PHD

Development of bond strength in hydraulic lime mortared brickwork

Zhou, Zhaoxia

Award date:
2012

Awarding institution:
University of Bath

Development of Bond Strength in Hydraulic Lime Mortared Brickwork

Submitted by

ZHAOXIA ZHOU

for the degree of Doctor of Philosophy

UNIVERSITY OF BATH

Department of Architecture and Civil Engineering

January 2012

COPYRIGHT

Signature of Author...

Acknowledgements

The work in the thesis was carried out in the Department of Architecture and Civil Engineering at the University of Bath between January 2006 and January 2009.

The author would like to thank Professor Pete Walker and Dr Dina D'Ayala, joint supervisors of this study. They have provided continuous support and professional guidance throughout the duration of the research. Their help, patience and time ensured that the project was completed successfully. The author would like to thank Professor Pete Walker in particular, who has been a great supervisor all the way through this long journey, not only contributing considerable expertise to the research, but also providing endless encouragement and support to help me through this most difficult time in my life. Special mention should be made to Dr Andrew Heath for designing the pneumatic loading system on the bond wrench test apparatus, and all of the laboratory staff in the department, Neil, Brian, Will, Sophie, Graham and Paul, who offered a big hand during the large amount of experimental work. Also thanks go to Lawrence, the bricklayer, who had built all the specimens.

The author would like to thank EPSRC for the funding to conduct this project, and also the collaborative research partners, the University of Bristol and the University of Bradford, and the associated industrial partners: in particular Lime Technology Ltd and Ibstock Ltd for the building materials provided; Castle Cement (now part of Heidelberger), Network Rail Ltd, BRE Ltd, Lhoist UK and Buro Happold, for their advice and guidance on the steering group.

Finally, thanks go to my family for the support and patience during the past few years, and my friends being around to make me smile.

Abstract

The first recorded use of hydraulic lime in construction can be traced back to at least two thousand years ago. Hydraulic lime, produced through either adding pozzolanic materials or calcining clay containing limestone, unlike air lime, can set and harden under water, developing strength through initial hydration reaction and subsequent carbonation. After WWII Portland cement mortars had almost completely replaced lime based mortars in modern construction. However, through conservation and specialist construction the benefits of hydraulic lime are becoming increasingly recognised. To support wider usage of these mortars there is a need for systematic study on the mortar properties and structural performance of lime mortared masonry.

This thesis presents findings from a research programme conducted to develop understanding of the mechanical properties of natural hydraulic lime (NHL) mortared brickwork. The work focussed on the flexural strength of NHL mortared brickwork. A variety of material and environmental factors, including lime grade and supplier, mix proportion, sand type and age, have been investigated. In addition the research has completed an in-depth study on the influence of brick absorption characteristics on bond development. The two methods of flexural wall panel and bond wrench testing to establish flexural strength have been compared. In addition to flexural strength, initial shear strength and compressive strength of brickwork has also been investigated.

A greater understanding of NHL mortared brickwork performance has been developed through this work. Performance of the brickwork has been related to properties of constituent materials and environmental factors. Recommendations for design performance of materials have been provided.

Content

List of Figures

List of Tables

1. Introduction

1.1 History

Lime mortars have been used for building throughout the history of civilisation. One of the earliest documented records of (non-hydraulic) lime use can be traced back to ancient Egypt circa 4000 BC (Boynton 1980). By 400 BC the Romans had created hydraulic mortars by adding to lime pozzolanic materials such as brick dust and volcanic ash (Davey 1971). Vitruvius, writing in his Ten Books on Architecture around 25 BC, left a detailed description of the materials and techniques required for hydraulic lime (Vitruvius 25 BC (2001 edition), Lechtman and Hobbs 1986). The use of lime mortars continued through history, forming the basis for the masonry structures of the great architectural movements, including Gothic, Renaissance, Georgian and Victorian periods in the UK.

In 1756 John Smeaton possibly produced the first natural hydraulic lime product by calcining Blue Lias limestone containing clay. By adding an Italian Pozzolanic volcanic soil the famous ‘Eddystone Lighthouse’ was realised; ‘Smeaton’s tower’ has been re-erected as a monument in Plymouth (Figure 1.1). Considered as one of the greatest authorities in hydraulic limes, Vicat started his research into the nature and use of limes in 1812 and published his investigations in 1818 and his main work in 1828 (Vicat 1837 (1997 edition)). He introduced the term 'hydraulic lime' to replace the earlier term 'water lime' used by Smeaton, and classified limes according to their hydraulicity: ‘feebly hydraulic’, ‘moderately hydraulic’ and ‘eminently hydraulic’, which are still used today (Ashurst 1997).

Figure 1.1 Monument of ‘Smeaton’s Tower’ in Plymouth

In 1796 James Parker patented a product called Roman or Natural cement using a higher content of clay in the raw materials, which produced higher strength than hydraulic lime (Oates 1998). One of the most important products to come from the development of hydraulic lime use is of course Portland Cement, invented by Joseph Aspdin in 1824. Aspdin produced cement by blending limestone, clay and some other minerals and calcining and grinding the burnt mixture into a fine powder. The improved consistency, higher strength and lower cost of Portland cement products ultimately made it more popular than lime. However, lime has played a very significant role in masonry construction for thousands of years. Prior to 1930, most masonry construction in the UK used only lime-based mortars.

Following WWII hydraulic lime was largely forgotten by the UK building industry for around half a century. However, widely documented problems using cement based mortars in the repair and restoration of historic masonry gave rise to a modern renewal of interest in lime mortars (Peroni 1981, HolmstroÈm 1981, Sumanov 1995, Moropoulou 1998, Hughes 1998, Callebaut 2000, Rautureau

2001, Beck 2003, Maravelaki-Kalaitzaki 2004, Kent 2005). The improved vapour permeability and beneficial low strength and stiffness make it better suited to mortar joints or renders with old, porous, weak strength masonry stones or bricks. Since the 1970s interest has stimulated a revival of non-hydraulic lime, including in particular the great 'West Front' projects at Wells and Exeter (Ashurst 1997). Following this, hydraulic lime, together with non-hydraulic lime, has made a return into modern construction, supported by a long history of proven performance.

Air lime sets by carbonation whilst hydraulic lime also gains strength through Pozzolanic reaction similar to that developed in cement. Non-hydraulic lime can therefore only set in air, whilst the use of hydraulic lime develops through its ability to set under water and its higher initial strength. One of its recent uses has been as a setting agent mortar for use in damp or exposed locations (NIEA 2009). Having advantages of both cement (initial set) and non-hydraulic lime (porosity and low strength), hydraulic lime works appropriately in the middle zone between the two material uses, suited for old structures maintenance and new building construction (Figure 1.2).

In 1997 Ashurst wrote '*… there is the beginning of a revival of hydraulic lime in British production and some excellent imported material from the continent, as there has been since the 17th century*'. Hydraulic limes are primarily sourced from France and elsewhere in Europe. Limes imported to the UK are mainly for the conservation of old masonry buildings. Presently there is only one major UK supplier of hydraulic lime: 'Singleton Birch' lime produced using Lincolnshire chalk. 'Castle Cement' lime, mostly used in this project, is a bright white French lime, whilst the widely used 'St. Astier' lime is produced in the Perigord area of Dordogne in France.

(a)

(b)

(a): St Pancras station, London (photo from Lime Tech website)
(b): Student Services Centre at University of Southampton

Figure 1.2 Hydraulic lime mortared buildings

Through its long history hydraulic lime has demonstrated its qualities and suitability for a range of projects. Gradually the knowledge, once common, is being re-established. However, current products may not have the same properties as the traditional hydraulic limes documented in historic literature. Modern investigation on the properties of current materials and applications in new and old buildings is required for better understanding and encouraging wider use of hydraulic lime mortars.

1.2 Manufacture of natural hydraulic lime (NHL)

Building lime (calcium hydroxide) is made by burning limestone (calcium carbonate). Initial burning produces quicklime (calcium oxide) which is slaked with water to form the much more stable calcium hydroxide. Pure calcium hydroxide sets by carbonation forming once more calcium carbonate and completing what is often referred to as the 'lime cycle'. The process of manufacturing hydraulic lime is very similar but includes the use of Pozzolanic materials either through selection of appropriate natural sources or addition of materials.

The modern manufacture of natural hydraulic lime includes the quarry mining of argillaceous or siliceous limestones, crushing and calcining, hydration and slaking with carefully controlled quantity of water, and grinding to achieve the required fineness (St Astier 2006). When burning limestone, the temperature needed for producing hydraulic lime is generally under 1200 ºC, lower than the temperature for cement (around 1400 ºC) but higher than that used for non-hydraulic quicklime production (usually under 1000 ºC). Limestone may contain silica, alumina, sulphates, iron, magnesium, manganese, potassium and other compounds. Small amount clay (aluminium silicate) in limestone decomposes at low temperature between 400ºC and 600ºC, and then combines with lime forming calcium silicates, aluminates and ferrites (mainly tricalcium silicate (C_3S) and dicalcium aluminate (C_2A)) at temperature above 800ºC. In the slaking process some free quicklime (C_aO) is converted to calcium hydroxide (CH) with a controlled amount of water (Ashurst 1997, Lanas et al. 2004).

High quality hydraulic lime products require a certain amount of tricalcium silicate (C_3S) to form in the calcination process. These provide the hydraulic set and strength development. However, tricalcium aluminate (C_3A) and soluble sulphates need to be maintained at suitably low levels to reduce the risk of sulphate attack, which builds up efflorescence and causes damage to mortar joints and masonry units (St Astier 2006).

Masonry construction typically uses 10 mm mortar joints to bond units together. The mortar must provide sufficient flexural strength and prevent rain and wind penetration into the interior. Annually around 50 million square metres of fired clay brick walling and 60 million square metres of concrete block walling are produced In the UK (Brick Development Association 2011), requiring around 1.5 billion litres of mortar. In recent years benefits of hydraulic lime mortar have been increasingly realised by the construction industry (Allen et al. 2003, De Vekey 2005).

Hydraulic lime (HL), natural hydraulic lime (NHL) and formulated lime (FL), as well as non-hydraulic air lime (CL), are currently available on the market for construction (BS EN 459-1: 2010). Hydraulic and formulated limes are formed by adding further compounds during calcining (HL) or by blending air limes with commercial products such as cement (FL). Specifications given in BS EN 459-1 classify different types of lime. The varying types of hydraulic limes can produce mortars of similar physical properties. However, conservationists often prefer natural hydraulic lime as it is considered more in keeping with traditional materials.

At present NHLs still only supply a relatively small specialist market. Historically NHL was produced at many locations at a small scale often by the masons. Presently Singleton Birch Ltd produces the only natural hydraulic lime in Britain. Most NHLs are imported from France, with a minor proportion from the Irish Republic (British Geological Survey 2005).

1.3 Benefits of NHL mortars

There are many benefits cited for using natural hydraulic lime mortars instead of cement or air lime based mortars (Schofield 1997, Cowper 1998, Holmes et al. 2002, Allen et al. 2003). Reasons given include performance and environmental benefits. The main benefits are listed below:

1. **Porosity and permeability:** Lime mortar is often said to be able to 'breath'; it is vapour permeable meaning it allows water, in vapour form, to pass through it. Depending on relative pressure differentials moisture movement can be from inside to outside or vice-versa. Vapour permeability is beneficial to masonry joints and surrounding fabric as it prevents build-up of damp, reducing risk of condensation problems (e.g. mould) and avoiding salt and frost damage. In historic building conservation lime mortar is preferred as it is softer than building stones, which makes it less durable and so sacrificial in preference to the masonry blocks.

2. **Beneficial low strength and stiffness:** Natural hydraulic lime mortar is generally much softer compared to cement based materials. Its low strength and stiffness, along with autogenous healing, means it more readily accommodates building movement. Micro-cracking due to shrinkage, minor building movement and so on, can be eliminated by the crystallisation of calcium hydroxide. Lower strength also facilitates recycling of the masonry units on demolition.

3. **Environmental impact:** Lime mortar is commonly regarded as having lower environmental impact than cement mortar. This is based on lower embodied carbon of lime (cradle to gate: 0.74 $kgCO_2/kg$) compared to

cement (cradle to gate: 0.83 kgCO_2/kg) (Hammond & Jones 2011). Both materials reabsorb carbon dioxide through carbonation, further reducing emissions. Lime materials carbonate at a much faster rate than cement products. However, the relative carbon footprint of mortar usage will also depend on binder usage; as a much stronger binder less cement may be required.

4. **Improved performance compared to air lime:** Compared to air lime, hydraulic lime mortars have higher initial strength, the ability to set underwater and improved frost resistance.

5. **Workability:** Hydraulic lime mortar has very good plasticity and workability, meaning it can be spread easily with a trowel and is highly cohesive when applied onto masonry unit surfaces. Freshly mixed mortar also has much longer workable life than cement mortar without the need for set retarders.

6. **Functionality:** Natural hydraulic lime is available in a range of strengths (NHL 2, NHL 3.5 and NHL 5), giving it a wider range of applications to different types of masonry and different weather conditions.

7. **Easy handling:** Unlike lime putty or slaking quicklime, natural hydraulic lime is supplied as a powder, like cement, which makes transport, storage and proportioning much easier and more accurate.

8. **Aesthetics:** From the aesthetic point of view lime mortar is attractive to architects with its traditional and beautiful appearance and less need for thermal expansion joints due to its ability to accommodate movement.

1.4 Aims and objectives of study

The lack of experimental data and deep understanding of materials has hindered the development of structural design guidance and so the wider uptake of hydraulic lime mortared masonry. When this project started in 2006 structural design codes for masonry structures did not include design data for lime mortared masonry. They still do not, although in December 2008 the NHBC Foundation published a 'Draft for Development Standard' on '*The structural use of unreinforced masonry made with natural hydraulic lime mortars-technical annex for use with BS 5628-1:2005*'. The document was prepared by BRE in conjunction with the Building Limes Forum; the design data proposed in the draft are based on very limited experimental test data.

This PhD study aims to take forward knowledge and understanding on the structural properties of natural hydraulic lime mortared brickwork. The approach is primarily experimentally supported where appropriate for improved understanding by analytical techniques of materials and performance. To date there has been no systematic investigation on the influence of various mortar and brick parameters on the properties of hydraulic lime mortared brickwork. The research focuses on a detailed study of the flexural bond strength of NHL mortared brickwork, although shear and compressive performance is also considered. Specific objectives of this work have been to:

1. Complete comprehensive experimental study on the effects of brick properties on the flexural bond strength of natural hydraulic lime mortared brickwork. Characterise the relative importance of brick water absorption and mortar properties.

2. Study carbonation development of natural hydraulic lime mortar specimens and compare with performance of joints in brickwork. Better understanding the effects of brick dewatering on carbonation of hydraulic lime mortars.

3. Study fresh and hardened properties of natural hydraulic lime mortars, including development of workability, water retention, carbonation, and strength. Relate constituent material properties to brickwork performance.

4. Assess suitability of bond wrench method of testing against wall panel tests as a means of determining flexural bond strength where plane of failure is parallel to bed joint direction.

5. Study performance of natural hydraulic lime mortared brickwork in shear and compression.

6. Compare performance of natural hydraulic lime mortared brickwork with conventional cement: lime: sand mortared brickwork.

