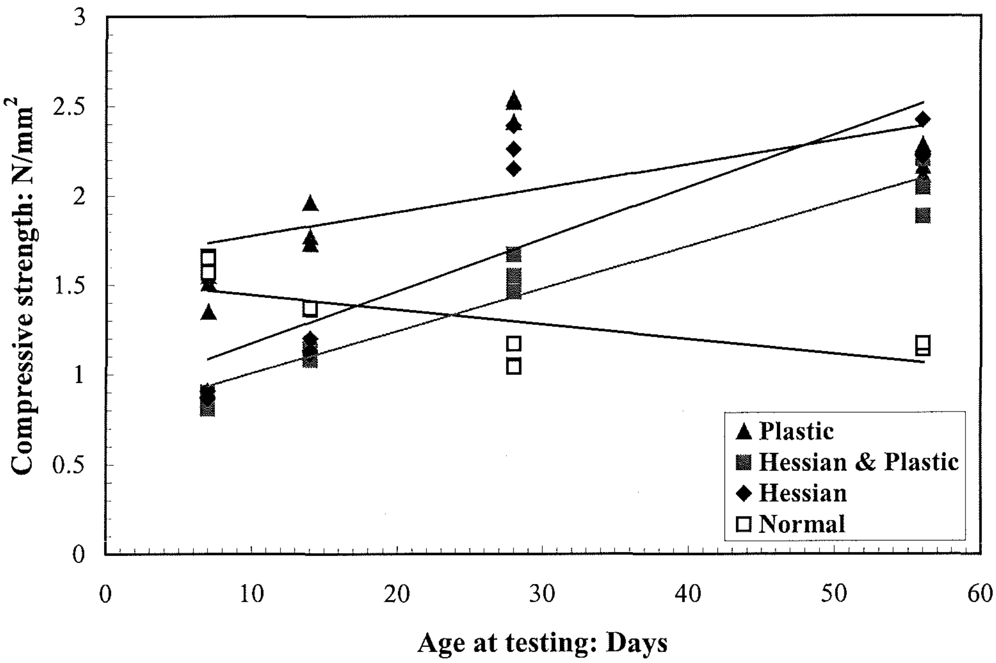


Fig. 6.14 – Compressive strength Vs age at testing of 1:3 ratio mortar cured under different regimes

The next experimental program in the present investigation was designed to study the effect of curing hydraulic lime mortars at different temperatures. For that purpose mortar cubes with 1:1, 1:2 and 1:3 Fen-X lime: coarse sand mix ratios, by volume, were prepared, cast, de-moulded after 2-4 days and cured at temperatures ranging from -14°C to +120°C for a period of 56 days when they were tested for compressive strength.

Fig. 6.15 shows the relationship between the compressive strength and age at testing for three different mix ratios cured at different temperatures. The figure shows that by curing the mortars at approximately 55°C the strength of all the mixes reached their optimum values. This temperature must be special for the type of hydraulic lime used in the present investigation (Fen-X). It was not clear which chemical reaction was responsible for achieving such a result. But there was no doubt that for Fen-X hydraulic lime a temperature of 55°C was the best for chemical transformation of $Ca(OH)_2$ to $CaCO_3$. The author believes that this result was due to a combined process of hydration and carbonation. Other types of hydraulic lime mortar may attain optimum values at different temperatures depending on their chemical compositions.

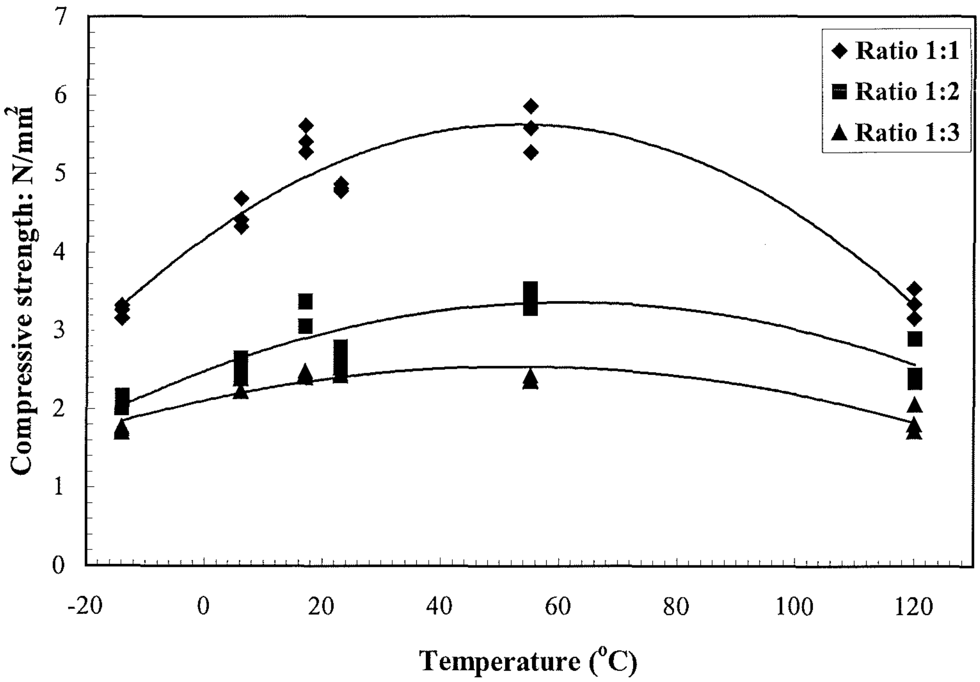


Fig. 6.15 - Compressive strength Vs temperature of different mix ratios cured at different temperatures

Unfortunately, no tests were carried out to find when the optimum value of compressive strength was achieved, because values presented here are for 56 days only. Another program should be carried out to test cubes at 1, 3 and 7 days curing.

The 1:1 and the 1:2 mix ratios both have an increase in strength of 40% at 55°C, while the 1:3 mix ratio increases by 27%. This was not a practical way of curing mortars at the present time, but after more investigation there could be a practise of curing lime mortars in this method to increase the compressive strength.

It was clear now why historic buildings constructed with lime mortar, by ancient civilisations, in hot countries survived for thousands of years despite the aggressive environment and natural disasters. Dry hot weather in a desert like environment helps hydraulic lime to hydrate and carbonate faster, whereas hot and humid weather in tropical like areas, help hydraulic lime to hydrate faster but the carbonation process becomes very slow because the mortar pores, most of the time, were filled with moisture blocking CO_2 from penetrating deeper into the mortar to speed up the chemical transformation of $Ca(OH)_2$ to $CaCO_3$. For carbonation to take place CO_2 should fill the mortar capillaries. It must be stressed that for a satisfactory development of strength, it was not necessary for all the lime to carbonate and indeed this was only rarely achieved in practise, but carbonation process will eventually be completed over a long period of time.

Heritage, Khalaf and Wilson (2000) carried out research on accelerating the curing of cement-based concrete's after 1, 2, 3 and 4hrs delay periods from casting using heat generated by passing direct electrical current (DEC) through the material. The heating regime consisted of a linear rise of 40°Chr to a maximum of 60 or 80°C. The results showed a great increase in the 24hrs compressive strength of electrically cured concrete's compared to concrete's cured in a water tank at 22°C in accordance with BS 1881: Part 111 (British

1983). The results also showed that for the 3hrs delay specimens, the compressive strength at 3 days under normal water curing was achieved in 24hrs curing at 60°C, whereas the compressive strength at 7 days under normal water curing was achieved in 24hrs curing at 80°C. Although the work carried out by the three researchers was mainly looking at curing of cement-based concrete at early days, the results achieved suggest that hydration of cementious materials do accelerate considerably by heat.

Work on concrete cured in water at different temperatures was reported by Neville (1995). Neville states that a higher temperature produces a higher strength during the first day, but for ages of 3 to 28 days, there was an optimum temperature which produces a maximum strength, but this optimum temperature decreases as the period of curing increases. Neville also reported that with ordinary (Type I) or modified Portland (Type II) cement, the optimum temperature to produce a maximum 28 day strength was approximately 13°C. For rapid-hardening Portland (Type III) cement, the corresponding temperature was lower.

6.7 POROSITY AND WATER ABSORPTION OF MATERIALS

The porosity and water absorption of lime mortars are very important factors in influencing water penetration, circulation, evaporation and resistance to freeze/thaw cycles. This section introduces the new test procedure, as discussed previously, for calculating the porosity and water absorption values of mortar involving the testing of mortar lumps under vacuum.

Fig. 6.16 shows the results for compressive strength, porosity and water absorption for the materials tested in this part of the investigation. The results reveal that for lime mortars water absorption and porosity decreases as compressive strength increases. This result was expected as strength, porosity and water absorption are all related to the number of air voids in the material.