7. Make recommendations for material design parameters for natural hydraulic lime mortared brickwork.

1.5 Thesis Structure

This thesis is comprised of eight chapters. Following this introductory chapter, Chapter 2 reviews previous research conducted to date on hydraulic lime mortar, cement mortared and lime mortared masonry found in the literature most relevant to this research. Chapter 3 presents the properties of the constituent materials used in the study, experimental specimen preparation and testing methods used. The experimental NHL fresh and hardened mortar properties are presented in Chapter 4, including flow table and sorptivity tests, the influence of constituent materials on mortar strength and mortar carbonation progress. The main work of this research is summarised in Chapters 5 and 6. Flexural strength with plane of failure ‘parallel to bed joint’ direction is examined and compared using both wall panel and bond wrench tests. Wall panel flexural strength where plane of failure is ‘perpendicular to bed joint’ direction is presented in Chapter 5. The influences of mortar and brick properties on the flexural strengths have been primary concerns of this work. The study on initial shear strength and compressive strength is presented in Chapter 7. In the final chapter a short summary and the main conclusions from each chapter are presented, followed by recommendations for further research.

BLANK PAGE

2. Literature review

2.1 Introduction

Since World War II Portland cement based mortars have largely replaced lime based mortars in modern masonry construction. However, over the past 30 years there has been increasing recognition that cement rich repair mortars were leading to damage of historic masonry buildings. Cement mortar's higher strength relative to historic masonry units and its lower porosity, which limits moisture movement through mortar joints, has given rise to damage and the need to use lime mortars in repair work has been rising (Holmström 1981, The Smeaton Project 1990, Fassina and Borsella 1993, English Heritage 1997, RILEM 1999, Callebaut et al. 2001, SPAB 2002, Al-Mukhtar and Beck 2006). In Europe lime mortars are now extensively used for restoration and conservation (Moropoulou et al. 1998, 2005, Bokan Bosiljkov 2001b, Fassina et al. 2002, Van Balen 2003, 2005, Maravelaki-Kalaitzaki et al. 2005, 2007). This has generated a renaissance in the use of lime mortars in modern masonry construction.

Limes are available as non-hydraulic lime (air lime) and hydraulic lime. Non-hydraulic lime hardens through carbonation (chemical reaction with atmospheric CO_2), whereas hydraulic lime also contains components that react with water and develop strength through hydration in addition to lime carbonation. The benefits of hydraulic lime have been widely recognised (Pasley 1997, Schofield 1997, Cowper 1998, Holmes and Wingate 2002, Allen et al. 2003), including good compatibility with historic masonry units, reduced environmental impact, movement accommodation, good water vapour permeability, easier brick recycling, self-healing ability, hardening under water and faster initial strength gain compared to air lime.

The properties and combination of mortar and masonry units are crucial for the long term performance of masonry following construction and so are the main considerations for designers. Both the structural characteristics and durability performance of masonry have been studied by many researchers. However in reflection of its widespread use most of the research has been on Portland cement based mortars. Various studies have focussed on understanding material parameters that influence mechanical and durability characteristics of mortar and masonry. Mortar factors including binder type and grade, aggregate property, binder-aggregate ratio and additive use have been recognised and investigated. To date the limited research on lime mortars has focussed on non-hydraulic lime rather than hydraulic lime. Notwithstanding the scarcity of closely related research, the greater body of previous research is broadly relevant to this study.

Previous studies on lime mortars are reviewed in the following section. Different test methodologies used for examining mechanical bond characteristics are outlined after. As most investigations into masonry properties have been on cement based masonry, this review focuses on the parameters that have concerned previous researchers. Currently, there are few investigations on the mechanical characteristics of masonry using hydraulic lime mortar, therefore, the review on this limited past work is followed in greater detail. The conclusions drawn from previous investigations are summarised at the end of the chapter.

2.2 Previous work on lime-based mortars

2.2.1 Introduction

Traditionally knowledge and experience on the manufacture and use of lime mortars were handed on verbally to the next generation. Rules for lime mortars would therefore reflect regional variations in the composition of raw materials. A system of widespread small-scale production resulted in significant variation in the quality of lime mortars. This inconsistency contributed to its replacement by cement mortars in the latter half of the twentieth century.

In recent decades modern research interest in lime mortars has been driven primarily by conservation work. Modern hydraulic lime mortars are sourced from a small number of industrial suppliers, providing a more consistent supply chain than traditionally available, which has facilitated research characterising material performance.

2.2.2 Overview of work on lime mortars

In the early 20th century hydraulic lime industry was highly developed in England and on the continent, with many different brands on the market. The classification and properties of hydraulic limes have been included from the earliest publications on lime mortars (Platzmann 1924, 1938, Cowper 1927, Searle 1935). Platzmann published articles on the definition, manufacture, properties, composition and production of natural and artificial hydraulic limes. It showed that the strengths of hydraulic lime mortars were higher than that formed using quicklime, but much lower than those using Portland cement. The study also noted that there seemed to be no direct relation between physical properties, such as density and crystalline structure, chemical composition of raw materials, and hardened properties of the different hydraulic lime mortars.

Property variations were influenced by variations in burning process, which in turn is in part influenced by physical properties of raw materials. The hardened mortar properties vary depending on the process of silicate formation, the reaction between calcium hydroxide and silica, alumina and iron oxide. These limes are preferred when there are special requirements for durability and weather resistance.

As with any material, the selection, preparation and formulation of constituents was established by a process of trial and error and this empirical knowledge passed from craftsman to craftsman over generations. However, standardization and specification are essential to develop the material application in the modern era. Charola et al. (1998) proposed series of tests as the basis for lime mortar standards. Their discussion gives guidelines for preparation, curing and standardization testing of hydraulic lime mortars.

The Foresight project, undertaken from 1998 by a team of researchers based at University of Bristol, has been the pioneer for research on hydraulic lime in recent years. This project dealt with constituent materials, mix design, mortar properties, workmanship, strength requirements, and durability in design and construction. The benefits of hydraulic lime were discussed. The study examined in detail plastic properties of fresh mortar and strength characteristics of hardened mortars. The research produced a general practice guide for using hydraulic lime mortar (Allen et al. 2003). However, properties of lime mortared masonry were not considered by the research project.

In practice, hydraulic lime has already been extensively applied in restoration of historic masonry (Callebaut et al. 2001, Maravelaki-Kalaitzaki et al. 2005, 2007, Al-Mukhtar et al. 2006). Callebaut et al (2001) used a variety of advanced technologies such as petrographical analysis, X-ray diffraction analysis (XRD), scanning electron microscopy (SEM) and chemical analysis, to identify the characteristics of the restoration mortar used in the St Michael’s church built in 1650-1666 in Belgium during nineteenth century (1853-1880). Test results, in agreement with the study of historical record, recognised that the mortar used for the church restoration was natural hydraulic lime mortar. The compatibility between the old original mortar and the restoration mortar has been proven to be a big success for over one hundred years.

Natural hydraulic lime NHL 3.5 with pozzolanic addition was selected for the restoration of a historic building where magnesian lime mortar was originally used in Greece (Maravelaki-Kalaitzaki et al. 2005). A variety of analyses on the repair mortar properties, including compressive strength, modulus of elasticity, capillary absorption, porosity and pore size distribution, were conducted to examine the suitability. After three years the new mortar and the old structure seemed well-matched through observation and infrared spectroscopy and X-ray diffraction analyses.

A study by Al-Mukhtar et al. (2006) focussed on studying the compatibility between lime mortars and French limestone tuffeau. Mortars were prepared using both non-hydraulic and hydraulic limes combined with fine aggregate obtained from crushing the tuffeau stone. The lime content varied between 5% and 50%. The mortars demonstrated good chemical compatibility between the limestone blocks and mortar. Mortar samples prepared with hydraulic lime had higher mechanical strength than mortars prepared with hydrated lime. There was little difference in capillary water absorption between hydraulic and non-hydraulic lime mortars with more than 15% lime content.

Hydraulic limes for building are divided into three sub-families as natural hydraulic lime (NHL), formulated lime (FL) and hydraulic lime (HL) in current national code BS EN 459-1:2010. Limes containing reactive silicates and aluminates, produced from impurities such as clay in raw materials before calcination, are referred to as natural hydraulic limes. Three types of natural hydraulic limes, NHL 2, NHL 3.5 and NHL 5, are used as standard strengths and characterised by 28-day compressive strengths (≤2 to ≥7, ≤3.5 to ≥10 and ≤5 to ≥15 N/mm^2 respectively) determined in accordance with BS EN 459-2:2010. BS EN 459 does not include guidance on mix proportions and procedures, curing methods, compatibility with masonry units and other aspects to assess the use of the material in construction. The limited use of lime mortars can to some extent be ascribed to the lack of understanding of the mortar properties and the masonry performance.

To date there has only been limited research undertaken on the engineering properties of lime mortars. Much work has focussed on the benefits of including air-lime in cement based mortar mixes. Previous work (Boynton and Gutschick 1964, Gazzola et al. 1985, Lawrence and So 1994, Sugo et al. 2001, Bokan Bosiljkov 2001, Schofield 2005, Tate 2005) has commented that air-lime, when added to cement and sand mixes, improve mortar workability, cohesion and adhesion. Lime addition reduces the shrinkage of hardened cement mortar and improves mortar porosity. Tate (2005) described the properties and specifications of cement lime mortars and concluded that lime properties are beneficial to both plastic and hardened mortar properties and the resultant masonry.

2.2.3 Influence of constituent materials and mortar workability on mortar performance

Studies have investigated the influence of lime grade, mix proportion and sand type on mortar properties through laboratory experiments (Stefanidou and Papayianni 2005, Pavía and Treacy 2006, Lawrence et al. 2006, Maravelaki-Kalaitzaki 2007, Ball et al. 2009), whilst others have been reported through case studies related to the repair of historic buildings (Bokan Bosiljkov

2001, Maravelaki-Kalaitzaki et al. 2005, Pavía et al. 2006, Pavía and Toomey 2008). The performances of mortars made using powdered air lime, with and without pozzolanas, lime putty, dolomitic lime, hydraulic lime and Portland cement, have been compared.

Some researchers (Sugo et al. 2001, Lawrence et al. 2006, Pavía et al. 2006, 2008, Seabra et al. 2007, Hanley and Pavía 2008) have concluded that initial workability of fresh mortar has effect on the properties of hardened mortar and more importantly on the compatibility with the masonry unit, including development of masonry bond. Studies have also explored the mortar parameters that influence mortar workability. Seabra et al. (2007) studied the rheological behaviour of fresh hydraulic lime mortar. They concluded that workability of fresh mortars is affected by the binder: aggregate ratio, kneading water content, and use of chemical admixtures.

Research conducted by Bokan Bosiljkov (2001) compared various mortars using industrial hydrated lime, lime-putty and traditionally prepared lime-putty. The study included three types of sand and the inclusion of additives. The proportion of lime and sand was maintained at 1:3 (by volume). Using 40x40x160 mm^3 mortar prisms the study indicated that the compressive and flexural strengths of plain non-hydraulic lime mortars after 90 days are a good approximation of their final longer-term performance. Mortar compressive strength ranged between 1.13 and 2.09 N/mm^2 with flexural strength varying between 0.37 and 0.70 N/mm^2 for the non-hydraulic lime mortars used.

Stefanidou and Papayianni (2005) reported on a study into the influence of aggregate properties of lime mortar properties, mainly focusing on aggregate content and grain size. Mortar strength, volume stability and capillary suction measurement were examined. The binder: aggregate ratios adopted were 1:1.5, 1:2.5, 1:3, 1:4 and 1:6. The highest strengths and lowest porosity were attained by richer lime mortar mixes (1:1.5, 1:2.5 and 1:3). Coarser aggregates contributed to stability as the volume changes were noticeably restricted and improved the long-term mortar strength. Compaction of the mortars reduced voids and increased the bond of lime paste with aggregate grains, benefiting the longer-term strength and weathering resistance.

Pavía et al. (2006) worked on selective testing of lime mortars from fat, feebly-hydraulic, moderately hydraulic and magnesian limes, to undertake monument repairs. Petrographic analysis informed selection of the type, origin and proportions of the raw materials used, providing base data for designing accurate mortar replicas. Density, porosity and water absorption tests were conducted to determine the properties governing the moisture movement of the mortars. As expected, the results indicated that lime mortars had higher porosity than the Portland cement mortars. The feebly-hydraulic lime mortar possessed the highest porosity and water absorption with the lighter microstructure than those shown by the fat and magnesian lime mortars, thus being more susceptible to failure in damp and exposed environments. The compressive strength of mortars, as expected, increased with the hydraulicity of the binder. Both fat and magnesian lime mixes were weaker than the mortars incorporating a hydraulic binder. Repair mortars were substantially less dense, more porous and permeable and mechanically weaker than the limestones and sandstones used in the monumental building.

In 2006 Pavía and Treacy also studied the compressive strength of NHL 2 and NHL 3.5 mortars. The study compared performance with lime putty, Portland cement and magnesian lime mortars for use in the repair of historic buildings. A sub-angular, glacial origin washed sand containing a high proportion of quartz aggregate was used. The mix proportions were 1:3 (binder: aggregate) for NHL2 and 1:2 for NHL3.5. The reported compressive strengths were 2.18

N/mm^2 and 2.37 N/mm^2 for NHL2 and NHL3.5 respectively after approximately 45 days, higher than both the air and magnesian lime mortars.

Lawrence et al. in 2006 conducted research focusing on the impact of lime: mortar ratio on compressive strength of air lime (CL90) mortars. A moderately hydraulic lime mortar, NHL3.5, was also used for comparison. The binder: aggregate ratio was kept a consistent 1:3 by volume. To obtain a workable mix more water was required for the air lime mortars compared to the hydraulic lime. The water: lime ratios for air lime mortars varied from 0.5 to 0.88 by volume whilst the ratios for NHL3.5 mortars varied from 0.38 to 0.63. Compressive strengths, up to 91 days, were insensitive to variations in water: lime ratio, whilst in contrast the choice of aggregate had a significantly greater impact on the strength characteristics of air lime mortars.

Maravelaki-Kalaitzaki (2007) indicated that mortars with coarse aggregates develop higher mechanical strength. Nevertheless, micro-pores interconnected with macro-pores are responsible for the low salt-decay resistance. An increase of binder content enhances the mechanical resistance but reduces the resistance to sulphate solutions, as the consequence of the small capillaries inhibiting salt crystallization. The mortar with the best performance consisted of medium graded aggregates and a 1:3 binder to aggregate ratio. Pores around 0.2 μm radius were cited to enable salts to crystallize without causing damage from crystallization pressure. The same result was corroborated by the research on the influence of grain size distribution on the mortar performance by Hentiques et al. (2004), using mono-granular sands and combinations of two or more sands.

Pavía and Toomey (2008) showed aggregates have a significant influence on the flexural and compressive strengths of feebly hydraulic NHL2 mortars. Four types of sand were used in the comparison. The binder to aggregate ratio was

1:3. The two very-angular and well-graded aggregates displayed high flexural strengths, average values around 1.8 and 1.6 N/mm^2 respectively, and compressive strengths, with average around 1.4 and 1.2 N/mm^2 respectively. The angular but less well-graded sand presented low strengths, around 1.2 and 0.7 N/mm^2 respectively for flexural strength and around 0.9 and 0.7 N/mm^2 respectively for compressive strength. It concluded that the sharpest sand, with appropriate range of particle sizes, developed the strongest mortar.

Pavía attributed the low flexural and compressive strengths of two sands to their high amounts of calcite, and suggesting that calcite content in aggregates tends to adversely affect mortar strength, although this conflicts with previous research (Vicat 1837, Holmes 2002, Lanas 2004). Pavía concludes that both physical property and chemical composition of the sand may determine mortar properties. It is hard to examine which influencing factor is more significant as many factors interact with each other and are almost impossible to be investigated separately. In Pavia's study it is likely that the finest graded sands would require more water during mixing, which in turn may cause higher drying shrinkage and decreasing strength. The weakest mortar strength produced can be attributed to high amount of fine silt and clay particles as stated in the study. Also the inferior grading and the largest average particle sized sand contained both angular and rounded particles leading to the highest porosity and water absorption, which may be part of the reason of its lowest mortar strength.

Hanley and Pavía (2008) reported on experiments into the workability of natural hydraulic lime mortars, using NHL2, NHL3.5 and NHL5, and its effect on hardened mortar strength, in order to specify appropriate flow value for optimising mortar properties. A well-graded siliceous aggregate was used, with a lime: aggregate ratio of 1:2.75 (by mass). Mortar workability was measured by initial flow test (flow table test). Three flow values, 165, 185 and 195mm, were controlled to examine workability for different mortar mixes and the resultant mortar compressive and flexural strengths after 28 and 56 days. Test results showed that the flow value, influenced by water content, had a significant effect on mortar strength. Each NHL type had a unique flow value that maximized its mortar strength with an appropriate level of workability. The optimal flow value increased with the hydraulicity of the hydraulic lime, around 165 mm for the NHL2 mixes, increasing to 185 mm for NHL3.5 and NHL5 mortars. However, it is clear that different water absorption bricks require different mortar workability.

To conclude, the materials used for mortar mixes have a crucial effect on the characteristics of both fresh and hardened mortar. In general, mortar strength improves with well-graded coarse aggregate and the increase of binder hydraulicity and content. The water/binder ratio or workability of fresh mortar also plays an important role in the hardened properties of mortar.

2.2.4 Influence of age on mortar performance

As one of the main characteristics of lime mortar, hardening of both non-hydraulic lime and hydraulic lime closely relate with the process of carbonation. The carbonation process (section 2.2.5) generally takes a much longer time to complete hydration. Longer-term age development for lime mortars is therefore more relatively important than cement mortars.

Research conducted by Lanas and Alvarez (2003) investigated the influence of curing time, binder: aggregate ratio, aggregate characteristics and porosity on the mechanical performance of non-hydraulic lime repair mortars. Two types of hydrated lime (CL90), two silica sand aggregates and two limestone aggregates were investigated. A series of tests on mortars with binder: aggregate ratios ranging from 1:1 to 1:5 (by volume) at different curing times up to 365 days were executed. Results showed significant improvements in both compressive and flexural mortar strengths after 28 days, independent of aggregate type and dosage. Compressive strength doubled or more between 28 and 365 days after casting. Lanas et al hypothesised that preservation of a certain $CaCO_3$: $Ca(OH)_2$ ratio contributes in an unknown way to the development of the highest mortar strength. As the $CaCO_3$: $Ca(OH)_2$ ratio varies with binder: aggregate ratio and age through carbonation, it was indicated that mortar with least binder: aggregate ratio attained its highest strength earlier (around 90 curing days) than mortars with higher binder: aggregate ratio. Therefore, it can be inferred that the mortars with different binder: aggregate ratios reach their peak strengths at different ages. The study noted that mortar strengths at early ages (between 3 and 28 days) were not conclusive as they were strongly influenced by the water content of the mixture. The test results also showed that mortar developed higher strengths as well as higher porosities (lower porosities in cement-based mortars) with increasing binder content. The porosity increase makes carbonation easier, so mortar strength improves with time. It was observed that the grain size distribution of the aggregates, the chemical and mineralogical composition, and the shape of aggregate grains also influenced the development of mortar strength. Adequate grain size distribution, use of calcitic aggregates, and angular shaped grains improved mortar strength.

In 2004 a similar long-term study on natural hydraulic lime mortar was also reported by Lanas et al, focussing mainly on the properties of natural hydraulic lime-based mortars. Curing time, binder: aggregate ratio, aggregate attributes and porosity were investigated. Hydraulic lime (grade HL5), silico-calcareous and pure limestone aggregates were studied. The binder: aggregate ratios prepared were 1:1, 1:2, 1:3, 1:4, and 1:5 (by volume). Tests were performed after curing times of 3, 7, 28, 91, 182 and 365 days. Three phases of hardening process were established. The mortars with high content lime (1:1 and 1:2 binder: aggregate ratios) in early ages up to 28 days developed 50% of their maximum values of strength, whilst leaner mortars (1:3, 1:4 and 1:5 binder:

aggregate ratios) developed close to 85-90% of their peak strength. The strength development is attributed to the hydration of several hydraulic compounds; C_3S (tricalcium silicate) contributes to the main strength in this period. C_3A (tricalcium aluminate) might accelerate the hydration of C_3S. Between 28 and 182 days the rate of compressive strength gain for the mortars decreased. During this phase C_2S (dicalcium silicate) and carbonation mainly contribute to strength development. In the long term of between 182 and 365 days, the strength of 1:1 and 1:2 mortars increased again, whilst 1:3, 1:4 and 1:5 ratios did not show any strength improvement. Mortars with more binder content showed higher compressive and flexural strengths, irrespective of the types of aggregate used. All 1:1 mortars reached M5 strength at 28 days. The 1:2 mortar made with limestone aggregates also obtained M5 class. The grain size distribution, chemical composition and the shape of aggregate grains have influences on the mechanical behaviour of the specimens. The difference of chemical compositions due to the raw materials used has caused the difference in the mechanical behaviours between natural hydraulic lime-based mortar and air lime mortar. Chemical hydration of NHL mortars provides several times higher strength than mortar with air (non-hydraulic) lime. However, they have similar strength development tendencies with curing time, binder: aggregate ratio and aggregate characteristics and similar characteristics of porosity.

Moropoulou et al. (2005) evaluated the strength development of several mixtures of historic mortars up to 15 months after casting. The results showed that natural hydraulic lime presented faster rate of mechanical evolution than lime putty and hydrated lime powder mortar. The weight ratio of the NHL2 mortar (1:2.3 NHL 2: aggregate by mass) acquired near peak compressive strength within the first month (3.05 N/mm^2), with little further gain afterwards. Whereas lime putty and lime powder mortar exhibited strength gains of 200-300% between one and 15 months, and were still in development after 15 months. The study reported a low ratio of compressive to flexural strength, which was attributed to a low elastic modulus.

Maravelaki-Kalaitzaki et al. (2005) reported on a study in which natural hydraulic lime was chosen for the restoration of historic masonry which had been deteriorated by natural weathering and a previous use of cement based material during the 20th century. Hydraulic lime (NHL 3.5 with pozzolanic additions) was chosen as the binder material and mixed with siliceous sand in proportions 6:14 by mass. The mortar compressive strength after one month curing time attained 3.48 N/mm^2, reaching 63% higher after 12 months. After 3 years, infrared spectroscopy of the repair mortar indicated that carbonation was still incomplete.

The long-term (up to 365 days) compressive strength development of natural hydraulic lime mortar has been examined by Ball et al. (2009), using 1:2 (by volume) NHL3.5: Croxden sand cylindrical specimens (18 mm in diameter and 36 mm in length). The hydraulic lime mortar developed lower strength than 1:2:9 cement: lime: sand mortar, reaching slightly below 2.0 Nmm^2 and 3.0 Nmm^2 respectively after approximately 40 days. There were no observed significant strength increases for both mortars between 40 and 365 days.

The studies conducted by the previous researchers have shown the strength development of lime mortar is a long-term slow process through hydration and carbonation. The factors such as chemical composition of constituent materials, grain size distribution of aggregates, binder/aggregate proportion and water/binder ratio have effects on mortar characteristics at both micro and macro levels during a long period.

2.2.5 Carbonation of lime mortars

The carbonation rate of calcium hydroxide in lime is determined by environmental conditions, such as carbon dioxide concentration, relative humidity and temperature (El-Turki et al. 2007). A study on the influence of relative humidity on the structural changes during carbonation of NHL 3.5 hydraulic lime, by El-Turki et al. (2007) showed lime exposed to 100% carbon dioxide at RH 97% exhibited higher carbonation rate than at RH 65%. The study reported that a thin fully carbonated layer of crystalline calcium carbonate was generated for the sample exposed to 97% RH but with uncarbonated calcium hydroxide still underneath, whilst the surface of the sample exposed to 65% R.H was not completely carbonated. Allen at al. (2010) showed that the compressive strength of NHL3.5 mortar cured in N_2 containing 400 ppm CO_2 was much higher than cured in pure N_2 at different ages (14, 28 and 56 days), due to the increase of carbonation rate.

Mortar carbonation is often examined by spraying pH indicator solutions such as phenolphthalein on the fracture surface. El-Turki et al. (2009) presented a highly sensitive microbalance technique for the real-time measurement of carbonation in cementitious materials; the material increases in mass with carbonation. Carbonation rates decreased with increasing binder hydraulicity. The CL90 mortar displayed the most rapid rate of carbonation, followed by NHL 2, then by NHL 3.5, with the NHL 5 mortar exhibiting the slowest carbonation rate. The Portland cement mortar mass gain was at a rate close to the CL90, but it was believed that this was not only due to carbonation, but also as a result of water absorption from the silicate hydration reaction, which was revealed by the differences in crystal morphology through comparing the scanning electron micrographs of NHL and PC carbonated surfaces. The results confirmed that the progression of carbonation is proportional to square root of time. In all cases the carbonation rate increased with environmental relative humidity.

El Turki et al (2009) also examined the effect of grain size on carbonation by preparing two mortars containing the particles passing through a 300 μm and a 150 μm sieve. The carbonation rate was shown to decrease as the sand particle size is increased. It revealed that sand particles acted as sites from the nucleation and growth of calcite crystals. The specific surface area of the sand decreased as sand grain size increased, which reduced the carbonation rate.

Ball et al. (2009) investigated the influence of mortar carbonation on the deformation through creep and shrinkage using hydraulic lime NHL 3.5 mortars. A 1:2 NHL 3.5: Croxden sand mortar mix was prepared and cylindrical specimens 18 mm in diameter and 36 in height were cast. After seven days of initial hardening, half of the specimens were coated with a layer of petroleum jelly to restrict the diffusion of carbon dioxide and water vapour into and out of the specimen, whilst half of the specimens were left uncoated. Lower compressive strengths and more intense phenolphthalein staining (indicating higher proportion of calcium hydroxide) were detected with the 'sealed' specimens. The strengths of the unsealed specimens achieved 1.9 N/mm^2, compared to 1.8 N/mm^2 for the sealed samples, at 63 days respectively. The study also suggested that mortar carbonation reduced creep (mortar deformation under load) over a period of 56 days.

2.2.6 Other aspects of lime mortar performance

In 2006 Pavía et al. published two papers, one comparing the durability of fat lime (lime putty) and feebly-hydraulic lime mortars (NHL 2) (Pavía and Treacy 2006), and the other presenting an assessment of lime mortars including fat (lime putty), feebly-hydraulic (NHL 2), moderately-hydraulic (NHL 3.5) and magnesian (mg) lime for repairing Ardamullivan Castle and Clonmacnoise Monastery (Pavía 2006). A Portland cement mortar was tested as a reference.

The research showed lime mortars developed higher porosity and moisture flow compared to Portland cement mortars, which made the structures more breathable through the mortar joints. However, the NHL 2 mortar showed highest porosity and water absorption by capillary suction than the air lime mortars. On this basis the NHL 2 mortar was considered less suited for damp and slightly exposed conditions than the air lime. This was contrary to the general accepted opinion that hydraulic lime is more durable than air lime.

Ball et al (2008) reported on experiments to measure the creep and drying shrinkage deformation of mortar samples under load. Performance of a 1:2 NHL 3.5 mortar was compared with that for 1:2:9 and 1:1:6 Portland cement: CL90: sand mortars. A logarithmic equation was developed to describe the strain development over time. The effect of relative humidity on deformation was studied over ten days on a 90-day old NHL mortar sample. A reversible relationship between changes in specimen dimension and relative humidity was observed. The relationship between the recorded deformation and the hydraulic proportions (Portland cement) was examined by using different mix designs of cement: CL90: sand mortars. A broadly linear relationship between strain rate and calcium hydroxide content was reported.

Allen and Ball (2010) studied the influence of brick dewatering on mortar creep under load and the effects of wetting and drying on NHL 3.5 mortar performance. Cylindrical specimens 18mm in diameter and 36 mm in length were used with 1:2 NHL 3.5: Croxden sand mixes. The specimens were dewatered by inverting the moulds, to allow the fresh mortar to come into contact with a highly absorbent brick surface for 15 minutes. Both dewatered and non-dewatered samples were exposed to atmospheres containing either pure nitrogen or nitrogen with 400 ppm CO_2. Mortar compressive strengths were tested after curing 14, 28 and 56 days. Specimens cured in 400 ppm CO_2 achieved much higher strengths than the specimens cured in an atmosphere of

100% N_2. The dewatering increased mortar strength greatly for the specimens cured in CO_2; the dewatered specimens reached around 4 N/mm^2 at 56 days, compared with the non-dewatered specimens that achieved around 3 N/mm^2.

The wetting and drying tests were controlled by Allen and Ball (2010) into cycles of 10 minutes wetting and 20 hours drying (much longer than the required times to saturate and dry the samples). Mortar mixes 1:1, 1:2, 1:3 and 1:4 NHL 3.5: Croxden sand, were tested at different ages (28, 56, 90 and 180 days). The results showed apparent strength increases compared to control specimens, which were more significant with more lime content in the mortar mixes, due to the dissolution and re-precipitation of calcium carbonate, resulting in further hydration and carbonation during each cycle. The long-term deformation of 1:2 NHL3.5: sand was observed and divided into creep, load-dependent deformation and shrinkage. Creep showed much more significant component than shrinkage in the first 14 days, whilst shrinkage was more significant later on.

El-Turki et al. (2010) compared effects of dewatering on the mortar strength using CL 90, NHL 2, NHL 3.5, NHL 5 and Portland cement. All mortar specimens were mixed in proportions 0.78:1:2 (water: binder: Croxden sand) by volume. As above the specimens were dewatered through 15-minute capillary suction from a high sorptivity clay brick (sorptivity, S = 2.5 mm min$^{1/2}$). Compressive strength testing on the non-dewatered and dewatered mortar specimens was carried out at 14, 28 and 56 days. Water loss from the mortars as a result of brick suction increased with the hydraulicity of the binder (CL 90 $\leq$ NHL 2 $\leq$ NHL 3.5 $\leq$ NHL 5 $\leq$ Portland cement). For all mixes, compressive strength increased with age and binder hydraulicity. Dewatering had a little effect on CL 90 mortar strength (reaching around 1 N/mm^2 at 56 days for dewatered specimens), whilst all hydraulic mortars displayed apparent strength increase as a result of dewatering; the Portland cement mortar showed the greatest increase in strength. Strength increase due to dewatering of the hydraulic lime mortars decreased with increasing hydraulicity. In conclusion El-Turki (2010) state that testing on mortar specimens cast in steel moulds will underestimate strength achieved in masonry. Using Raman Spectroscopy and scanning electron microscope (SEM), the microstructure and composition analysis of mortars were investigated. The results revealed that dewatering had influenced hydration reactions, and therefore the growth of silicates. It was suggested that mortar strength increased through mortar particle consolidation and a growth of silicate phases in water located between sand grains. Mortar open porosity determined by vacuum saturation showed little change between the dewatered and non-dewatered mortars. Hydraulic limes displayed the mid-range porosity (32%), compared to the highest (41%) from CL 90 mortar and the lowest (18%) of the Portland cement mortar. The authors noted that the porous microstructure of the mortar correlated with mechanical performance.