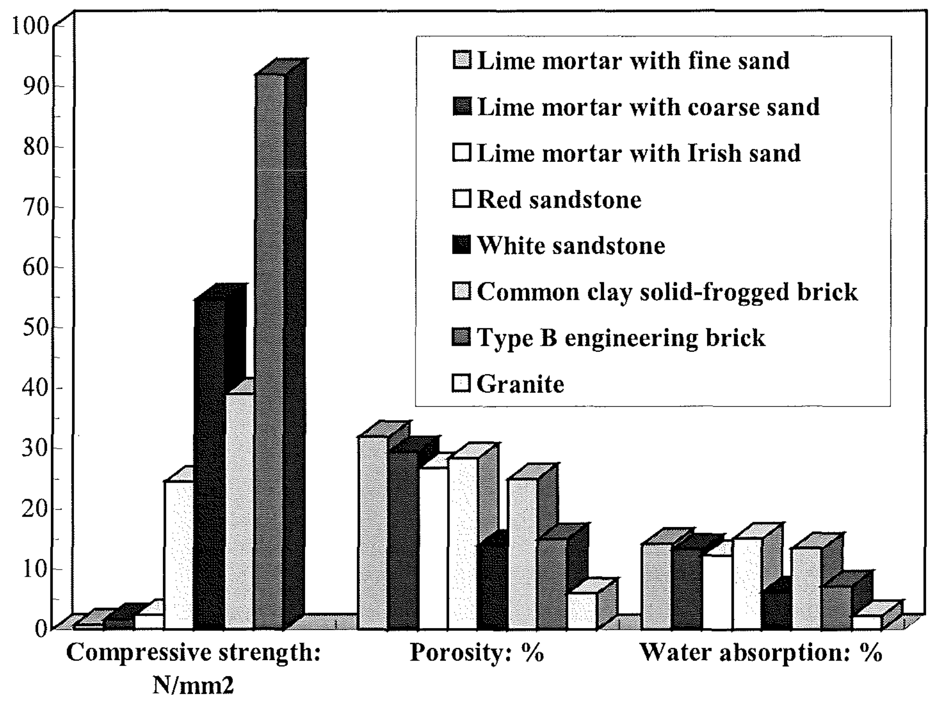


Fig. 6.16 - Compressive strength, porosity and water absorption for engineering materials

The figure shows that lime mortars have good values of porosity and water absorption compared to other materials. These values were achieved despite lime mortars low compressive strength. This phenomenon was another unique property of lime mortar which explains why this material was still functioning as a bonding mortar in old historic buildings and monuments for thousands of years.

A remarkable example of the good values of porosity and water absorption can be demonstrated by comparing results from tests on lime mortar made with coarse sand and red sandstone. Lime mortar has a porosity of 29.44% and water absorption of 13.26% but only has a compressive strength of 1.59N/mm^2, whereas the red sandstone has a porosity of 28.38% and water absorption of 15.12% and a compressive strength of 24.58N/mm^2. Although the lime mortar only has approximately 7% of the compressive strength of the red sandstone, the porosity and water absorption are very similar and proves that hydraulic lime materials are compatible as a material to red sandstone regarding the movement of water and so can be used for restoration.

Compatibility of materials are very important if two different materials are to be used together in construction. The results showed that lime mortar made with coarse sand and Irish sand (also coarse sand) have similar values of porosity and water absorption to red sandstone and common clay brick. Combining these materials together will behave similarly as one material to any changes in temperature and moisture. Most sandstone and limestone used in the past and present have values of porosity and water absorption very similar to the values of lime mortar, which makes stonework compatible in behaviour regarding the circulation and evaporation of rainwater.

The main reason for such a unique property of lime mortar compared to other materials tested in the programme was related to the product of carbonation and hydration and its microstructure. A carbonated mortar has a fine structure with a high percentage of fine voids relative to coarse voids. Fig. 6.17 shows a magnified section of (a) red sandstone and (b) hydraulic lime mortar.

Although the porosity of the two materials are similar the air void structure was different. The red sandstone has either larger or more voids, while the hydraulic lime mortar has smaller or less voids but these are joined by capillary tubes. These capillary tubes and air voids take up approximately the same amount of area as the larger voids in the red sandstone and so they produces similar porosity and water absorption results.

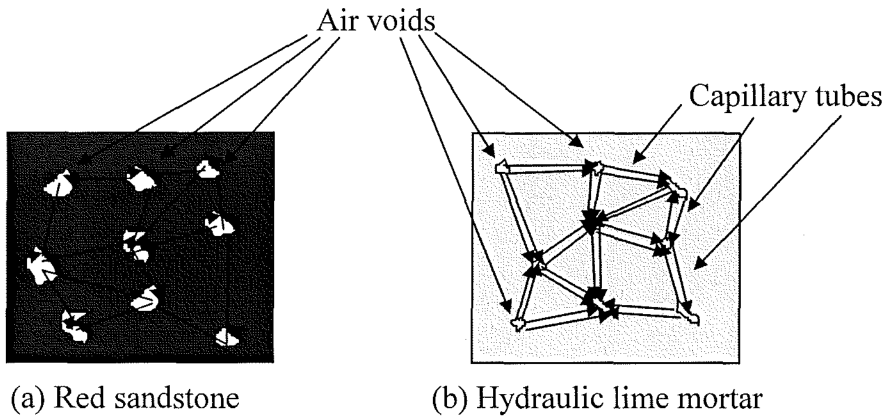


Fig. 6.17 - Air void placement of (a) red sandstone and (b) hydraulic lime mortar

The graph shows a general rule the higher the compressive strength the lower the porosity and water absorption. An example of this was the white sandstone which has a compressive strength of 54.68N/mm^2 over twice that of red sandstone (24.58N/mm^2). However, the white sandstone has approximately half the values of porosity (13.96%) and water absorption (6.22%) than red sandstone (porosity 28.38% and water absorption 15.12%). This was due to the white sandstone having less air voids in its structure and so producing low porosity and water absorption but a high compressive strength.

Renovating and re-pointing work on stones with such a varied high compressive strength, lime mortar was an ideal material to be used. The lime produces a mortar joint which disintegrate by weathering before the stones. Also as the lime has a high porosity the rainwater will flow from the stones through the lime mortar. In any renovating or re-pointing work it was important to consider the use of a weak mortar which if disintegrated can be replaced in the future. The worse scenario was to use a strong mortar which will prevent the normal circulation of rainwater through the stonework and leads to the degeneration of the original stones.

Fig. 6.18 shows the same types of sandstone and clay bricks compressive, porosity and water absorption. The lime mortar shown has Fen-X lime: coarse sand ratios of 1:1, 1:2 and 1:3 cured in air and in water. The figure further proves that lime mortars have high porosity values despite low compressive strength. The interesting aspect of this figure was the fact that the porosity and water absorption of the lime mortar cured in air decreases as the lime: sand ratio decreased. This confirms that the more lime added to the mix the higher the porosity if cured normally in air. This corroborates what was stated earlier about the phenomenon of lime mortars and how they have functioned as a bonding material for thousands of years.

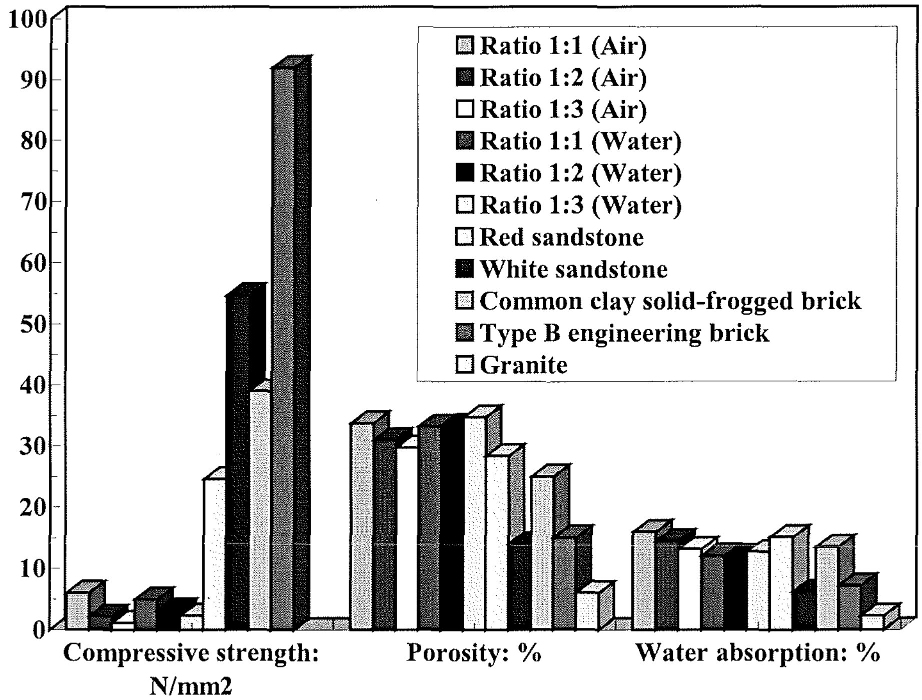


Fig. 6.18 - Compressive strength, porosity and water absorption results for different engineering materials

In both cases of the porosity and water absorption of lime mortars cured in air are approximately higher or equal to the sandstone but the compressive strength has a much lower value.

Fig. 6.18 also shows the compressive strength, porosity and water absorption for ratios 1:1, 1:2 and 1:3 cured in water. These values show again a low compressive strength but high porosity and water absorption for lime mortar. However, unlike the mortars cured in air the porosity and water absorption do not decrease but slightly increase as the lime: sand ratio increases. This different reaction to the mortar cured in air was due to the water penetration. The water penetrates, producing more air voids in the mortar during curing. Once the mortar has dried some of these air voids are still present causing higher porosity than the mortar cured in air. Some of the voids in the mortar will disappear during curing due to autogenous healing of lime which will be responsible for the reduction in porosity.

The above findings promote carrying the next part of this experimental program, whereby the effects of the addition of cement on the properties of hydraulic lime are investigated.

6.8 THE ADDITION OF CEMENT ON LIME PROPERTIES

The reason for testing the effect of the addition of cement to lime mortars was to show that lime can be used on modern materials. The designer can choose a mix which was suitable for the purpose of the work by adding cement to lime to get the desirable strength, colour or durability. Fig. 6.19 shows that the compressive strength of St. Astier lime (low strength) increased dramatically by the addition of cement. The effect was more pronounced by looking at the 56 days compressive strength in Fig. 6.20. The Fig. 6.20 shows that the compressive strength increases linearly as the amount of cement increases. This suggests that the properties of cement seem to dominate the lime. This means that mortar made from such a mix would result in a mortar with properties approaching that of cement. Similarly, the setting and hardening of samples made of a mix of cement and lime seem to take much shorter periods than samples made from pure St. Astier lime.

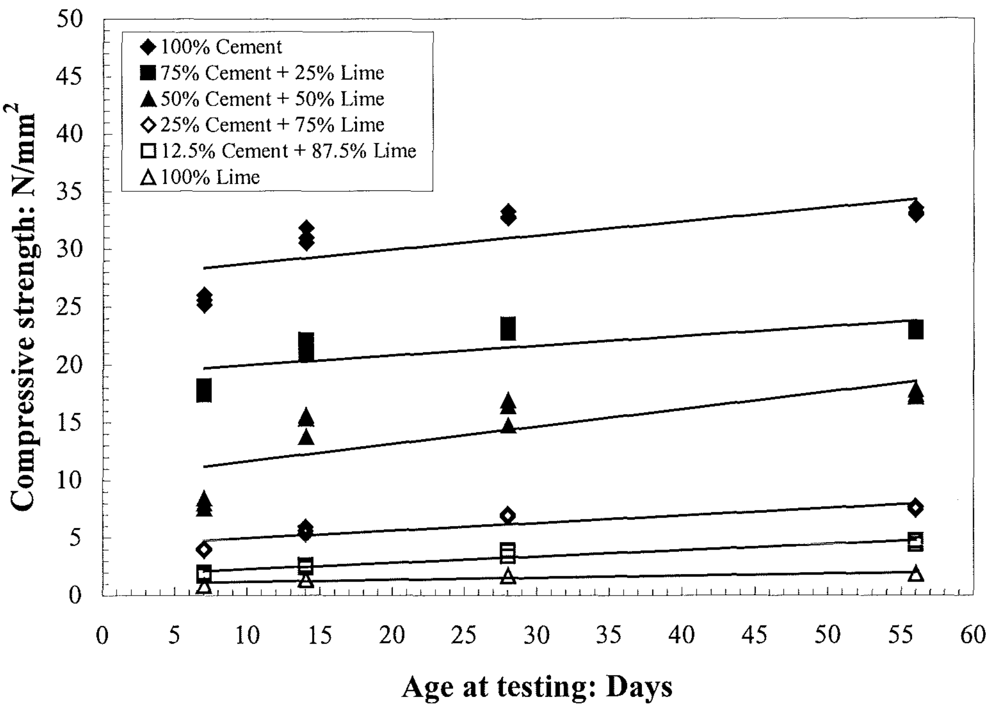


Fig. 6.19 - Compressive strength Vs age at testing for different percentages of cement added to lime

These findings suggest that the cement crystals form their matrix at the expense of the lime. If the lime was predominant or has a retarding affect it would not be expected to see such a sharp rise in compressive strength, effectively creating a curve relationship more than a straight line. Therefore, in cement and lime mix, the cement and not the lime has a predominant effect on the properties of the mortar.

The rate of carbonation for the 100% lime cubes was quite slow and the strength achieved was low compared to cement and lime or 100% cement cubes. With the lime-based mortars being as weak as the investigation shows, it would be important to find a way of increasing the rate of carbonation without reverting to the addition of cement if possible.

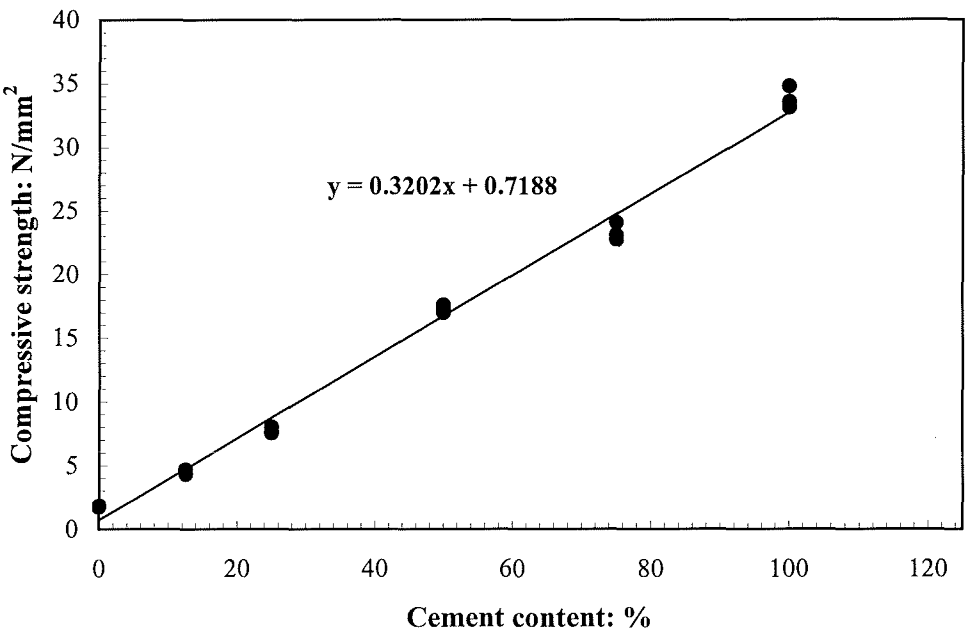


Fig. 6.20 - Compressive strength Vs cement content (%) for 56 day testing

From the Authors point of view, there was no harm in adding small percentages of cement to the lime as long as this addition has no effect on the adjacent stone work. To satisfy compatibility of materials the porosity and water absorption of the lime/cement mortar and the masonry units used should be determined and checked beforehand to ensure that their values are approximately equal.

6.9 CONCLUSIONS

The compressive strength values suggest that the three pre-packaged hydraulic limes used in this part of the investigation were from different origins. The three types can by categorised as follows: St. Astier (French) (low strength), Fen-X (Italian) (mid strength) and Jura Cement Fabriken (Swiss) (high strength). Therefore the mid strength hydraulic lime (Fen-X) was chosen to carry out most of the tests in the present study.

The compressive strength values for all three hydraulic lime mortars were significantly lower than for cement mortar. The strength of the mortar cubes produced using Jura Cement Fabriken (Swiss) (the strongest hydraulic lime) were 20% lower than mortar cubes made with OPC. This suggests that cement mortars are good when used with strong low porosity clay bricks but have a destructive action when used with soft high porosity stones.

The results showed that mortar cubes made with coarse sand (5mm maximum size crushed concrete sand) were stronger in both compression and splitting strengths than those made with fine sand. There were three explanations for this: (a) The shape of the particles, surface texture and better interlocking of particles in a crushed concrete sand. (b) These particles naturally are stronger, rougher, tougher compared to the lime paste surrounding them. (c) The method by which the sand was batched for mixing. If the sand was batched by volume the fine sand should have more solid particles in the measured volume than the coarse sand. This means that the actual ratio of binder to sand was higher for fine sand mortar compared to coarse sand mortar.

Using different sand sizes greatly affects the strength of a mortar as the coarse sand creates more air voids in the mortar and therefore produces better hydration and carbonation. The thinner the lime mortar the greater penetration of air (CO_2), a product of this will be increased carbonation and as a result a greater increase in strength.

Despite low compressive and splitting strengths, the lime mortars achieved high tensile and shear bond strength with the brick units relative to cement mortars. This in effect gives masonry walls constructed with lime mortars better bond strength and resistance to water penetration through the masonry unit/mortar joint interface.

Cement mortars are considerably stronger than lime mortars which suggests that cement mortars are good when used with strong low porosity clay bricks but have a destructive action when used with soft high porosity stones.

Steel mould gave the highest strength at the start of testing, but the percentage gain in strength with time was the lowest. The scabbold mortar gave the lowest strength at the start of testing, but the percentage gain in strength with time was the highest. Scabbolding increases the penetration of air deeper into the hydraulic mortar cube which results in improving the carbonation and increasing the strength over time.

Hydraulic lime mortars showed more hydraulic reaction at early days for mixes with a high proportion of lime. The percentage of lime in the mix greatly effects the development of strength with time. The lime mortar made with 1:1 mix ratio started the hydration process using free water added to the mix at early days then used the humidity in the air to continue the hydration and carbonation process later. The increase in strength with age for this type of mortar was a clear indication that the combined hydration and carbonation reactions of hydraulic lime were occurring at a faster rate for mortars with a low proportion of sand compared to mortars with a high proportion.

Specimens cured in water have a higher compressive strength than the specimens cured in air. The results showed that the improvement in strength was better for the high sand content mortars (1:2 and 1:3 ratios) than the low sand content cubes (1:1 ratio). The reason was attributed to the higher percentage of sand, whereby the presence of crushed coarse particles improved the overall strength and stiffness of mortar.

Although not practical, curing mortars underwater produces a consistent increase in strength over time for all three mix ratios. Curing a 1:3 mix ratio mortar in water achieved a higher strength than curing a 1:2 mix ratio mortar in air, this will be cheaper for use in construction. The results also showed that curing mortars under some type of sheet like plastic or hessian increases the strength of the mortar.