El-Turki et al. (2010) also studied the influence of wetting and drying cycles (10 minutes wetting and 20 hours drying) on hydraulic lime mortars to evaluate the significance of moisture control in site practice. More binders including NHL 2 and 5, CL 90 and Portland cement, were tested for both short-term (1, 3, 7 and 14 days) and long-term (28, 56, 90 and 180 days) exposure. The wetting and drying cycles generally increased strength for the NHL 2, 3.5 and 5 and Portland cement mortars. There were little strength changes during 28-180 days, which indicated that the strength increases took place at early ages. The study suggested that the strength increase could be attributed to an increasing rate of hydration and carbonation reactions as a result of the cycling.

Ince et al. (2011) investigated the water retaining ability of NHL mortars through desorptivity tests using a modified American Petroleum Institute pressure cell. The influences of mortar hydraulicity, applied pressure, mix composition and elapsed time after mixing on desorptivity were studied. Mortars were prepared using different binders, including CL90, NHL 2, 3.5 and 5 and Portland cement. The variations in desorptivity were examined with changes in binder: sand ratio, water: binder ratio, applied pressure, sand grading and elapsed time after mixing.

2.3 Testing methods used for masonry characterisation

To date a wide variety of testing methods have been employed to measure masonry strength. Methods include testing on direct tensile strength (Sinha 1983, Jukes 1998, Almeida et al. 2002), flexural strength on wall panels (Ritchie 1961, Grimm and Tucker 1985, Gabby 1989, Sinha et al. 1997, BS EN 1052), bond wrench tests on stack bonded prisms (Venu Madhava Rao 1995, Sarangapani 2005, Khalaf 2005, BS EN 1052-5: 2005) and shear bond strength (Sinha 1983, Marzahn 1996, BS EN 1052-3: 2002, Lourenco et al. 2004, Sarangapani 2005, Venkatarama Reddy 2007). The different names such as direct tensile strength, flexural bond strength and bond wrench strength, having been used by different researchers, only mean the various approaches to perform tests, but they actually induced similar tensile stress normal to bed joint. In this thesis, they are generally named as flexural strength or flexural bond strength of masonry.

Differences due to varying testing methods and materials used have complicated direct comparisons between the results derived by different researchers. In this section the main test methods for measurement of flexural bond strength and shear strength are reviewed.

2.3.1 Methods used to measure bond strength

Research on bond strength of masonry has been carried out with a variety of methods, with varying specimen dimensions such as large-scale walls, wallettes, pier specimens, bond wrench prisms, brick couplets and small-scale brick-mortar core specimens (Sugo 2001), and varying loading arrangements such as bending and direct tension. However, with new methods increasingly proposed, comparison between test results from different measuring approaches has become more difficult.

The current British and Euro-Norm Standards (BS EN 1052-2:1999, BS EN 1052-5:2005 and BS EN 1996-1-1:2005 (Eurocode 6)) for masonry allow two methods for measurement of flexural bond strength: wall panel tests and bond wrench test. As a relatively new method, bond wrench test was created by Hughes and Zsembury in 1980 and gradually standardised in different countries (Scrivener 1992): USA (ASTM 1986), Australia (SAA 1988), UK (BSI 2005, De Vekey reported its use in the UK in 1991). Nevertheless there has been some reticence in the UK to accept the bond wrench test. The wall panel tests and bond wrench test are both used in this study and described in Chapter 3. In this section previous research methodologies are presented and reviewed.

Boynton and Gutschick (1964) indicated crossed-brick couplet test in ASTM (Figure 2.1) was most widely used for determining tensile bond strength at that time, although there was a general lack of reproducibility and the meticulous specimen preparation in laboratory being criticised for not simulating exposure conditions.

Grimm and Tucker (1985) investigated the relationship between masonry flexural strength and quality of work, including variation in course height, the size of test specimens, and the method of loading. The theoretical work was verified by experimental test on wall panels under uniform load and prisms under equal concentrated load at the one third span points (Figure 2.2).

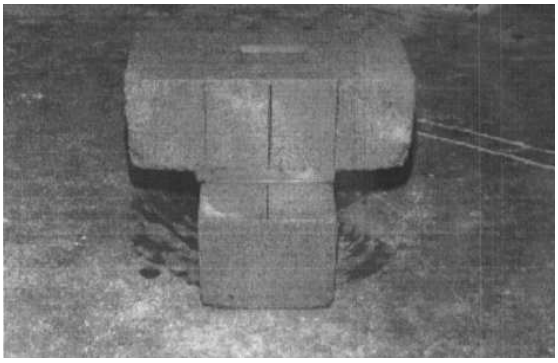


Figure 2.1 Couplet for tensile bond strength test
(Boynton and Gutschick 1964)

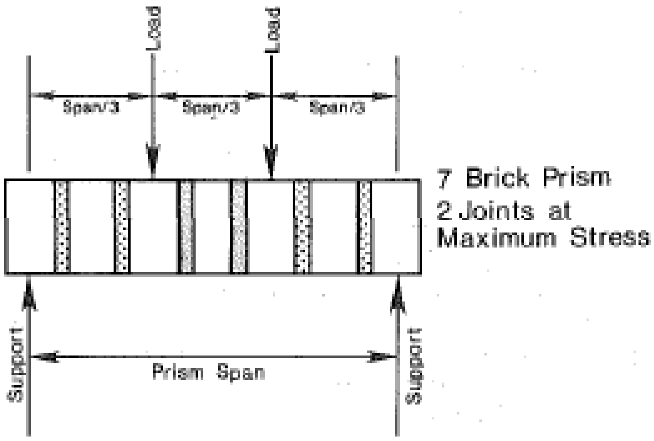


Figure 2.2 Brick prism loading
(Grimm and Tucker 1985)

Sinha et al. (1997) performed a test to determine the failure criterion of masonry in biaxial bending (Figure 2.3). Based on British Standards, two kinds of tests were used to determine the flexural strength of wall panels for plane of failure parallel and perpendicular to bed joints. These are similar to the methods in BS EN 1052-2, except the tests were carried out in horizontal position and with loads on or close to the mortar joints. Experimental and theoretical analyses were carried out to investigate the performance of brickwork under both axial and biaxial bending. Equations were established to predict the cracking and failure behaviour.

Jukes et al (1998) and Almeida et al. (2002) summarised various methods to investigate the tensile strength of masonry under uniaxial tension, including direct tensile tests for couplets (Figure 2.4-2.7) and crossed brick couplet (Figure 2.8). Khalaf (2005) mentioned another crossed couplet direct tensile test (Figure 2.9).

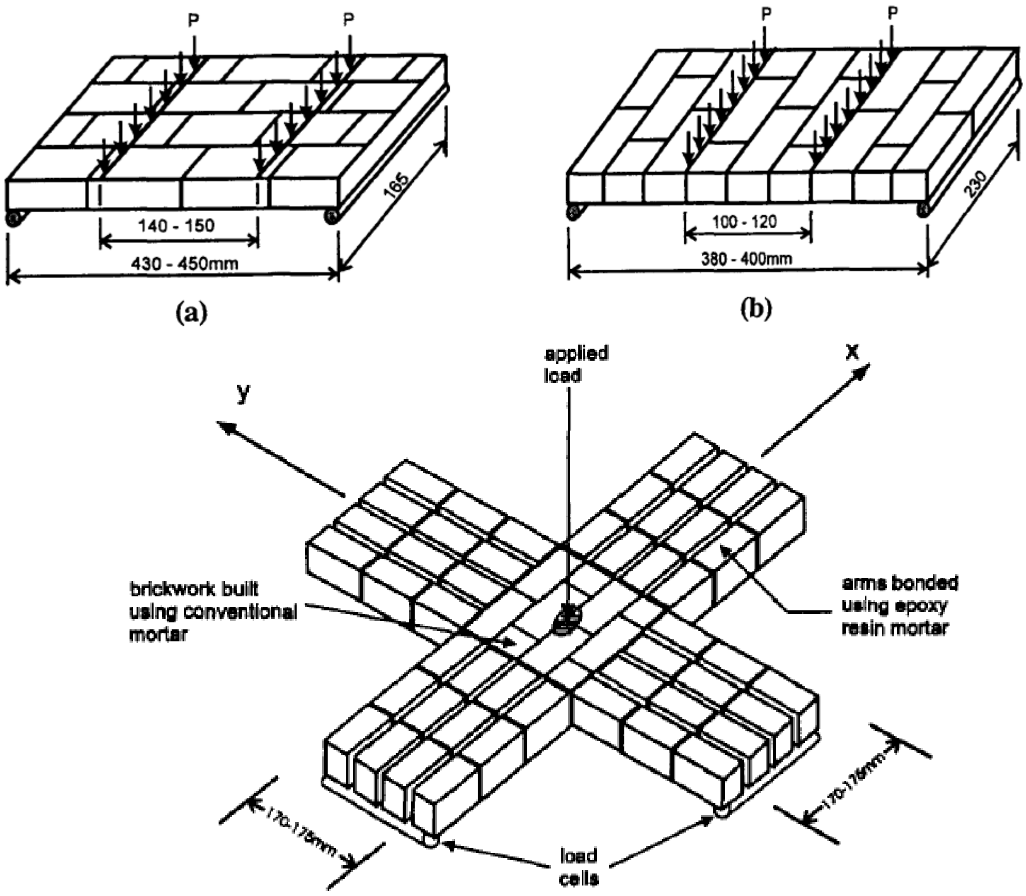


Figure 2.3 Configuration of two types of four-point loading panel walls and cross beam (Sinha et al. 1997)

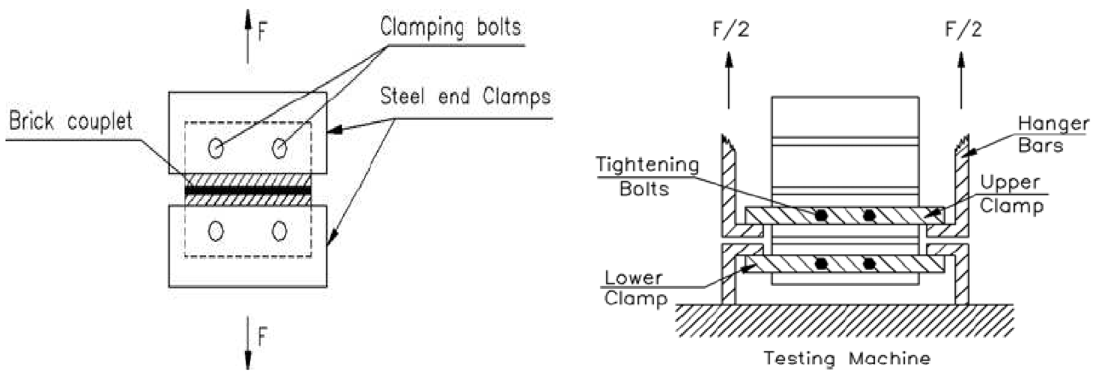


Figure 2.4 Couplet test using special clamps or clamps

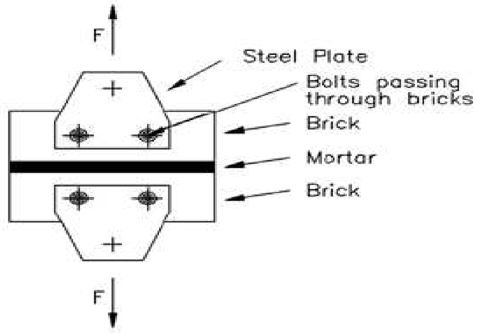


Figure 2.5 Couplet test using holes and bolts

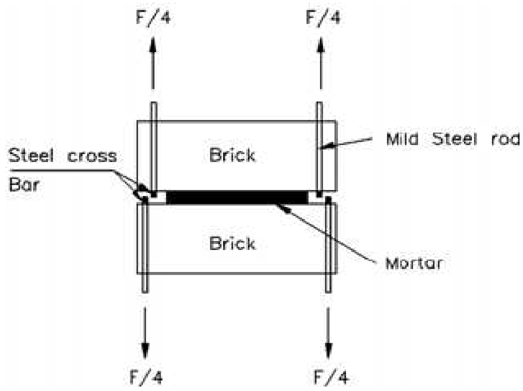


Figure 2.6 Sheffield test

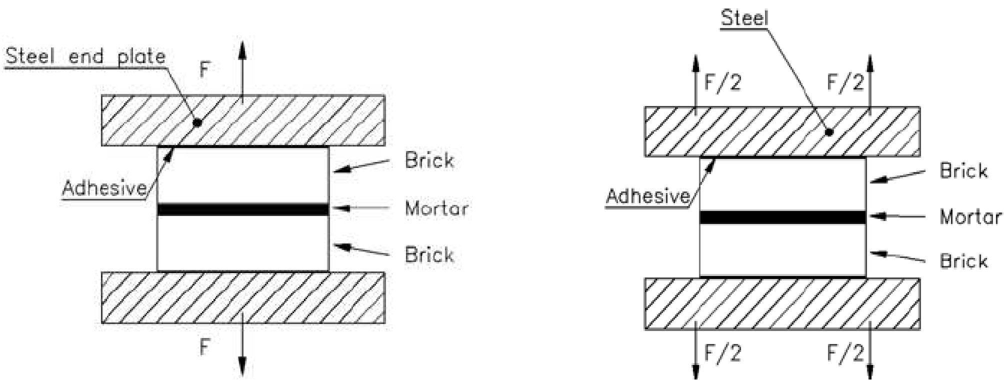


Figure 2.7 Steel plates glued with adhesive

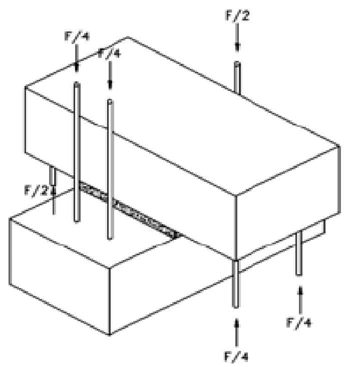


Figure 2.8 Crossed brick couplet

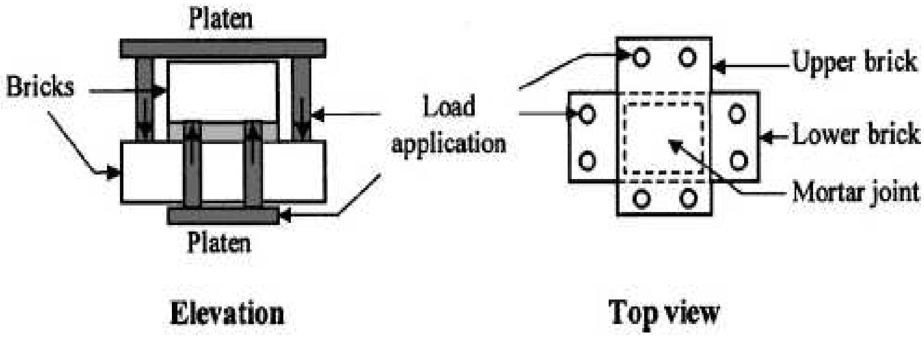


Figure 2.9 Crossed couplet tensile bond test setup

Khalaf (2005) proposed a new test for determining masonry flexural bond strength (Figure 2.10). Brick specimens were constructed with two bricks in a Z-shaped configuration, and three-point loading was applied to cause a flexure failure. Equations were derived to calculate the bond strength, with two assumptions being used for the induced stress distribution at the brick-mortar interface: linear stress distribution and parabolic stress distribution. The results showed that the new testing method could efficiently determine flexural bond strength.

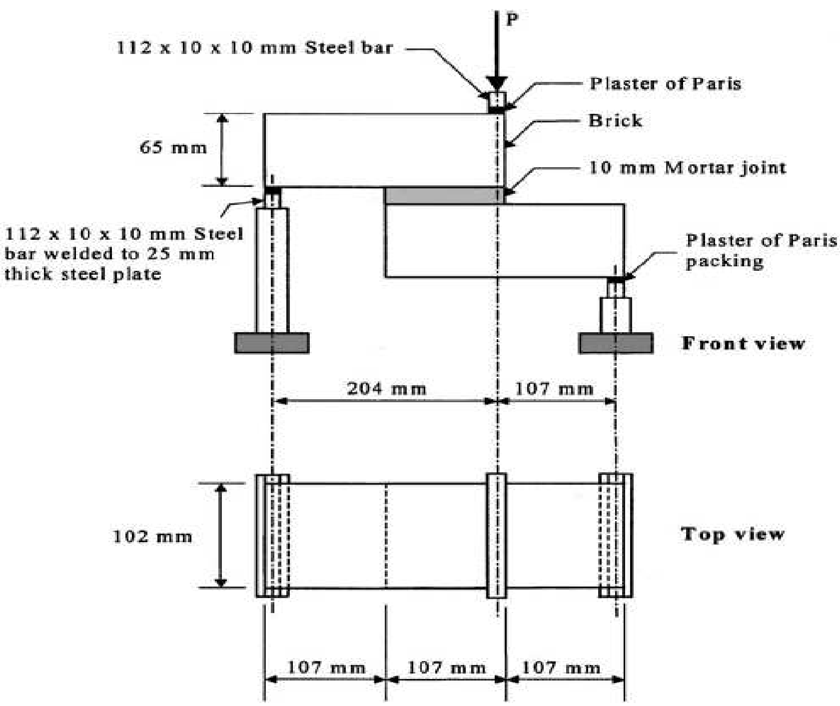


Figure 2.10 Test setup for Z-shaped specimens
(Khalaf 2005)

Sarangapani et al. (2005) reported a modified bond wrench test setup for investigating brick-mortar flexural strength with five-brick-high stack bonded prisms (Figure 2.11). Load was applied on the top brick of the prism through a pulley and clamping brackets, which produced a moment and triggered a flexure failure in the prism. This setup was used in an attempt to address concerns about the non-uniform stress state of the joints close to the grips in the conventional bond wrench test set-up. However, only one value of flexural bond strength is obtained for each prism in this modified set-up, moreover, there is a preference for the mortar joint failure which is away from the clamping grips.

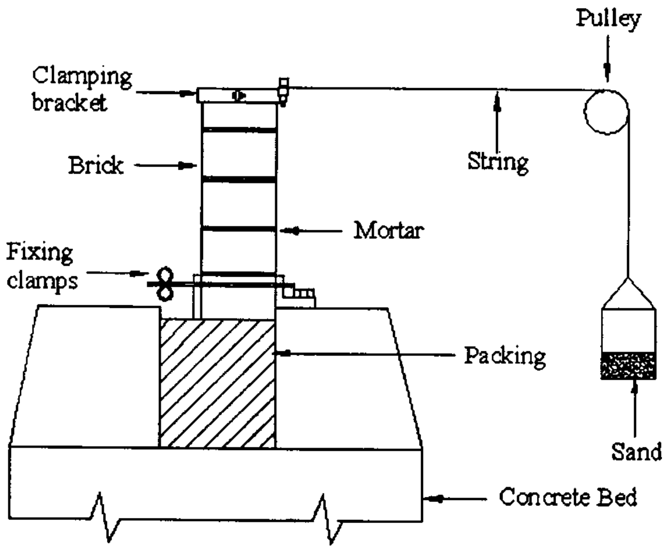


Figure 2.11 Modified bond wrench test setup (Sarangapani et al. 2005)

2.3.2 Methods used to measure shear strength

Sinha (1983) tested brickwork shear bond with full-scale and 1/6th scale bricks (Figure 2.12). Full-scale bricks were used to study the influence of sand grading on shear bond strength, whilst 1/6th scale bricks were tested in a modified soil mechanics shear box for examining the effect of brick moisture content at laying and compression load on brickwork specimens during the curing period.

Marzahn (1996) tested the shear-bond behaviour of small masonry specimens constructed with sand-lime bricks and clay bricks (Figure 2.13). The shear failure criteria of wall panels and different test arrangements for small specimens were summarised. By comparing unreinforced masonry, grouted masonry, and vertically reinforced masonry, some general proposals for prediction of shear strength were given. Shear failure in the joints was initiated in the mortar by joint slip at higher brick compressive strength, but at lower brick compressive strength shear failure was initiated by compression failure within the brick. Marzhan stated that the holes and gaps of perforated clay bricks enable smoother failure behaviour because the webs of the holes fail step wise rather than suddenly. In the study, the author also conducted experiments to determine the shear strength of mortar prisms in order to predict the shear strength of the masonry (Figure 2.14). The test has not been widely adopted by other researchers.

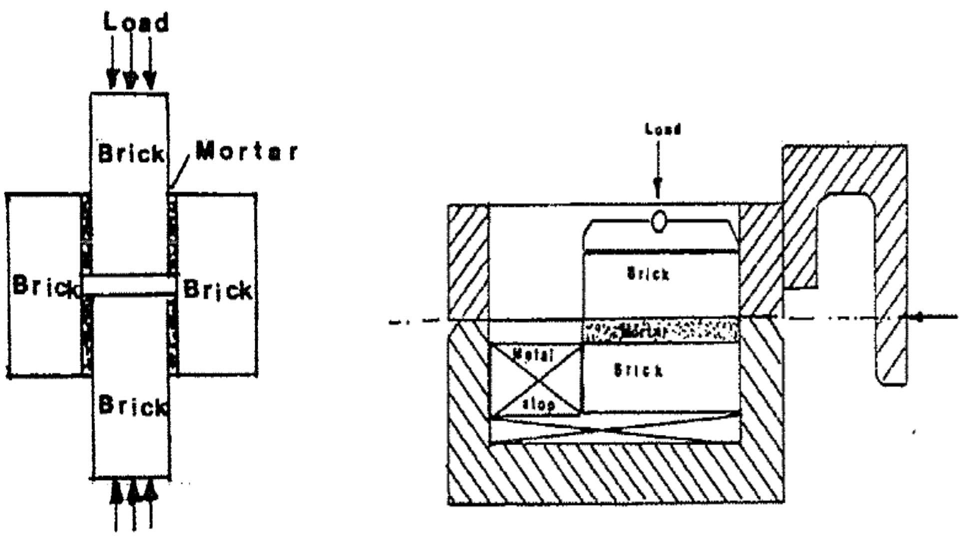


Figure 2.12 Shear bond test using full-scale (left) and 1/6 scale (right) bricks (Sinha 1983)

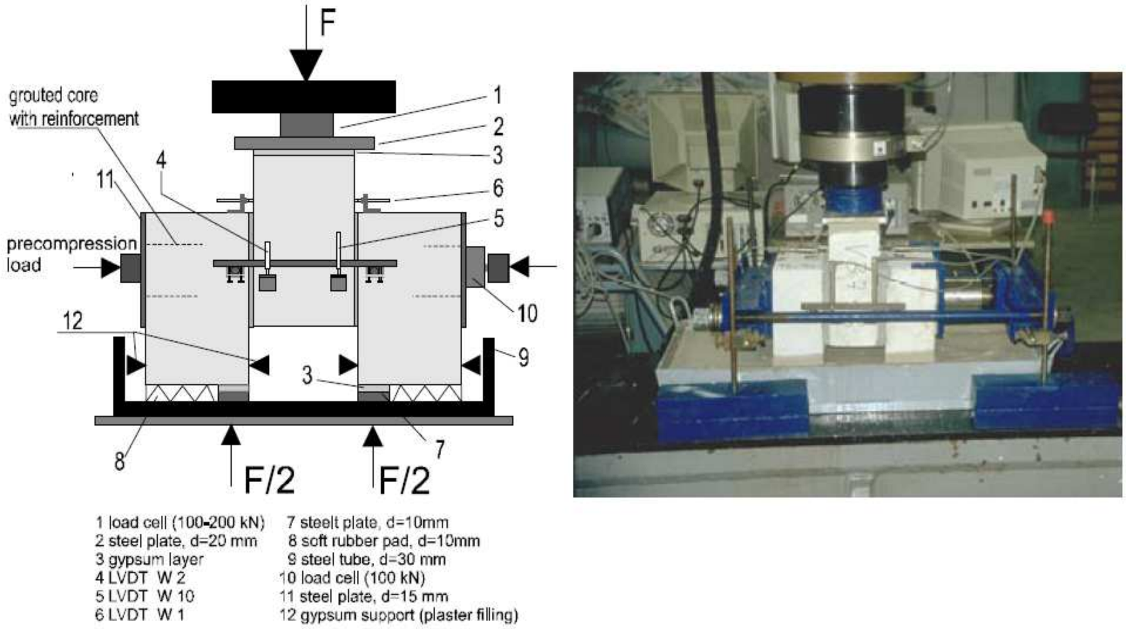


Figure 2.13 Testing arrangement with prestressing (Marzahn 1996)

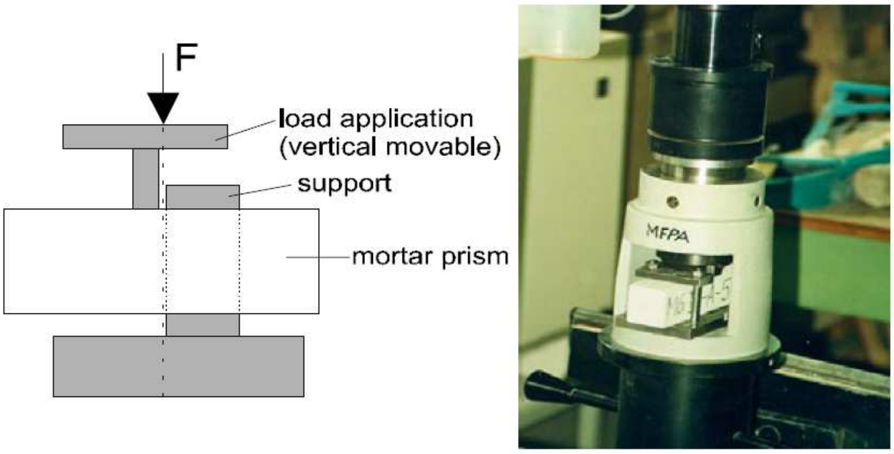


Figure 2.14 Determination of mortar shear strength

Lourenco et al. (2004) discussed the different test methods to determine shear performance: the couplet test; the van der pluijm test; and the triplet test (Figure 2.15) and stated that none of them can produce an absolutely uniform distribution of normal and shear stresses. However, as the triplet has been the standard test in Europe, it was selected and then improved to use in testing stack-bonded masonry wallette (Figure 2.16).

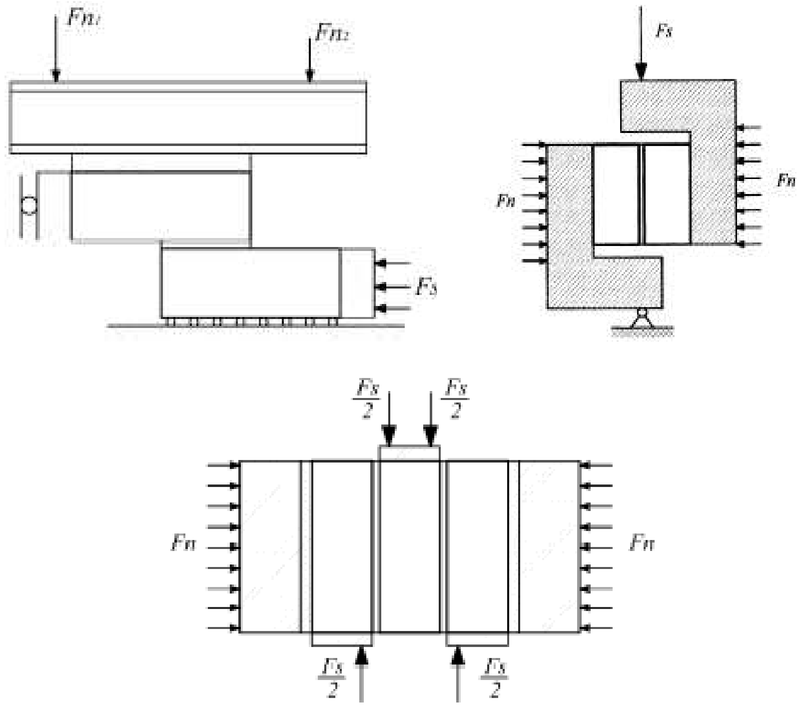


Figure 2.15 Shear tests: (a) couplet test (b) van de pluijm test (c) triplet test (Lourenco et al. 2004)

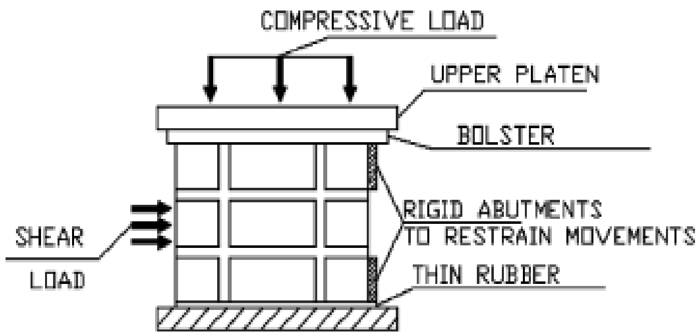


Figure 2.16 Shear test setup of stack bonded masonry

Sarangapani et al. (2005) reported on a study of brick-mortar shear bond strength using the test setup shown in Figure 2.17. The top and bottom bricks were restrained by steel blocks and the brick in the middle was gradually loaded until the bond in the triplet specimen failed. In this approach shear bond strength is determined without pre-compression; one brick triplet specimen gives one test result, unlike in British Standard, one initial shear strength (pre-compression load is zero) is obtained by linear regression of at least nine specimen tests (detailed in Section 3.5.4)

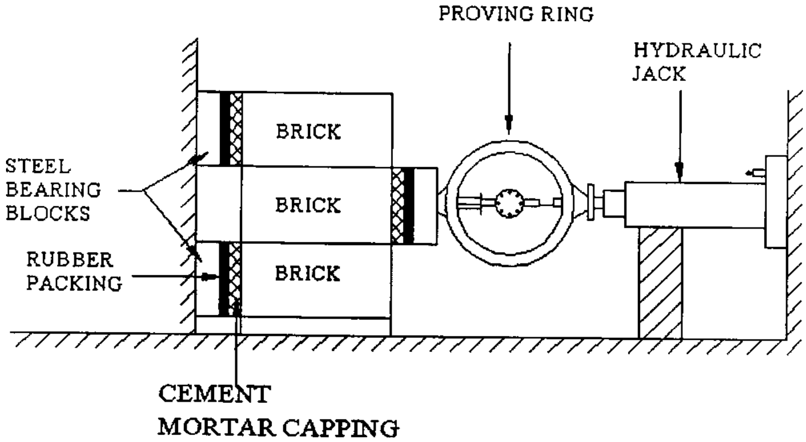


Figure 2.17 Shear bond test setup
(Sarangapani et al. 2005)

Gabor et al. (2006) presented a numerical and experimental analysis of the in-plane shear behaviour of hollow brick masonry panels. In order to determine shear behaviour parameters, a test method using specimens in double shear has been employed (Figure 2.18). The experimental device can simultaneously apply a constant horizontal load and a steadily increasing vertical shear load to the specimen during tests.