The author recommends that masonry walls constructed with hydraulic lime mortar should be covered with plastic sheets for 10-14 days to protect the lime mortar joints from drying out and to keep enough moisture for the hydration process to occur. This method is the easiest, cheapest and most practical method of curing. Spraying the walls with water will also help the process of hydration. After 10-14 days of moist curing, the walls should be uncovered to allow the lime mortar joints to dry out for the carbonation process to start.

Hydraulic lime mortars can be cured at a range of temperatures and therefore they have been used all over the world from the coldest to the warmest countries. The optimum compressive strength of Fen-X hydraulic lime mortars tested was achieved at a temperature of approximately 55°C. This temperature must be special for the Fen-X hydraulic lime. Other types may attain their optimum compressive strength at different temperatures depending on their chemical composition. Reaching an optimum compressive strength at a specific temperature would be a result of a combined process of hydration and carbonation reactions.

As a result of the present investigation, the answer to why historic buildings constructed with lime mortars, in hot areas of the world, by ancient civilizations have survived for thousands of years despite the aggressive environment and natural disasters. Dry hot weather, in desert like areas, help hydraulic lime hydrate and carbonate faster and achieve a better strength, whereas cold, wet and humid weather helps hydraulic lime to hydrate faster but the carbonation process will be slow and may take years to complete. This will be due to the blockage of pores with moisture part of the year, which stops the penetration of CO_2 deeper into the mortar to speed up the chemical transformation of $Ca(OH)_2$ to $CaCO_3$.

Lime mortars have high values of porosity and water absorption compared to other building materials. These values were achieved despite their low compressive strength. This phenomenon was another unique property of lime mortar which explains why this material has been functioning as a bonding mortar in old historic buildings and monuments for thousands of years.

Lime mortar was proved to be compatible in its properties to many sandstone and limestone despite its low compressive and splitting strengths. Lime mortar made with coarse sand or Irish sand (another coarse sand) have similar values of porosity and water absorption to red sandstone and common clay bricks of considerably higher compressive and splitting strengths. Compatibility of the materials is very important if different materials were to be used together in a building. Materials of approximately equal porosity and water absorption (compatible) circulate rainwater as if they were made of one material.

The hydraulic lime mortar will weather first, as it has a low compressive strength and therefore weaker, and can be replaced faster and at less cost than the stone or brick. Hydraulic lime mortars allow the masonry wall to breathe. Water can travel through the structure to run off and not catch on ledges or cracks etc. The main reason for such a unique property of lime mortar compared to the other materials tested in the programme was related to the product of carbonation and its microstructure. It seems that fully carbonated mortar has a fine structure with very few voids; some of them are so small that water cannot penetrate.

The compressive strength of cubes made with St. Astier hydraulic lime (low strength) increased dramatically by the addition of cement. The setting and hardening of samples made with lime/cement took much shorter periods to take place than the 100% pure St. Astier lime samples. This suggests that the cement crystals form their matrix at the expense of lime. Therefore, in cement/lime mixes, the cement and not the lime has a predominant effect on the properties of the mortar.

From the Authors point of view, there was no harm in adding small percentages of cement to the lime as long as this addition has no effect on the adjacent stone work. To satisfy compatibility of materials the porosity and water absorption of the lime/cement mortar and the masonry units used should be determined and checked beforehand to ensure that their values are approximately equal.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 GENERAL SUMMARY

This thesis presents a comprehensive study into the use of hydraulic lime for the restoration and conservation of buildings and structures. The experimental results presented in this thesis proved that hydraulic lime could be successfully used as a mortar for the restoration and repair of Historic Buildings. The results also showed that the mortars produced with hydraulic lime did not perform as well as mortars produced with cement in terms of strength. However, the mortar still had a strength which would make it suitable for most applications. The thesis has also proved that the use of cement with natural building stone can have a detrimental effect on the inner and outer surface of the structure. The results reveal that the porosity of mortar is extremely important to the stability of the structure.

Chapter 2 presents a comprehensive literature review on hydraulic lime and its use in restoration and conservation. History, sources, characteristics and types of lime were presented along with reasons for its use in the restoration and conservation of natural building stone and brickwork. Also presented was a review of uses in the industry, strengths and the lime revival. Plus, procedures for testing lime mortars.

Chapter 3 offers background information on natural building stones, including their characteristics and properties, showing a better understanding of the materials used.

Chapter 4 reveals the inappropriate uses of stone cleaning, the methods used and the problems involved and the effects of waterproofing on structures.

Chapter 5 reports the experimental work carried out on hydraulic lime, Ordinary Portland Cement (OPC), natural building stone and brickwork. All materials and tests were shown and the loads applied and strengths are provided in Appendix A.

Chapter 6 presents the results of the experimental investigation carried out into the use of hydraulic lime for restoration and conservation of structures. The chapter presented the results of the tests carried out on three types of lime and cement. The effects of aggregate sizes, different moulds, mix ratios and the addition of different percentages of cement were studied. Different curing regimes and temperature changes were also investigated. The porosity of different hydraulic lime mortars, natural building stones and brickwork were also analysed.

7.2 CONCLUSIONS

1. The literature review carried out during the course of this study showed that lime was one of the oldest building materials recorded. The Romans made the biggest contribution to the development of lime by mixing quicklime with pozzolans and aggregate. The discovery of cement, by Joseph Aspdin in 1824, and the desire for speed of construction, the employment of less knowledgeable craftsmen and aggressive marketing by the cement companies, contributed to the decline in the use of lime as a mortar and its relevant traditional techniques.

2. The review showed that CO_2 emissions in the manufacture of lime are 20% less than cement. During the carbonation process lime mortars and renders can nearly absorb their own weight of CO_2 from the atmosphere.

3. The review showed that hydraulic lime covers materials that vary in properties such as setting times and strength development, but they are never to be thought of or used as a cement substitute. Hydraulic limes are characterised by good workability, low shrinkage, salt and frost resistance, adequate compressive and good flexural strength. The properties of hydraulic lime are influenced by the existence of certain impurities and by the methods of burning and slaking. If clays or other suitably reactive forms of silicates and aluminates are present in the original limestone the resulting lime will have hydraulic properties. The strength of hydraulic lime mortar is developed by two processes, hydration and carbonation.

4. Modern buildings were made of hard, impermeable materials, so hard and impermeable mortars, renders and plasters were well suited. Problems arise when using modern materials and techniques for the restoration of old buildings. Lime mortars absorbs the water mostly through the joint, the moisture also evaporates through the joint. Cement mortars are impermeable and so the moisture circulates and evaporates through the stone causing severe stone decay. The material used for the restoration should be compatible with the original material and masonry used in the past.

5. The review showed that natural building stone have a wide variety of colours and textures available to the designer and engineer. The stones strength, weathering resistance and other physical properties are controlled by the method of formation and the geological history. Stones can be placed geologically into one of three groups; igneous rocks, sedimentary rocks and metamorphic rocks. Despite their wide variety, relatively few types of stones are suitable for masonry construction. In addition to accessibility and ease of quarrying, the stone must satisfy the requirements of strength, hardness, workability, porosity, durability and appearance. Some of the stones that satisfy these requirements are granite, limestone, sandstone, marble and slate.

6. The review showed that stonework should not be cleaned unless the soiling and pollutants start causing the deterioration of masonry. Stone cleaning can be divided into three methods: water, chemical and mechanical (abrasive). Inappropriate cleaning and waterproofing of masonry buildings was a major cause of deterioration of buildings and should never be considered without suitable

investigations. Improper cleaning can accelerate the deteriorating effect of the pollutants by 15-20%.

7. Results of the testing programme carried out in the present investigation showed that the compressive strength of the three pre-packaged hydraulic limes used were from different origins. The three types can by categorised as follows: St. Astier (French) – low strength, Fen-X (Italian) – mid strength and Jura Cement Fabriken (Swiss) – high strength. The mid range hydraulic lime (Fen-X) was therefore chosen to carry out the rest of the tests in the present study.

8. The compressive strength values for all three hydraulic lime mortars tested were significantly lower than that for cement mortar. The strength of the mortar cubes produced using Jura Cement Fabriken (Swiss) (the strongest hydraulic lime) were 20% lower than mortar cubes made with OPC. This suggests that cement mortars are good when used with strong low porosity clay bricks but have a destructive action when used with soft high porosity stones.

9. The results showed that mortar cubes made with coarse sand (5mm maximum size crushed concrete sand) were stronger than those made with fine sand. There were three explanations for this: (a) The shape of the particles, surface texture and better interlocking of particles in crushed concrete sand, (b) these particles naturally are stronger, rougher, tougher compared to the lime paste surrounding them, (c) The method by which the sand was batched for mixing. If the sand was batched by volume the fine sand should have more solid particles in the measured volume than the coarse sand. This means that the actual ratio of binder to sand

was higher for fine sand mortar compared to coarse sand mortar.

10. Despite low compressive and splitting strengths, the lime mortars achieved high flexural tensile and shear bond strength with the brick units relative to cement mortars. This in effect gives masonry walls constructed with lime mortars better bond strength and resistance to water penetration through the masonry unit/mortar joint interface.