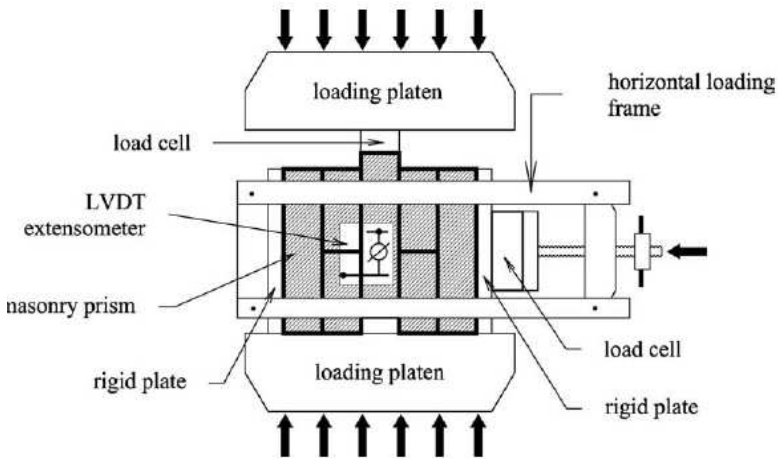


Figure 2.18 Experimental setup for shear test on masonry prism
(Gabor et al. 2006)

Reddy et al. (2007) explored different methods for improving the shear-bond strength of soil-cement block masonry and researched the influence of shear-bond strength on masonry compressive strength (Figure 2.19). Rough textured blocks can yield a higher shear-bond strength compared to blocks with a plain surface. Use of surface coatings, like cement slurry coating and epoxy coating, significantly increases the shear-bond strength, but the introduction of frogs is not effective. In situations where the masonry unit modulus is greater than that of the mortar, compressive strength and stress-strain characteristics of the soil-cement masonry are not significantly affected by the variations in shear-bond strength.

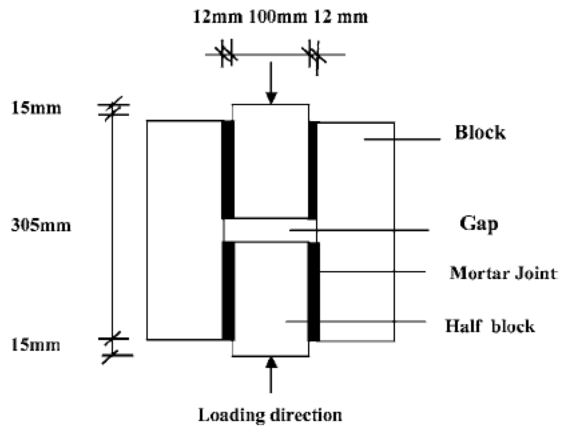


Figure 2.19 Triplet specimen for shear-bond strength
(Reddy et al. 2007)

2.4 Previous research on masonry bond strength

Bond between unit and mortar generally is weaker than masonry units themselves. Achieving a good bond is an important aspect of masonry construction. Adequate bond strength is required not only for masonry possessing sufficient resistance to lateral loads such as wind and earthquake, but is also a necessity for preventing rain penetration and restricting cracks as the requisite of serviceability and durability of structures.

A number of investigations, addressing various aspects of bond development between masonry unit and mortar at the macro and micro level, can be found in the literature. However, although almost all investigations pertain to cement or cement: lime mortar, previous research provides a good background for studying the bond properties of hydraulic lime mortar based masonry.

2.4.1 Introduction

Most previous studies worked on load bearing performance of masonry, whilst some referred to weather resistance such as rain penetration of masonry (Ritchie and Davison 1962, Boynton and Gutschick 1964, Borchelt and Tann 1996, Borchelt et al. 1999). Early researchers such as Boynton and Gutschick (1964) have already recognised and summarised numerous factors having effect on masonry bond strength, extent of bond (brick surface area to which mortar adheres to) and bond durability of masonry. Other researchers (Goodwin and West 1982, Sinha 1983, Groot 1993, Lawrence and Page 1995, Sugo et al. 2001) also reviewed on the influencing factors of masonry bond.

The literature is mainly focussed on the properties of mortar and masonry unit. Mortar properties having been studied include (Ritchie and Davison 1962, Boynton and Gutschick 1964, Sinha 1983, Venu Madhava Rao et al. 1996, Borchelt et al. 1996, 1999, Choubey et al. 1999, Sugo et al. 2001, Venkatarama Reddy and Gupta 2006):

- Mortar constituent material characteristics, mix proportions, water retention, mortar strength, initial flow and air content.

Masonry unit characteristics cited as influencing bond include (Ritchie and Davison 1962, Boynton and Gutschick 1964, Grandet et al. 1972, Sinha 1983, Lawrence and Cao 1988, McGinley 1990, Groot 1993, Lawrence and Page 1994, De Vitis et al. 1995, Venu Madhava Rao et al. 1996, 2007, Borchelt et al. 1996, 1999, Choubey et al. 1999, Walker 1999, Sugo et al. 2001, Sarangapani et al. 2002, Fouad 2005, Mukhtar and Beck 2006, Venkatarama Reddy and Gupta 2006):

- Water absorption characteristics, moisture content of unit at the time of construction, bedding surface of masonry unit such as surface texture and frog depth and size, pore size and distribution and mineralogical composition.

Other parameters were also reviewed (Ritchie and Davison 1962, Boynton and Gutschick 1964, Sinha 1983, Lawrence and Page 1995, De Vitis et al. 1995, Choubey 1999, Lawrence and Page 1995, Sugo et al. 2007):

- Age.
- Workmanship: time interval between laying mortar and placing brick, filling or fullness of joints, mortar joint thickness, pressure applied on brick during construction and elapsed time before re-tempering mortar, dust on the units.
- Environmental factors: temperature, humidity, and curing procedures.

The following review considers previous work on material and methodological differences of masonry bond strength. However, most research has been conducted with cement mortars; to date there has been little investigation into bond developed by lime mortared masonry.

2.4.2 Influence of mortar properties on bond performance

A great deal of research in the literature has worked on benefits of including air-lime in cement based mortars. Previous work (Ritchie and Davison 1962, Boynton and Gutschick 1964, Gazzola et al. 1985, Lawrence and So 1994, Venu Madhava Rao et al. 1996, Borchelt et al. 1996, 1999, Sugo et al. 2001, Bokan Bosiljkov 2001, Sarangapani 2002, Schofield 2005, Tate 2005) has commented that air lime, when added to cement and sand mixes, increase mortar workability, water retention, cohesion and adhesion, and therefore improve bond development between brick and mortar.

Ritchie and Davison (1962) studied the effect of mortar properties on brick wall panels, using 1:1:6 cement: lime: sand constructed with medium suction bricks (approximately 1.0 $kg/m^2/min$). Both bond strength and resistance to water penetration of brickwork considerably increased with the flow ability of fresh mortar (up to the highest flow if it is still workable). The increase of water retention by adding lime in mortar, combined with bricks (suction approximately 2.2 $kg/m^2/min$), also significantly improved the masonry bond strength and the resistance to moisture penetration.

Boynton and Gutschick (1964) reviewed a range of mortar properties such as mortar strength, water retention, flow ability and air content, influencing on masonry bond strength, bond extent (percentage of adhesion between brick-mortar) and durability (resistance to cracking and water penetration). Several studies, including Palmer and Parsons (1934), Structural Clay Products Institute (1961), Redmond (1962) and Fishburn (1961, 1964), were summarised. It is concluded that bond strength generally increases with cement mortar strength, but it may be reduced when high strength mortar contains a very low content lime, especially when high absorption bricks are used. The researchers agreed that addition of lime to cement mortar improved mortar water retention, plasticity and inherent cohesion, which played an important role in bond formation. High initial mortar flow (without affecting workmanship) improved bond strength development, whilst high air content was detrimental to bond as microscopic bubbles prevent mortar from contacting with the brick at the interface. Extent of bond was mainly examined by wall leakage test. The contribution of lime in cement mortars enhanced the fullness of the joint and bonding with the brick. The slow hardening and elasticity of cement lime mortar helped to reduce generation of cracks and the self-healing ability of the lime to improve the durability of the masonry bond.

Sinha (1983) assessed the effect of sand grading on brickwork bond tension and bond shear strengths. Three sands with fineness modulus (determined by adding the cumulative percentage retained on each of a specified series of sieves and dividing the sum by 100) 2.27, 1.95 and 1.23 respectively, were used in 1:1.25:3 cement: lime: sand mortars, combined with three types of bricks with different water absorption (Total Water Absorption (TWA): 6.5, 15.0 and 25.6% and IRA: 0.93, 1.74 and 2.57 kg/m^2/min respectively). For each brick bond shear strength was consistently higher than bond tension strength. The influence of sand grading on both bond strengths was significant; the medium fineness modulus sand with well-graded particle size distribution achieved greatest bond strength, and the coarsest sand with the highest fineness modulus developed stronger bond than the finest sand.

Lawrence and So (1994) studied the influence of sand type, mortar mix and air content on flexural bond strength of stack-bonded brickwork. Commonly used materials in the Sydney region in Australia, including six sands, five mortar mixes and three types of bricks, were chosen. The mortar mix with lime developed consistent good bond with all sand types, whilst the bond strengths using mortar without lime were significantly affected by brick properties; high suction brick (IRA 7.36 kg/m^2/min, TWA 10.1%) in some cases showed severe bond strength reduction with high strength lime-free mortar (same as Boynton and Gutschick concluded), compared to the relatively medium and low suction bricks (IRA 3.00 kg/m^2/min, TWA 5.0% and IRA 0.39 kg/m^2/min, TWA 4.5% respectively). The results also concluded air entrainer, used for increasing mortar workability but commonly overdosed, caused considerably reduced bond wrench strength with the bricks. This effect of overdosing air entraining additives on bond development is much like the study of excessive use of fireclay as plasticiser (Page 1992); bond decreased remarkably with fireclay content.

Venu Madhava Rao et al. (1996) performed an experimental study on bond wrench strength. Masonry units, including stabilized mud blocks, stabilized soil-sand blocks and fired clay bricks, combined with five mortars, were studied. For the three cement: sand mortars (1:4, 1:6, 1:10) flexural bond strength increased with cement content and the resultant mortar strength, irrespective of masonry unit types. Test results showed that the two combination mortars: cement: soil: sand (1:1:6) and cement: lime: sand (1:1:10) consistently improved bond strength, irrespective of unit types. This is attributed to the better particle grading of mortar with the presence of soil or lime, which increases mortar water retentivity and facilitates the brick-mortar bond development at the interface.

Choubey et al. (1999) investigated flexural bond strength of wall panels using calcium silicate bricks. With cement mortar mixes changing from 1:3 to 1:4.5 and 1:6 (by volume), the reductions of flexural 'parallel to bed joint ' strength were approximately 19-35%, and flexural 'perpendicular to bed joint ' strength decreased even more, 21-52%. Flexural bond strengths reduced by 36-44% with the sand fineness modulus decreasing from 2.96 to 2.03.

The above studies on the parameters influencing bond development in cement mortar masonry mainly include initial flow, air content and mortar strength. The benefits of combination mortars (mostly by adding lime) in cement mortar are indicated. Cement lime mortar can achieve higher bond strength than stronger lime-free cement mortar, especially when high absorption brick is used. Bond strength generally increases with mortar initial flow and decreases with air content.

Little research has been conducted on bond characteristics of lime mortared masonry. Bokan Bosiljkov (2001) performed bond wrench testing on brick couplets constructed with solid fired clay brick and 1:3 (by volume) mortar mixes using hydrated lime, industrial lime putty, and traditional lime putty with and without additives and fibres. The strength results ranged between 0.09 and

0.24 N/mm^2. Masonry using hydrated lime and industrial lime-putty mortar developed similar bond strength, whilst traditional lime-putty mortar achieved higher bond strength. Using small amounts of additives can increase or decrease the bond strengths, which depends on the type and amount of added pozzolanic material and the uniformity of the pozzolanic particles distribution in the mortars.

Pavía et al. (2010) studied flexural bond strength of clay brick combined with NHL 2, NHL 3.5 and NHL 5, concentrating on the influence of mortar water retention, water content, flow value, workability and binder hydraulicity. Nine mortars with 1:2.5 binder: aggregate (by weight) and varied initial flows of 165mm, 185mm and 195mm, were used. The 24-h total water absorption of the brick used for the study was 10.7%, but with a high IRA value of 3.22 kg/m^2/min. The bricks were immersed in water for up to 20 minutes before construction in order to attain a moisture content of approximately 70% of saturation. The average flexural bond strength at 28 days achieved 0.28 N/mm^2, 0.34 N/mm^2 and 0.42 N/mm^2 for NHL 2 mortar with flow values 165, 185 and 195 mm respectively; NHL 3.5 mortar developed 0.20 N/mm^2, 0.59 N/mm^2, 0.61 N/mm^2 and NHL5 mortar reached 0.32 N/mm^2, 0.50 N/mm^2, 0.48 N/mm^2 respectively for the corresponding flows. The high water retention of NHL mortars (94.2%~99.5%) helped mortar bond with brick. As Ritchie and Davison noted, bond strength improved with mortar flow up to its workable limit. In this study results indicated mortar water retentivity had a more significant influence than lime hydraulicity on bond strength.

2.4.3 Influence of masonry unit properties on bond performance

Research on the influence of mortar characteristics on masonry bond has been summarised in the previous section. However, it is well known that brick type has a significant influence on the resultant bond performance. A number of researchers (see 2.4.1) have investigated the influence of masonry unit on masonry bond development. The unit properties studied mainly include material characteristics (clay, calcium silicate, concrete and stone), surface texture, water absorption, initial rate of absorption (suction) and moisture content at laying. The initial dewatering of fresh mortar during construction, caused by the suction from masonry unit, is widely recognised as a vital factor in determining the quality of final masonry bond (Ritchie and Davison 1962, Boynton and Gutschick 1964, Goodwin and West 1982, Gazzola et al. 1985, McGinley 1990, Lawrence and So 1994, Borchelt et al. 1996, 1999).

Ritchie and Davison (1962) investigated the influence of brick IRA on masonry bond. Test results showed (Figure 2.20) greatest bond strength was achieved with brick suction ranging 10-20 g/ 30in.^{2}/min (0.52-1.03 kg/m^2/min), and the strength dropped rapidly once the suction exceeded 30 g/ 30in.^{2}/min (1.55 kg/m^2/min). Comparative testing was performed for examining the effect of wetting high suction bricks (varying from 38-75 g/ 30in.^{2}/min (1.96-3.87 kg/m^2/min)). Results indicated that wetting bricks significantly improved bond strength and reduced the quantities of water passing through wall panels during leakage testing. A comparison between bond strength of perforated and solid low suction bricks (using the same material and manufactured at the same plant) was also conducted. Wall panels with solid bricks achieved much higher bond than bricks with holes. The difference in bond performance was more than the perforation effect caused by the reduced contact surface area.