11. Casting lime mortars in steel moulds gave the highest strength at the start of testing, but the percentage gain in strength with time was the lowest. The scabbold mortar gave the lowest strength at the start of testing, but the percentage gain in strength with time was the highest. Increasing the penetration of the hydraulic mortars with air by scabbolding increases strength over time. Although the type of mould does not make a great deal of difference scabbolding the mortar after de-moulding helps the carbonation process and ultimately increases the strength.

12. Hydraulic lime mortars showed more hydraulic reaction at early days for mixes with a high proportion of lime. Lime mortar made with 1:1 mix ratio started the hydration process using free water added to the mix at early days then used the humidity in the air to continue the hydration and carbonation process later. The increase in strength with age for this type of mortar was a clear indication that the combined hydration and carbonation reactions of hydraulic lime were occurring at a faster rate for mortars with a low proportion of sand compared to mortars with a high proportion.

13. Specimens made with hydraulic lime mortars cured in water have a higher compressive strength than the specimens cured in air. The results showed that the improvement in strength was better for the high sand content mortars (1:2 and 1:3 ratios) than the low sand content cubes (1:1 ratio). The reason was attributed to the higher percentage of sand, whereby the presence of crushed coarse particles improved the overall strength and stiffness of mortar.

14. The author recommends that masonry walls constructed with hydraulic lime mortar should be covered with plastic sheets for 10-14 days to protect the lime mortar joints from drying out and to keep enough moisture for the hydration process to occur. This method is the easiest, cheapest and most practical method of curing. Spraying the walls with water will help the process of hydration. After 10-14 days of moist curing, the walls should be uncovered to allow the lime mortar joints to dry out for the carbonation process to start.

15. Hydraulic lime mortars can be cured at a range of temperatures and therefore has been used all over the world from the coldest to the warmest country. The results showed that the optimum compressive strength of Fen-X hydraulic lime mortars tested was achieved at a temperature of approximately 55°C. This temperature must be special for the Fen-X hydraulic lime. Other types may attain their optimum compressive strength at different temperatures depending on their chemical composition.

16. As a result of the present investigation, the answer to why historic buildings constructed with lime mortars, in hot areas of the world, by ancient civilizations

have survived for thousands of years despite the aggressive environment and natural disasters. Dry hot weather, in desert like areas, help hydraulic lime hydrate and carbonate faster and achieves better strength, whereas cold, wet and humid weather helps hydraulic lime to hydrate faster but the carbonation process will be slow and may take years to complete. This will be due to the blockage of pores with moisture part of the year, which stops the penetration of CO_2 deeper into the mortar to speed up the chemical transformation of $Ca(OH)_2$ to $CaCO_3$.

17. Lime mortars have high values of porosity and water absorption compared to other building materials. These values were achieved despite their low compressive strength. This phenomenon was another unique property of lime mortar which explains why this material has been functioning as a bonding mortar in old historic buildings and monuments for thousands of years. The main reason for such a unique property of lime mortar compared to other materials tested in the programme was related to the product of carbonation and its microstructure. It seems that fully carbonated mortar has a fine structure with very few voids; some of them are so small that water cannot penetrate.

18. Results of tests on porosity support Conclusion no. 17, by showing that lime mortars made with coarse sand have approximately similar values of porosity and water absorption to red sandstone and common clay bricks of considerably higher compressive and splitting strengths. Materials of approximately equal porosity and water absorption circulate rainwater as if they were made of one material. Compatibility of the materials is very important if different materials were to be used together in a building.

19. The compressive strength of cubes made with St. Astier hydraulic lime (low strength) increased dramatically by the addition of cement. The setting and hardening of samples made with lime/cement took much shorter periods to take place than the 100% pure St. Astier lime samples. This suggests that the cement crystals form their matrix at the expense of lime. Therefore, in cement/lime mixes, the cement and not the lime has a predominant effect on the properties of the mortar.

20. From the Author point of view, there was no harm in adding small percentages of cement to the lime as long as this addition has no effect on the adjacent stone work. To satisfy compatibility of materials the porosity and water absorption of the lime/cement mortar and the masonry units used should be determined and checked beforehand to ensure that their values are approximately equal.

7.3 SUGGESTIONS FOR FUTURE RESEARCH

Further research and case studies will be required in order to produce standards for the use of hydraulic lime in the restoration and conservation of structures. Until a standard becomes available, the use of hydraulic lime in the restoration and conservation of structures will be restricted.

The durability of hydraulic lime mortars could be investigated further by testing specimens for resistance to frost attack. This would involve subjecting hydraulic lime mortars to alternate freezing and thawing for a specified number of cycles and then assessing the mortar for visible damage and testing the mortar for loss in strength. By comparing the hydraulic lime mortar performance with mortars produced with cement and hydraulic lime it will be possible to assess the frost resistance of hydraulic lime.

Further research into the properties of lime and stone as a material bonded together requires investigation. Looking at compressive, splitting, shear and tension tests for different bonds between hydraulic lime and sandstone and limestone.

The resistance of hydraulic lime mortar to sulphate attack could be determined by storing the mortar in a solution of sodium or magnesium sulphate. By subjecting the mortar samples to alternate wetting and drying, the damage owing to the crystallisation of salts is accelerated. The effects of the exposure to these salts can then be quantified by testing the mortar's strength, its expansion and loss of weight.

Further investigation into the microstructure of hydraulic lime mortars. Comparing the structures of hydraulic lime in different circumstances and cement mortars. Adding different percentages of cement to hydraulic lime mortars and studying the structure change and the effect on lime mortars properties especially porosity.

Investigation into the use of lime putty and its properties, including compressive, splitting, flexural and torsional strength is required. Plus background knowledge and understanding should be shown.

Further research and in particular case studies and trials over a longer period of time are required in order to investigate the overall performance of hydraulic lime. These trials could also be used to quantify the performance of hydraulic lime mortars financially as well as on a material basis.

GLOSSARY

Admixtures or additive: In concrete, plaster, etc., a substance other than aggregate, cement, or water, added in small quantities to the mix to alter its properties or those of the hard concrete. The most important admixtures for concrete are accelerators, air-entraining agents, plasticizers and retarders but there are many others including anti-frost, bonding, colouring, corrosion-inhibiting, damp-proofing, expanding, fungicidal, gas-forming, germicidal, grouting, insecticidal and non-shrinking agents.

Air-entraining agent: An admixture to concrete or cement, that drags small bubbles of air, about 1mm or smaller in diameter, into the mix. The bubbles increase the workability, allowing both sand and water contents to be reduced. One agent used is vinsol resin, a residue from the distillation of pine tree stumps. The frost resistance of the concrete or mortar is improved both during setting and after hardening.

Alumina or Aluminium oxide (Al_2O_3): An important constituent of ordinary clays (in chemical combination), as well as corundum.

Binder: Cement, tar, bitumen, gypsum, plaster, lime or similar material used for joining masonary.

Calcine: To heat ore or mineral for some time at a high temperature to drive off carbon dioxide and water.

Calcite ($CaCO_3$): Crystalline calcium carbonate found in marble and other limestones.

Carbonation: The process by which lime (calcium hydroxide, $Ca(OH)_2$) reabsorbs carbon dioxide (CO_2) in moist conditions and reverts to calcium carbonate ($CaCO_3$). As a result of this chemical change the lime mortar becomes relatively harder, more stable and less soluble than in its uncarbonated state.

Cementation index: A measure of the strength and speed of hydraulic set.

Clay: Very fine-grained soil of colloid size, consisting mainly of hydrated silicate of aluminium. It is a plastic cohesive soil which shrinks in drying, expands on wetting, and when compressed gives up water. Under the electron microscope clay crystals have been seen to have a platy shape in which for Wyoming bentonite the ratio of length to thickness is about 250 to 1 (like mica). For other clays it is about 10 to 1. Clays are described for engineering purposes by their consistency limits.

Coefficient: A numerical or constant factor in an algebraic term.

Cohesion of soil: The stickiness of clay or silt, absent from sands, characteristics of clays. It is the shear strength of clay, which generally equals about half its unconfined compressive strength.

Corundum or Alumina (Al_2O_3): A very hard mineral used as an abrasive, since its harness is only less than that of diamond.

Curing: The process of gradual drying and hardening of lime mortar under appropriate conditions.

Density: The weight per unit volume of a substance (at a temperature stated for solids and liquids only when great accuracy is required).

Diffusion: The movement of the molecules of gases in all directions which causes them to intermingle without ventilation current, in a way which is often contrary to gravity.

Durable: Enduring, resisting wear, etc.

Fat lime: High calcium lime, usually defined as containing a minimum of 98% calcium oxide (quicklime).

Gypsum: A chalk like mineral used to make plaster of Paris and fertilizer.

Hardcore: Hard lumps of stone, brick, furnace slag, old concrete, etc., suitable for filling soft ground in a foundation or under a road, etc.

Hydrated Lime: Calcium hydroxide ($Ca(OH)_2$) (slaked lime). In the UK building industry the term is normally only applied to the industrially produced 'builders lime' which is generally an inferior form of calcium hydroxide powder. (Accurately the term should apply to any form of calcium hydroxide, which may be non-hydraulic or hydraulic lime, in a wet or dry form).

Hydration: The combination of water with any substance such as lime or minerals, responsible for the alteration of minerals in weathering, the formation of hydrated lime, the setting of cement and so on.

Induration: To make hard, to grow hard.

Modulus of Elasticity: For any material the ratio of the stress (force per unit area) to the strain (deformation per unit length). It is expressed in units of stress, and is usually constant up to the yield point.

Plasticity: A description of the ease of spreading and cohesiveness of a mortar mix.