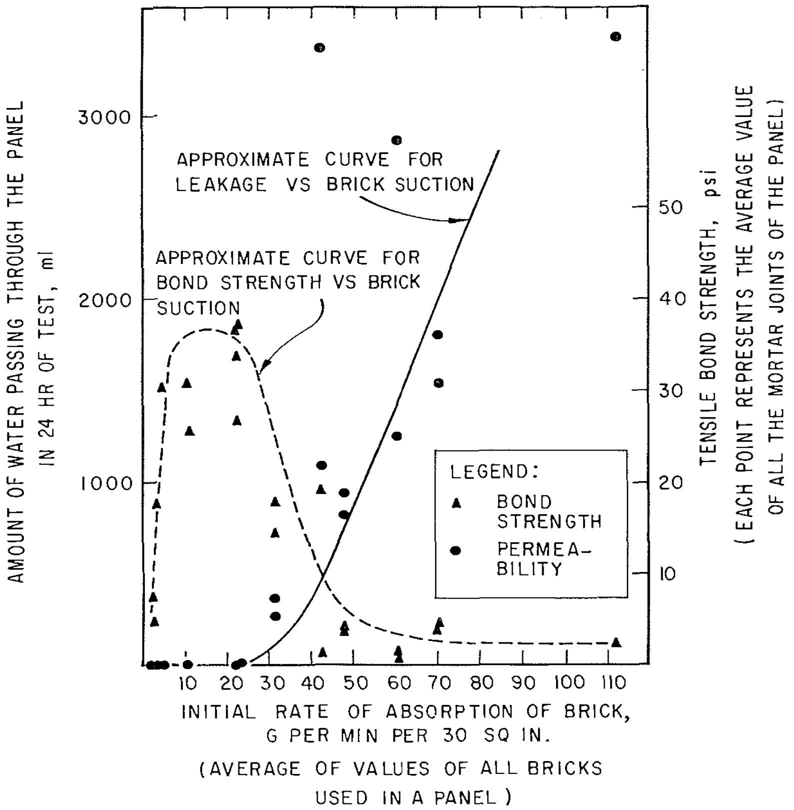


Figure 2.20 Influence of brick suction on bond strength and water permeability of wall panels (Ritchie and Davison 1962)

Boynton and Gutschick (1964) summarised previous studies on masonry bond and concluded that brick water suction and unit texture have significant influence on bond strength. The research by Palmer and Parson (1934) and by the Structural Clay Products Institute (1961) was reviewed. Palmer and Parson established the relationship of bond strength to brick suction and mortar mixes (Figure 2.21). It shows medium absorption bricks achieve higher bond strength than low and high absorption bricks, bricks with IRA around 20 g/ 30 in.^{2}/min (1.03 kg/m^2/min) obtaining maximum strength. The Structural Clay Products Institute proposed similar point of view and stated that bricks with IRA at laying ranging between 5-20 g/ 30in.^{2}/min (0.26-1.03 kg/m^2/min) develop better bond. High IRA bricks (over 60 g/ 30in.^{2}/min or 3.09 kg/m^2/min) develop very poor bond and require wetting before use, whilst low absorption bricks (low than 5 g/ 30in.^{2}/min or 0.26 kg/m^2/min) better use mortars with low water content and good retentivity. Boynton and Gutschick affirmed unit surface texture (such as roughness degree) has significant effect on bond strength, like wire-cut or textured units develop better bond than smooth die-skin surfaced units.

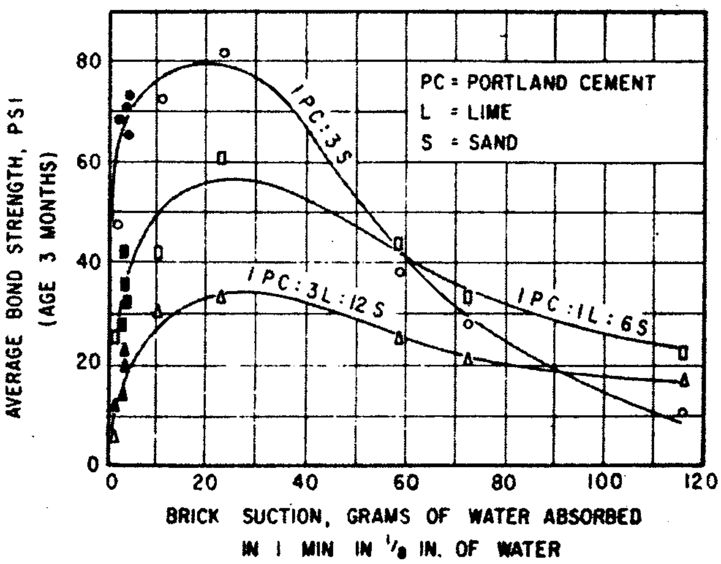


Figure 2.21 Relationship of flexural bond strength to brick IRA and mortar composition
(Palmer and Parsons 1934, cited by Boynton and Gutschick 1964)

McGinley (1990) studied the influence of brick IRA on bond strength of masonry. Ten wire-cut extruded clay and shale bricks, with a wide range of IRA 0.14-2.00 kg/m^2/min (corresponding 5-h boil water absorption ranges 5.6-11.2 % and 24-h immersion water absorption ranges 4.0-8.4%), were combined with type N and S (cement: lime: sand 1:1:6 and 2:1:9 respectively) pre-packaged masonry cement mortars for construction of seven-brick high stack bonded specimens.
Test results show an optimum range of IRA for bricks achieving high bond strength (Figure 2.22). For bricks outside this range, with either low or high IRA, bond strength is significantly reduced. This is explained by McGinley that low IRA brick absorbs less mortar paste interlocking into the brick pores close to interface, whilst high IRA of brick causes mortar micro-cracking at the interface when hardening. The optimum ranges of brick IRA reckoned in this research are 5-10 g/ 30in.^{2}/min (0.26-0.52 kg/m^2/min) for type N mortar and 5-15 g/ 30in.^{2}/min (0.26-0.77 kg/m^2/min) for type S mortar. The ranges are narrower than other research work, which is attributed to the low flow of mortar used in

this research. The compatibility between mortar flow ability and brick suction is required for developing good bond at the brick-mortar interface.

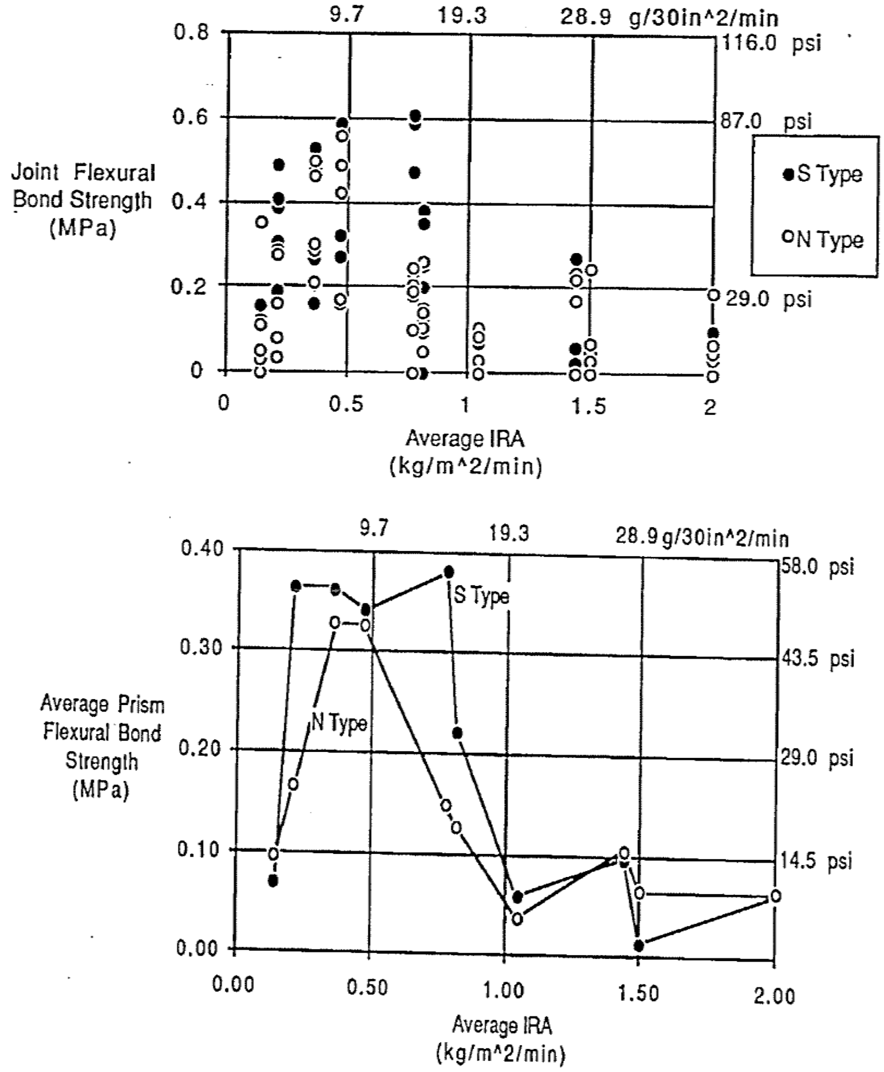


Figure 2.22 Relationship between flexural bond strength and IRA of bricks (McGinley 1990)

There is some other research work, such as Lawrence and So (1994), reaching the same conclusion as above: brick absorption is an important factor influencing bond strength development. There is an optimum range for the water absorption of bricks achieving high masonry bond, and outside the range, either low or high absorption bricks develop low bond. To summarise, the above various recommendations on optimum IRA range are generally in 5-30 g/ 30in.^{2}/min (0.25-1.55 kg/m^2/min).

Borchelt and Tann (1996) studied brickwork bond strength with using low IRA bricks (less than 5 g/ $30in.^2$/min or 0.26 kg/m^2/min). Two low suction bricks with IRA 1.0 and 4.3 g/ $30in.^2$/min (corresponding to 0.05 and 0.22 kg/m^2/min respectively) were compared with a medium IRA brick (15.1 g/ $30in.^2$/min or 0.78 kg/m^2/min). Seven mortar mixes including Portland cement lime, mortar cement and masonry cement, were used. Results showed Portland cement lime mortar produced consistent bond strength, whilst masonry bond with mortar cement and masonry cement mixes were more dependent on brick types. The research concluded that the decrease of mortar water retention improved the bond strength of low IRA bricks, and a good compatibility between low suction brick and low water retention mortar can achieve higher bond strength than using medium suction brick.

Following the above study, Borchelt et al. in 1999 investigated the flexural bond strength of bricks with IRA higher than 30 g/ $30in^2$/min (1.55 $kg/min/m^2$). Two bricks with IRA 1.85 and 2.38 $kg/min/m^2$ were compared with a medium suction brick (0.76 $kg/min/m^2$, same brick as the above study, but from a later production batch). All bricks were combined with same seven types of mortar as above. The high IRA bricks were constructed dry or wet (15-min water immersion and 5-min drying under laboratory conditions), under bag-curing (enclosed in plastic bags immediately after construction) or laboratory air curing conditions, to examine the effects of curing conditions on bond development.

Results indicated that high absorption bricks are capable of developing bond strength similar to medium absorption bricks. The high IRA bricks did not need to be wetted to achieve good bond when Portland cement: lime mortar was used, but needed to be wetted before use when masonry cement or mortar cement was used. There was no consistent trend observed for the difference between bag-curing and air-curing specimens.

The bond between brick and mortar is a very important property to consider when selecting brick and mortar combinations. The compatibility between the two materials plays a vital role in bond formation. Based on the research by Borchelt et al. (1996, 1999), the Brick Industry Association technical guidance (2006) recommends general rules for the selection of bricks based on IRA values for different mortar types, including Portland cement, mortar cement and masonry cement mortars.

Sarangapani et al. (2002) investigated the influence of brick absorption on flexural bond strength using low-strength high-absorption fired clay bricks with four different cement mortars. The rate of brick water absorption over different periods of time, the transport of water from mortar to brick, and the influence of the duration of brick-mortar contact on the mortar moisture content were examined. The moisture transport from mortar to brick was very substantial with the high absorbent bricks, which led to very low water: cement ratios for mortars one hour after contact with brick, but the cement: lime: sand mortar retained sufficient water for proper hydration with the presence of lime nevertheless. The use of moisture barriers (cement slurry and epoxy coatings) did not help in preventing moisture movement from mortar to brick. Results indicated that the masonry bond strength was correlated with the flexural strength of the weak bricks, which was signified by brick failure rather than failure at the brick-mortar interface. The study recommended that high absorption bricks should be partly saturated before construction to allow proper cement hydration and therefore better bond strength development.

Masonry unit absorption, undoubtedly, is a key factor influencing on bond strength. Work investigating influence of brick water absorption characteristics on bond development has, to date, largely focussed on initial rate of absorption (IRA, suction), total water absorption (24-h immersion test and 5-h boiling test) and more recently sorptivity (Reda Taha et al. 2001a, 2001b, Yuen and Lissel

2009). Total water absorptions only reflect the disparity between dry and fully saturated states of brick. A number of researchers have attempted to track brick absorption through to complete saturation, concluding the one-minute IRA test is not a good representation of the dewatering action of the brick on mortar (Lawrence and Page 1994, De Vitis et al. 1995, Choubey et al. 1999).

Although codes prefer to use suction rate or total water absorption, both measurements have different limitations in describing the absorption performance of masonry units in relation to bond development. No single parameter seems able to completely characterise the complex dynamic (time dependent) interaction with the mortar in bond strength development. Sorptivity test, as a method of measuring water permeability of materials over time, has been used for some porous building materials such as concrete, and nowadays is proposed for brick.

Reda Taha et al. (2001a, 2001b) reviewed the theory of sorptivity and its existed applications. Based on the test method provided by ASTM draft 1996, experiments were performed on eight types of clay bricks. Five oven-dried bricks were tested for each type. Sorptivity test is a method to measure the rate of capillary water action through the pore structure of bricks. The mass of the bricks were recorded at specific time intervals. Relationships between the brick mass change versus the square root of time were established. Results showed sorptivity test is a reproducible measurement, with a low coefficient of variation generally ranging between 4-10%. The total water absorption and IRA tests were also undertaken. However, there was no strong correlation found between these criteria.

In addition to water absorption, other properties of masonry units, such as material composition and frog details on surface, have also been evaluated for their effects on bond development. An experimental study was conducted on flexural bond strength of various blocks and bricks by Venu Madhava Rao et al. (1996). Stabilised mud block, stabilised soil-sand block and fired clay brick were used with various mixes of cement: sand, cement: soil: sand and cement: lime: sand mortars. Irrespective of mortar mixes, the stabilised soil-sand block masonry achieved the greatest bond wrench strength, whilst fired brick developed the weakest bond strength. This can be mainly attributed to different mineralogical compositions of materials and partly correlated to the different depths and widths of frogs on the surfaces of the masonry units.

Sarangapani et al. (2005) made an attempt to enhance masonry bond strength by producing 10 mm deep surface impressions on brick faces, including a number of holes or additional frogs. Flexural bond strength and shear bond strength were examined, using high water absorption clay bricks constructed with several selected cement mortars. Test results indicated that brick surface texture had a significant influence on bond development at the interface, and the additional frogs improved bond strength. Brick surface treatment can be a method for enhancing bond in masonry.