Porosity: A measure of the proportion of pores in the mass of a material.

Pozzolanic material: Material containing fine particles of reactive silicate and alumina, and sometimes iron oxides, which will react with calcium hydroxide and water to produce calcium silicate hydrate which gives a chemical set to the mortar. Common sources of pozzolanic materials are volcanic ash and volcanic sands, coal and wood ash and certain other vegetable ashes, and soft fired clay products such as brick and tile. Some Scottish sands have mild pozzolanic properties derived from feldspars and other minerals of volcanic origin.

Quicklime or Calcium oxide (CaO): The highly caustic material produced by calcining limestone ('lime burning').

Setting time: The time taken for a hydraulic mortar to achieve its chemical set. The term is also frequently applied to the drying and hardening of non-hydraulic mortars although there is no finite setting time which can be measured.

Shear: The load acting across a beam near its support. For uniformly distributed load or for any other symmetrical load, the maximum shear is equal to half the total load on a simply supported beam, or to the total load on a cantilever beam.

Shrinkage: The shrinkage of concrete during hardening can amount to 0.0004 of its length at one year or half this value at two months.

Silica (SiO_2): Silicon dioxide which occurs as crystalline quartz and non-crystalline chalcedony, agate, flint, sardonyx and many other varieties. The greater part of sand, sandstone and quartzite is silica. Although some of its varieties are semi-precious gems, silica is the commonest known solid material.

Strength: 1) The strength of a material is measured by its greatest safe working stress. This is equal to the yield point or the ultimate strength or the proof stress divided by an appropriate factor of safety. 2) The strength of a structural part is its ability to resist the loads which fall on it.

Tensile: A pulling force or stress. Metals and wood take tension well, but masonary, including concrete, is generally not allowed to take any tension except in the dispersal of concentrated loads.

Torsion: The twisting effect of a force on a shaft applied tangentially, like the twist on a haulage drum which winds rope on to its circumference.

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Appendix A
Tables showing strengths

Table A.1 - Compressive strength of three types of lime and cement mortar with lime/cement:sand ratio of 1:3

Days	OPC (N/mm^2)	JCF (Swiss) (N/mm^2)	Fen-X (Italian) (N/mm^2)	St. Astier (French) (N/mm^2)
7	27.37	3.45	1.78	0.88
7	25.59	3.51	1.82	0.86
7	25.18	4.02	1.94	0.71
14	31.49	5.41	2.78	1.37
14	31.82	5.55	2.86	1.41
14	32.31	5.24	2.69	1.27
28	32.06	6.47	3.37	1.67
28	33.71	6.49	3.42	1.57
28	32.49	6.31	3.63	1.61
56	32.16	6.86	3.73	1.71
56	34.27	6.69	4	1.98
56	32.92	7.04	3.78	1.78

Table A.2 - Compressive strength of St. Astier lime with different percentages of cement added – Lime/cement:sand ratio of 1:3

Days	100% Cement (N/mm^2)	75% Cement + 25% Lime (N/mm^2)	50% Cement + 50% Lime (N/mm^2)	25% Cement + 75% Lime (N/mm^2)	12.5% Cement + 87.5% Lime (N/mm^2)	100% Lime (N/mm^2)
7	25.6	17.45	7.56	3.93	2.03	0.87
7	25.2	17.78	8.01	4.12	1.71	0.91
7	26.05	18.2	8.44	4.01	1.89	0.82
14	30.56	20.98	15.63	5.98	2.56	1.43
14	31.02	21.38	13.79	5.34	2.41	1.47
14	31.87	22.16	15.37	5.63	2.66	1.35
28	33.23	22.69	14.69	7.02	3.91	1.73
28	32.63	23.43	16.89	6.78	3.34	1.68
28	32.75	22.93	16.39	6.98	3.78	1.62
56	33.53	22.78	17.38	7.41	4.68	1.89
56	32.92	22.91	17.81	7.73	4.75	1.92
56	33.12	23.12	17.2	7.65	4.41	1.82

Table A.3 - Compressive strength of Fen-X hydraulic lime and cement mortar mixed with coarse and fine sand with lime/cement:sand ratio of 1:3

Days	Cement: Coarse (N/mm^2)	Cement: Fine (N/mm^2)	Lime: Coarse (N/mm^2)	Lime: Fine (N/mm^2)	Lime: Irish white (N/mm^2)
7	14.1	12.86	1.94	1.1	1.85
7	14.6	14.05	2.05	1.02	1.94
7	14.8	13.56	1.98	1	2.01
14	18.9	14.18	1.82	1.08	2.36
14	18.25	14.3	1.93	1.02	2.47
14	18.12	15.37	2.07	1.09	2.42
28	24.33	15.47	2.12	1.09	2.30
28	26.6	16.37	1.86	1.13	2.28
28	25.65	18.61	1.94	1.1	2.13
56	28.73	16.55	1.8	0.88	2.48
56	26.86	17.47	1.64	0.8	2.37
56	28.92	17.31	1.61	0.84	2.22

Table A.4 - Tensile splitting strength of Fen-X lime/cement mortars made with coarse and fine sand - Ratio 1:3 (lime/cement:sand)

Days	Cement: Coarse (N/mm^2)	Cement: Fine (N/mm^2)	Lime: Coarse (N/mm^2)	Lime: Fine (N/mm^2)
7	2.06	1.25	0.18	0.11
7	1.91	1.19	0.16	0.14
7	2.12	1.26	0.2	0.14
14	2.23	1.38	0.17	0.11
14	2.37	1.57	0.17	0.12
14	2.48	1.49	0.17	0.13
28	2.38	1.74	0.15	0.1
28	2.58	1.81	0.15	0.11
28	2.43	1.62	0.15	0.11
56	3.23	1.95	0.11	0.09
56	3.29	1.95	0.13	0.08
56	3.4	1.97	0.14	0.08

Table A.5 - Flexural bond strength of Fen-X lime/cement mortars made with coarse and fine sand – Ratio 1:3 (lime/cement:sand)

Days	Cement: Fine (N/mm^2)	Cement: Coarse (N/mm^2)	Lime: Coarse (N/mm^2)	Lime: Fine (N/mm^2)
28	0.83	0.57	0.39	0.08
28	0.69	0.52	0.35	0.07
28	0.76	0.55	0.31	0.06
56	0.62	0.31	0.31	0.1
56	0.55	0.38	0.31	0.09
56	0.65	0.37	0.31	0.1

Table A.6 - Torsional bond strength of Fen-X lime/cement mortars made with coarse and fine sand - Ratio 1:3 (lime/cement:sand)

Days	Cement: Fine (N/mm^2)	Cement: Coarse (N/mm^2)	Lime: Coarse (N/mm^2)	Lime: Fine (N/mm^2)
28	0.77	0.65	0.32	0.14
28	0.82	0.61	0.27	0.11
28	0.73	0.67	0.23	0.14
56	0.98	0.72	0.21	0.1
56	0.89	0.76	0.18	0.11
56	0.96	0.77	0.19	0.1

Table A.7 - Flexural strength of lime mortars cast in different moulds made with coarse sand - Ratio 1:3 (lime/cement:sand)

Days	Steel mould (N/mm^2)	Polystyrene mould (N/mm^2)	Scabbold mould (N/mm^2)
14	0.33	0.37	0.28
14	0.34	0.31	0.3
14	0.33	0.34	0.34
28	0.45	0.48	0.43
28	0.46	0.44	0.45
28	0.45	0.46	0.42

Table A.8 - Compressive strength of Fen-X hydraulic lime mortar prisms with lime: sand ratio of 1:3 by volume cured in different moulds

Days	Steel mould (N/mm^2)	Polystyrene mould (N/mm^2)	Scabbold mould (N/mm^2)
14	1.62	1.43	1.17
14	1.54	1.32	1.14
14	1.53	1.44	1.18
14	1.5	1.51	1.13
14	1.57	1.36	1.07
14	1.6	1.41	1.09
28	1.73	1.25	1.4
28	1.64	1.37	1.53
28	1.69	1.3	1.49
28	1.64	1.4	1.49
28	1.58	1.32	1.5
28	1.62	1.26	1.48

Table A.9 - Compressive strength of Fen-X lime mortars made with coarse sand, cured in air - ratio 1:1, 1:2, 1:3 and 1:4 (lime/cement:sand)

Days	Ratio 1:1 (N/mm^2)	Ratio 1:2 (N/mm^2)	Ratio 1:3 (N/mm^2)	Ratio 1:4 (N/mm^2)
7	2.43	1.95	1.66	0.71
7	2.2	2	1.65	0.73
7	2.37	2.12	1.57	0.72
14	3.74	2.2	1.37	0.67
14	3.51	2.04	1.36	0.71
14	3.41	2.06	1.37	0.72
28	4.39	1.97	1.17	0.66
28	4.19	2.05	1.05	0.66
28	4.21	2.08	1.04	0.69
56	5.94	2.17	1.14	0.66
56	6.11	2.27	1.17	0.66
56	6.04	2.19	1.17	0.6

Table A.10 - Compressive strength of Fen-X lime mortars made with coarse sand and cured under different regimes - Ratio 1:1 (lime/cement:sand)

Days	Hessian (N/mm^2)	Hessian and Plastic (N/mm^2)	Plastic (N/mm^2)	Normal (N/mm^2)
7	4.11	4.19	4.87	1.98
7	4.28	4.7	4.7	2.1
7	4.44	4.9	4.57	2.15
14	3.74	3.21	4.1	3.74
14	3.48	3.7	4.31	3.51
14	3.73	3.53	4.12	3.41
28	5.26	5.36	4.88	4.39
28	4.88	5.36	5.31	4.19
28	4.76	5.12	5.62	4.21
56	7.14	8.16	8.67	5.94
56	7.65	7.14	8.16	6.11
56	7.5	7.96	7.65	6.04

Table A.11 - Compressive strength of lime mortars made with coarse sand and cured under different regimes - Ratio 1:2 (lime/cement:sand)

Days	Plastic (N/mm^2)	Hessian and Plastic (N/mm^2)	Hessian (N/mm^2)	Normal (N/mm^2)
7	2.37	1.74	1.68	1.95
7	2.47	1.93	1.61	2
7	2.33	1.88	1.56	2.12
14	3.29	3.27	2.93	2.2
14	3.43	3.65	2.75	2.04
14	3.14	3.32	2.99	2.06
28	3.69	2.67	2.57	1.97
28	3.62	2.38	2.52	2.05
28	3.55	2.32	2.47	2.08
56	4.33	4.28	4.36	2.17
56	4.54	4.43	4.11	2.27
56	4.44	4.33	4.04	2.19

Table A.12 - Compressive strength of lime mortars made with coarse sand and cured under different regimes - Ratio 1:3 (lime/cement:sand)

Days	Plastic (N/mm^2)	Hessian and Plastic (N/mm^2)	Hessian (N/mm^2)	Normal (N/mm^2)
7	1.55	0.9	0.91	1.66
7	1.51	0.81	0.87	1.65
7	1.35	0.87	0.87	1.57
14	1.77	1.1	1.13	1.37
14	1.96	1.08	1.2	1.36
14	1.73	1.14	1.12	1.37
28	2.41	1.55	2.26	1.17
28	2.54	1.46	2.15	1.05
28	2.52	1.67	2.39	1.04
56	2.28	1.88	2.42	1.14
56	2.11	2.04	2.22	1.17
56	2.16	2.2	2.23	1.17

Table A.13 - Compressive strength of Fen-X lime mortars made with coarse sand and cured in water - ratios 1:1, 1:2 and 1:3 (lime:sand)

Days	Ratio 1:1 (N/mm^2)	Ratio 1:2 (N/mm^2)	Ratio 1:3 (N/mm^2)
7	2.36	1.71	1.3
7	2.25	1.58	1.16
7	2.28	1.64	1.17
14	3.04	2.18	1.7
14	3.14	1.99	1.6
14	2.98	2.05	1.63
28	4.06	2.9	1.98
28	4.2	2.92	1.79
28	4.14	2.79	1.98
56	5.29	3.52	2.57
56	5.61	3.54	2.32
56	4.95	3.18	2.33

Table A.14 - Compressive strength of Fen-X lime mortars made with coarse sand and cured in air and water - Ratios 1:1, 1:2 and 1:3 (lime:sand)

Days	Ratio 1:1 (Air) (N/mm^2)	Ratio 1:2 (Air) (N/mm^2)	Ratio 1:3 (Air) (N/mm^2)	Ratio 1:1 (Water) (N/mm^2)	Ratio 1:2 (Water) (N/mm^2)	Ratio 1:3 (Water) (N/mm^2)
7	1.98	1.95	1.66	2.36	1.71	1.3
7	2.1	2	1.65	2.25	1.58	1.16
7	2.15	2.12	1.57	2.28	1.64	1.17
14	3.74	2.2	1.37	3.04	2.18	1.7
14	3.51	2.04	1.36	3.14	1.99	1.6
14	3.41	2.06	1.37	2.98	2.05	1.63
28	4.39	1.97	1.17	4.06	2.9	1.98
28	4.19	2.05	1.05	4.2	2.92	1.79
28	4.21	2.08	1.04	4.14	2.79	1.98
56	5.94	2.17	1.14	5.29	3.52	2.57
56	6.11	2.27	1.17	5.61	3.54	2.32
56	6.04	2.19	1.17	4.95	3.18	2.33

Table A.15 - Compressive strength of Fen-X lime mortars made with coarse sand and cured at different temperatures - Ratios 1:1, 1:2 and 1:3 (lime:sand)

Temperature	Ratio 1:1 (N/mm^2)	Ratio 1:2 (N/mm^2)	Ratio 1:3 (N/mm^2)
-14	3.16	2.16	1.77
-14	3.32	2.01	1.7
-14	3.26	2.03	1.74
6	4.32	2.59	2.38
6	4.68	2.4	2.22
6	4.41	2.64	2.23
17	5.41	3.37	2.48
17	5.61	3.06	2.45
17	5.28	3.38	2.4
23	4.81	2.68	2.52
23	4.78	2.53	2.42
23	4.87	2.79	2.45
55	5.27	3.29	2.42
55	5.58	3.53	2.35
55	5.86	3.45	2.37
120	3.34	2.34	1.8
120	3.16	2.9	1.71
120	3.53	2.43	2.06

Table A.16 - Compressive strength, porosity, and water absorption for different materials

	Lime mortar with fine sand	**Lime mortar with coarse sand**	**Lime mortar with Irish sand**	**Red sandstone**	**White sandstone**	**Common clay solid-frogged brick**	**Type B engineering brick**	**Granite**
Compressive strength: (N/mm^2)	0.84	1.68	2.36	24.58	54.68	39	92	
Porosity: %	31.95	29.44	26.77	28.38	13.96	25	15	6
Water absorption	14.21	13.26	12.25	15.12	6.22	13.5	7.2	2.3

Table A.17 - Compressive strength, porosity, and water absorption for different materials

	Ratio 1:1 (Air)	**Ratio 1:2 (Air)**	**Ratio 1:3 (Air)**	**Ratio 1:1 (Water)**	**Ratio 1:2 (Water)**	**Ratio 1:3 (Water)**	**Red sand stone**	**White sand stone**	**Common clay solid-frogged brick**	**Type B enginee ring brick**	**Granite**
Compressive strength: (N/mm^2)	6.04	2.19	1.17	4.95	3.18	2.33	24.58	54.68	39	92	
Porosity: %	33.75	30.95	29.7	33.22	33.35	34.72	28.38	13.96	25	15	6
Water absorption	15.95	14.41	13.13	12.07	11.96	12.71	15.12	6.22	13.5	7.2	2.3

APPENDIX B

Athens Charter (1931) and Venice Charter (1964)

B.1 INTRODUCTION

The broad objective of this thesis is to contribute to the understanding of the characteristics and behaviour of lime and lime based mortars for the repair and conservation of historic buildings. At present, as previously stated, there is no set standards for the use of lime for restoration or conservation. However, through the years, research has been carried out and documents have been published. These documents do not give strict standards but give guidelines to the restoration and conservation of historic buildings. This appendix will offer an introduction to the Athens Charter of 1931 and the Venice Charter of 1964.

B.2 ATHENS CHARTER OF 1931

A remarkable document, adopted at the First International Congress of architects and Technicians of Historic Monuments, which took place in Athens in 1931, under the auspices of the League of Nations. Powys, author of "Repair of Ancient Buildings", still a seminal work, who was secretary of Society for the Protection of Ancient Buildings (SPAB) at the time was a signatory. The real importance of the Athens Charter was that it represented the first major initiative to stimulate international debate on conservation issues. Several general conclusions were reached concerning, the protection of monuments, administrative and legislative measures, aesthetic enhancement, restoration of monuments, deterioration, restorative techniques and international co-operation. These gave rise to seven main resolutions - the "Carta del Restauro". While they now seem somewhat inconclusive, and no.5 may now even be viewed with some suspicion, they are well worth repeating:

1. International organisations for restoration on operational and advisory levels are to be established.
2. Proposed restoration projects are to be subjected to knowledgeable criticism to prevent mistakes which will cause loss of character and historical values to the structures.
3. Problems of preservation of historic sites are to be solved by legislation at national level for all countries.
4. Excavated sites which are not subject to immediate restoration should be reburied for protection.
5. Modern techniques and materials may be used in restoration work.
6. Historical sites are to be given strict custodial protection.
7. Attention should be given to the protection of areas surrounding historic sites.

Despite their tentative nature, these resolutions were not re-examined until the 2nd International Congress, which did not take place until May 1964, where it approved the Venice Charter.

B.2.1 General principles

The Conference heard the statement of the general principles relating to the protection of monuments. Whatever may be the variety of concrete cases, each of which are open to a different solution, the Conference noted that there predominates in the different countries represented a general tendency to abandon restorations in total and to avoid the attendant dangers by initiating a system of regular and permanent maintenance calculated to ensure the preservation of the buildings.

When, as the result of decay or destruction, restoration appears to be indispensable, it recommends that the historic and artistic work of the past should be respected, without excluding the style of any given period.

The Conference recommended that the occupation of buildings, which ensures the continuity of their life, should be maintained but that they should be used for a purpose which respects their historic or artistic character.

B.2.2 Administrative and legislative measures regarding historical buildings

The Conference heard the statement of legislative measures devised to protect buildings of artistic, historic or scientific interest and belonging to the different countries.

It unanimously approved the general tendency which, in this connection, recognises a certain right of the community in regard to private ownership. It noted that the differences existing between these legislative measures were due to the difficulty of reconciling public law with the rights of individuals. Consequently, while approving the general tendency of these measures, the Conference was of the opinion that they should be in keeping with local circumstances and with the trend of public opinion, so that the least possible opposition may be encountered, due allowance being made for the sacrifices which the owners of property may be called upon to make in the general interest.

It recommended that the public authorities in each country be empowered to take conservatory measures in cases of emergency. It earnestly hoped that the International Museums Office would publish a repertory and a comparative table of the legislative measures in force in the different countries and that this information would be kept up to date.

B.2.3 Aesthetic enhancement of ancient buildings

The Conference recommended that, in the construction of buildings, the character and external aspect of the cities in which they are to be erected should be respected, especially in the neighbourhood of ancient buildings, where the surroundings should be given special consideration. Even certain groupings and certain particularly picturesque perspective treatment should be preserved.

A study should also be made of the ornamental vegetation most suited to certain buildings or groups of buildings from the point of view of preserving their ancient character. It specially recommends the suppression of all forms of publicity, of the erection of unsightly telegraph poles and the exclusion of all noisy factories and even of tall shafts in the neighbourhood of artistic and historic buildings.

B.2.4 Restoration of buildings

The experts heard various communications concerning the use of modern materials for the consolidation of ancient buildings. They approved the judicious use of all the resources at the disposal of modern technique and more especially of reinforced concrete. They specified that the work of consolidation should whenever possible be concealed in order that the aspect and character of the restored building may be preserved. They recommended their adoption more particularly in cases where their use makes it possible to avoid the dangers of dismantling and reinstating the portions to be preserved.

B.2.5 Deterioration of ancient buildings

The Conference noted that, in the conditions of present day life, buildings throughout the world were being threatened to an ever-increasing degree by atmospheric agents.

Apart from the customary precautions and the methods successfully applied in the preservation of building statuary in current practice, it was impossible, in view of the complexity of cases and with the knowledge at present available, to formulate any general rules.

The Conference recommended:

- That, in each country, the architects and curators of buildings should collaborate with specialists in the physical, chemical, and natural sciences with a view to determining the methods to be adopted in specific cases;
- That the International Museums Office should keep itself informed of the work being done in each country in this field and that mention should be made thereof in the publications of the Office.

With regard to the preservation of monumental sculpture, the Conference was of opinion that the removal of works of art from the surroundings for which they were designed was, in principle, to be discouraged. It recommended, by way of precaution, the preservation of original models whenever these still exist or if this proves impossible, the taking of casts.

B.2.6 Technique of conservation

The Conference was gratified to note that the principles and technical considerations set forth in the different detailed communications were inspired by the same idea, namely:

In the case of ruins, scrupulous conservation was necessary, and steps should be taken to reinstate any original fragments that may be recovered (anastylosis), whenever this was possible; the new materials used for this purpose should in all cases be recognisable. When the preservation of ruins brought to light in the course of excavations was found to be impossible, the Conference recommended that they be buried, accurate records being of course taken before filling-in operations were undertaken.

The Conference mentions that the technical work undertaken in connection with the excavation and preservation of ancient buildings calls for close collaboration between the archaeologist and the architect.

With regard to other buildings, the experts unanimously agreed that, before any consolidation or partial restoration was undertaken, a thorough analysis should be made of the defects and the nature of the decay of these buildings. They recognised that each case needed to be treated individually.

B.2.7 Conservation of buildings and international collaboration

- Technical and moral co-operation.

The Conference, convinced that the question of the conservation of the artistic and archaeological property of mankind was one that interested the community of the States, which are wardens of civilisation,

Hopes that the States, acting in the spirit of the Covenant of the League of Nations, will collaborate with each other on an ever-increasing scale and in a more concrete manner with a view to furthering the preservation of artistic and historic monuments;

Considers it highly desirable that qualified institutions and associations should, without in any manner whatsoever prejudicing international public law, be given an opportunity of manifesting their interest in the protection of works of art in which civilisation has been expressed to the highest degree and which would seem to be threatened with destruction;

Expresses the wish that requests to attain this end, submitted to the Intellectual Co-operation Organisation of the League of Nations, be recommended to the earnest attention of the States.

It will be for the International Committee on Intellectual Co-operation, after an enquiry conducted by the International Museums Office and after having collected all relevant information, more particularly from the National Committee on Intellectual Co-operation concerned, to express an opinion on the expediency of the steps to be taken and on the procedure to be followed in each individual case.

The members of the Conference, after having visited in the course of their deliberations and during the study cruise which they were able to make on this occasion, a number of excavation sites and ancient Greek monuments, unanimously paid a tribute to the Greek Government, which, for many years past, has been itself responsible for extensive works and, at the same time, has accepted the collaboration of archaeologists and experts from every country.

The members of the Conference there saw an example of activity which can but contribute to the realisation of the aims of intellectual co-operation, the need for which manifested itself during their work.

- The role of education in the respect of monuments.

The Conference, firmly convinced that the best guarantee in the matter of the preservation of monuments and works of art derives from the respect and attachment of the peoples themselves;

Considering that these feelings can very largely be promoted by appropriate action on the part of public authorities;

Recommends that educators should urge children and young people to abstain from disfiguring monuments of every description and that they should teach them to take a greater and more general interest in the protection of these concrete testimonies of all ages of civilisation.

- Value of international documentation.

The Conference expresses the wish that:

1. Each country, or the institutions created or recognised competent for this purpose, publish an inventory of ancient buildings, with photographs and explanatory notes;
2. Each country constitute official records which shall contain all documents relating to its historic buildings;
3. Each country deposit copies of its publications on artistic and historic buildings with the International Museums Office;
4. The Office devote a portion of its publications to articles on the general processes and methods employed in the preservation of historic buildings;
5. The Office study the best means of utilising the information so centralised.

B.3 VENICE CHARTER OF 1964

The historic buildings of generations of people remain to the present day as living witnesses of their age old traditions. People are becoming more and more conscious of the unity of human values and regard ancient buildings as a common heritage. The common responsibility to safeguard them for future generations was recognised. It was their duty to hand them on in the full richness of their authenticity.

It was essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions.

By defining these basic principles for the first time, the Athens Charter of 1931 contributed towards the development of an extensive international movement which has assumed concrete form in national documents, in the work of ICOM and UNESCO and in the establishment by the latter of the International Centre for the Study of the Preservation of Cultural Property. Increasing awareness and critical study have been brought to bear on problems which have continually become more complex and varied. The Venice Charter examined the Charter in order to make a thorough study of the principles involved and to enlarge the scope in a new document.

B.3.1 Aims

The intention in conserving and restoring buildings was to safeguard them no less as works of art than as historical evidence. The concept of an historic building embraces not only the single architectural work but also the urban or rural setting in which was found the evidence of a particular civilisation, a significant development or an historic event. This applies not only to great works of art but also to more modest works of the past which have acquired cultural significance with the passing of time. The conservation and restoration of buildings must have recourse to all sciences and techniques which can contribute to the study and safeguarding of architectural heritage.

B.3.2 Conservation

It is essential to the conservation of buildings that they be maintained on a permanent basis. The conservation of buildings was always facilitated by making use of them for some socially useful purpose. Such use was therefore desirable but it must not change the lay-out or decoration of the building. It was within these limits only that modifications demanded by a change of function should be envisaged and may be permitted.

The conservation of a building implies preserving a setting which was not out of scale. Wherever the traditional setting exist, it must be kept. No new construction, demolition or modification which would alter the relations of mass and colour must be allowed.

A building was inseparable from the history to which it bears witness and from the setting in which it occurs. The moving of all or part of a monument demands it or where it was justified by national or international interest of paramount importance. Items of sculpture, painting or decoration which form an integral part of a building may only be removed from it if this was the sole means of ensuring their preservation.

B.3.3 Restoration

The process of restoration is highly specialised operation. Its aim was to preserve and reveal the aesthetic and historic value of the building and was based on the respect of the original material and authentic documents. It must stop at the point where conjecture begins and in this case moreover any extra work which was indispensable must be distinct from the architectural composition and must bear contemporary stamp. The restoration in any case must be preceded and followed by an archaeological and historical study of the building.

Where traditional techniques prove adequate, the consolidation of a building can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.

The valid contributions of all periods to the building of a structure must be respected, since unity of style was not the aim of a restoration. When a building includes superimposed work of different periods, the revealing of the underlying state can only be justified in exceptional circumstances and when what was removed becomes of little interest and the material which was brought to light was of great historical, archaeological or aesthetic value and its state of preservation good enough to justify the action. Evaluation of the importance of the elements involved and the decision as to what may be destroyed cannot rest solely on the individual in charge of the work.

Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence. Additions cannot be allowed except in so far as they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings.

B.3.4 Excavations

Excavations should be carried out in accordance with scientific standards and the recommendation defining international principles to be applied in the case of archaeological excavation adopted by UNESCO in 1956.

Ruins must be maintained and measures necessary for the permanent conservation and protection of architectural features and of objects discovered must be taken. Furthermore, every means must be taken to facilitate the understanding of the building and to reveal it without ever distorting its meaning.

All reconstruction work should however be ruled out. Only anastylosis, that was to say, the reassembling of existing but dismembered parts can be permitted. The material used for integration should always be recognisable and its use should be the least that will ensure the conservation of a building and the reinstatement of its form.

B.3.5 Publication

In all woks of conservation, restoration or excavation there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs. Every stage of the work of clearing, consolidation, rearrangement and integration, as well technical and formal features identified during the course of the work, should be included. This record should be placed in the archives of a public institution and made available to research workers and if possible published.

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