Most studies on the influence of masonry unit properties on bond strength are focussed on water absorption characteristics. Optimum brick suction ranges for achieving high bond strength are suggested (Palmer and Parsons 1934, Ritchie and Davison 1962, McGinley 1990, Lawrence and So 1994). Even though the ranges are quite different for various units, the same trend has been followed: medium absorption bricks achieve greatest bond strength, whilst low and high absorption bricks outside optimum range reduce bond strength. However, the research results conflict with design guidance on masonry. Both BS 5628 (withdrawn in April 2010) and the UK NA to BS 1996-1-1:2005 give higher characteristic flexural strength value to low water absorption bricks (5-h absorption less than 7%) than medium water absorption bricks (5-h absorption 7-12%).

2.4.4 Influence of moisture content of masonry units at laying on bond strength

As previously discussed, water absorption of masonry units has significant influence on bond strength The moisture content of units at laying directly correlated with its absorption capability. Therefore, research on moisture content is important for better understanding bond mechanism and developing good bond in masonry.

Sinha (1983) investigated the influence of brick moisture content before laying on both brickwork bond tension and bond shear strengths, using mortar (1:1/4:3 cement: lime: sand) and 1/6 scale bricks (24-h water absorption: 12.7%, 5-h boiling absorption: 13.8%). To obtain different moisture contents, bricks were dipped in water for different periods of time: 5 sec, 2 min, 5 min, 10 min and 2 hours. The results showed both the tensile and shear bond strengths were significantly influenced by wetting bricks, and the effect on bond tension strength was more substantial.

Sinha suggests that, for given combination of materials, there is likely to be an optimum value of moisture content for developing maximum bond, which were approximately two-thirds of the total 24 hour immersion water absorption value. Although, this is in fact likely to vary with materials, depending on factors such as brick water absorption and mortar water retention property, brickwork bond strength tends to increase for wetter bricks up to the maximum bond, and thereafter the bond strength decreases rapidly until the saturation moisture content of brick is approached when the strength falls off.

Venu Madhava Rao et al. (1996) examined the influence of moisture content of stabilized mud block and fired clay brick on flexural bond strength of masonry. Two mortar mixes, 1:4 cement: sand and 1:1:6 cement: soil: sand mortars, were used. Moisture contents of units were controlled by soaking the units for certain times. Dry and fully saturated units were also tested. The test results corroborated moisture content of masonry units had an apparent effect on masonry bond development. There was different optimum moisture content for each unit type that produced maximum bond strength. The optimum moisture contents at laying were 13% for the fired clay brick (approximately 85% of its total water absorption) and 11% for the stabilized mud block (76% of its total water absorption), As reported by Sinha previously, bond strength fell very rapidly as the moisture content of unit increased beyond its optimum level.

The effect of unit suction rate at laying (corresponding to its moisture content) on the flexural strength of calcium silicate brick masonry was studied by Choubey et al. (1999). For a given brick, nine different values of suction rate were selected by altering the initial moisture content to the brick at laying. Suction rate decreases as brick moisture content increases. Masonry flexural bond strength was highly sensitive to unit suction rate at laying. Maximum bond strength was observed at a suction rate of 0.84 kg/mm^2/min, which corresponds to an immersion time of 10 minutes (two-thirds of the maximum immersion time in the test brick). This roughly corresponds to optimum unit moisture content at laying, for maximum bond, as two-thirds of the maximum absorption of brick, which is consistent to Sinha's earlier conclusion. In Choubey's research, the bond strength when the brick's were laid saturated was roughly one-third of maximum bond strength. It was also mentioned that same conclusion was applied to sand lime bricks and clay bricks.

Walker (1999) performed an experimental study on moisture content effect on masonry bond strength, using pressed earth blocks. Various blocks with different moisture levels were combined with various mortar mixes (cement: lime: sand and soil: cement). Individual optimum moisture content was revealed for each combination of block and mortar for achieving maximum bond strength.

For same type of block constructed with various mortars, optimum moisture content varied roughly 40-70% of its total water absorption; the better water retentivity the mortar used has, the lower the optimum moisture content is. Various blocks, combined with same 1:3:12 cement: lime: sand mortar, had different optimum moisture contents (ranging 40-70% of their total water absorption) for maximum resultant bond strength.

Venkatarama Reddy and Gupta in 2006 also investigated the influence of moisture content of soil-cement block at laying on flexural bond strength. Three blocks with varied cement contents, and four types of mortars including cement: soil, cement: sand and cement: lime: sand, were used. As reported by Walker, different optimum moisture content was required for different combination of block and mortar achieving maximum bond strength. For the three blocks, optimum moisture content ranged from 50% to 75% of their corresponding total water absorption. Dry and saturated blocks developed reduced strength, approximately 20-55% of maximum bond strength, but with different reasons. Dry units quickly absorb water from fresh mortar resulting incomplete mortar hydration, whilst saturated units prevent mortar hydration products from penetrating into the pores of unit surface. Both situations impede effective bond formation at the interface.

The studies reviewed above have some common points:

- Moisture content of masonry units at laying has a significant influence on bond strength.
- Dry and saturation significantly reduces flexural bond strength, whilst partially saturated units achieve maximum masonry strength value. The optimum moisture content is dependent on the masonry unit and mortar used.

- Bond strength improves with moisture content increase; peak bond strength is achieved with the optimum unit moisture content; bond strength falls rapidly after moisture content increases beyond the optimum value.

2.4.5 Other studies on bond performance

In addition to mortar and unit properties, many other parameters have also been considered to influence bond development in masonry (Ritchie and Davison 1962, Goodwin and West 1982, Sinha 1983, Lawrence and Page 1994, 1995, Borchelt et al. 1999, Sugo et al. 2007). These include:

- **Workmanship**: surface cleanliness of masonry unit, time interval between spreading mortar and laying brick, tapping impact when bricks are bedded in mortar, mortar re-tempering before use, mortar joint thickness, curing procedure, ambient temperature and humidity, pre-compression load on brickwork assembly.
- **Age:** curing time of specimens before testing.

Ritchie and Davison (1962) studied the influence of workmanship during construction on masonry bond, including time interval between laying a bed of mortar and placing the brick, the tapping pressure given to bricks during construction, the elapsed time before re-tempering mortar for use and mortar joint thickness. Bond strength decreased rapidly with the time interval increasing from 30 to 60 to 90 seconds, same with the masonry resistance to water penetration. The study on water penetration of masonry showed most of leakage was through the interface between brick-mortar, with only a tiny quantity of water passing through the bricks, which stresses the importance of bond formation at the interface for the durability of masonry.

The tapping effect was examined by comparison between using different weights of hammer and a bricklayer's normal work. Walls built by the bricklayer obtained the highest bond strength, and brickwork used the heavier hammer achieved higher strength than the ones made by the light hammer. The influence of the interval time before re-tempering mortar for construction was studied with medium suction brick (around 0.8 $kg/m^2/min$) and 1:1:6 cement: lime: sand mortar. The mortar used immediately after mixing developed highest bond strength, and the longer mortar stood before re-mixing, the lower the bond of brickwork obtained. The study on the effect of joint thickness was performed by varying from 15 to 6 mm, in steps of 3 mm. The test indicated bond strength decreased with thinner mortar joints.

Boynton and Gutschick (1964) overviewed some research masonry bond development. The review, in addition to the work by Ritchie and Davison (1962), supplemented moving or tapping unit after mortar has started hardening was detrimental to bond formation. Ritchie and Davison as well as Boynton and Gutschick pointed out that the bond extent (effective contact area) between brick and mortar does not always correlate with bond strength. Masonry with high bond strength may have incomplete bond extent, which results in weak resistance to rain penetration, whilst full extent at the interface may develop low bond strength, although there is interaction between the two. Thus good bond in masonry relates to several aspects such as bond strength, bond extent as well as good weather (water) tight joints.

Test standards for measuring flexural bond strength of masonry require the application of a dead weight pre-compressive stress of $2.0\sim5.0\times10^{-3}$ N/mm^2 on specimens throughout curing period (BS EN 1052). Sinha (1983) explored the influence by varying the pre-compression load on specimens. Stress levels applied on brick couplets increased incrementally up to 55 kN/m^2, which was equivalent to the loading by one-storey height brickwork. Test results showed there was no significant influence on the resultant masonry performance of bond tension and bond shear strengths.

In an investigation on flexural bond strength of calcium silicate brick masonry by Choubey et al. (1999), the flexural strengths were reduced by 20-35%, with mortar joint thickness increasing from 10 mm to 15 mm (contrary to Ritchie and Davison's earlier statement). Moreover, bond strength of the 10 mm thick joint masonry, when coarser sand in mortar mixes changed to finer sand, reduced more significantly than the 15 mm bed joint masonry. The thinner the mortar joint is, the more apparent the effect of sand fineness modulus on masonry bond.

De Vitis et al. (1995) investigated the influence of age on the development of bond wrench strength, using four masonry unit types (extruded clay, dry pressed clay, concrete and calcium silicate) and two mortar types (1:1:6 cement: lime: sand and 1:5 cement: sand + water thicker Dynex), tested at 12 different ages. Short term tests were undertaken at 1, 2, 4, 8 hours and 1, 2, 3, 7 days, whilst longer term tests were performed at 7, 14, 28 days, 3 and 6 months.

For the short term tests, mean bond strength in all cases increased with age. Coefficients of variation (CV) ranged from 9-33%. The long term tests generally exhibited increasing bond strength (CV ranged 11-30%) even though strength reduction sometimes appeared. In Australian Standard AS 3700-2001, 7-day bond strength is used in masonry design, whilst results of this study indicated 7-day strengths were on average 65% of their corresponding final strengths. A statistical expression of the relationship between bond strength and age was proposed for each unit type. Investigation on the long-term (up to 7 days) absorption of the four units indicated water absorption took around 1 day to complete except for the calcium silicate brick which took 4 days. The bond formation process at the brick-mortar interface takes much longer time than one minute, and therefore IRA test is not a good indicator for describing the unit suction characteristics.

The long-term bond strength development and mortar microstructure were investigated by Sugo et al. (2007). A 1:1:6 cement lime mortar combined with dry pressed clay masonry units were tested at 3, 7, 28, 90, 180 and 365 days by small-scale uniaxial tension on 25 mm diameter cores taken from brick couplets. As with the study by De Vitis et al. (1995), significant variation in bond strength was observed. The maximum strength was achieved at 180 days, 32% higher than the 7-day value used for design. Significant bond reduction appeared at 90 and 365 days, about 8% and 21% respectively stronger than the 7-day strength. Variations of bond strength were noticed for all ages (CV ranged 12-22%), and there was an overall bond increase with age, even though a poor correlation exhibited between data points and their linear regression. The microstructure of mortar paste at each age was studied with using scanning electron microscopy (SEM) and X-ray diffraction techniques. However, there were no significant differences observed for the mortar microstructures between 28 and 365 days, and the bond strength changes over this period of time could not be explained in this study.

2.4.6 Studies on hydraulic lime mortared masonry

At present, there is a lack of systematic investigations on masonry properties using hydraulic lime mortars. Not much relevant research has been published to date. Hughes and Taylor performed the first experiments in 2005. The University of Bristol led the STI LINK Project (2007) ‘Engineering with lime’ that included some lime mortared masonry tests. NHBC Foundation in Dec. 2008, together with BRE and the Building Limes Forum, published a draft for development standard on NHL mortared masonry based on the STI Link project work.

Hughes and Taylor (2005) investigated the compressive and flexural strengths of wall panels by using high absorption brick (20-24% water absorption) and two types of quicklime, moderately hydraulic and dolomitic-hydraulic lime (produced from Blue Lias (BL) and Charlestown (CH) limestones respectively). Mortars were mixed by mass batching (calculated with 1:3 dry hydrate produced from quicklime: sand by volume) and prepared as hot-lime (dry-slaking) mixes with medium-coarsely graded 'Clodach building' sand using the dry-slaking method.

The compressive strength of BL quicklime mortar at 28 days ranged between 1.5-2.4 N/mm^2, whilst CH mortar ranged between 2.2-3.2 N/mm^2. Both mortars developed strength with curing time and increased average 25% higher strength up to 73 days, achieving 2.4-2.5 N/mm^2 and 3.2-3.5 N/mm^2 for BL and CH mortars respectively.

Difficulties were experienced with some brickwork specimens during curing, caused by late hydration and expansion of lime due to insufficient hydration with the underdeveloped hot mixing technology. Up to 73 days, the masonry made with BL mortar developed compressive strength between 1.72-2.72 N/mm^2, much lower than the CH mortared masonry ranging between 4.20-7.34 N/mm^2. Masonry flexural strength parallel to bed joints achieved 0.08 and 0.16 N/mm^2 (only two results obtained) for BL mortar, whilst between 0.09 and 0.26 N/mm^2 for CH mortar. Masonry flexural strength perpendicular to bed joints ranged 0.06 and 0.15 N/mm^2 for BL mortar, whilst CH mortared masonry developed 0.20 N/mm^2 (only one result).

The experimental results of masonry were compared with the predictions from

BS 5628 (withdrawn in 2010). The compressive strength, flexural strengths parallel and perpendicular to bed joints, achieved 12-48% of the predicted values for BL mortar, and 25-79% of the predicted strengths for CH mortar. The large discrepancies, together with the significant variations of the test results, were attributed to the unsound quicklime dry slaking technology, the inconsistent workmanship produced by trainee masons and also probably the insufficient wetting for some of the high absorption bricks before construction.

The STI 'Engineering with Lime' team presented some strength results of hydraulic lime mortar and the mortar based masonry walls at the Exeter Sumacon conference in March 2007. The results are shown below (Table 2.1). The research worked on the properties of mortar using NHL 2, NHL 3.5 and NHL 5 limes with different volume ratios from 1:1 to 1:4 (lime: sand). Masonry compressive and flexural (parallel and perpendicular to bed joint) strengths have been determined by using low, medium and high absorption bricks combined with M2 class mortar. Results show the compressive strengths, no matter what type bricks are used, are about double of design characteristic strengths in BS 5628. However, the results of masonry flexural strengths are generally lower than the characteristic strengths given in the current standard UK NA to BS EN 1996. The values are about 26%-46% and 46%-116% of the predicted characteristic flexural parallel and perpendicular strengths respectively. Unlike UK NA to BS EN 1996, compressive strength rather than water absorption of bricks is used in this study for categorising brick types.

Table 2.1 Strengths of mortar and masonry using hydraulic lime

Mortar designation (hydraulic lime mortar)	NHL 2 Lime:sand (by vol.)	NHL 3.5 Lime:sand (by vol.)	NHL 5 Lime:sand (by vol.)	Mean compressive strength (N/mm^2, 91d)	NA to BS 1996-1-1:2005	
					Compressive strength class	Mix designation
HLM 5	---	1:1	1:2	5.0	M4	III
HLM 3.5	---	1:1/2	1:3	3.5	M4	III
HLM 2.5	---	1:2	1:4	2.5	M2	IV
HLM 1	1:2	1:3	---	1.0		
HLM 0.5	1:3	1:4	---	0.5		

(a) Equivalent hydraulic lime mortar mixes and comparison to British Standard

Brick water absorption	Brick compressive strength (N/mm^2)	Wall compressive strength for M2 HL mortar (N/mm^2)	BS 5628 (withdrawn) Wall compressive strength (N/mm^2)	
			M2 mortar	M4 mortar
Low	50	16.6	7.1	8.4
Medium	35	13.9	5.6	6.9
High	30	14.9	5.1	6.3

Brick water absorption	Brick compressive Strength (N/mm^2)	Wallette M2 mortar (N/mm^2)		NA to BS 1996-1-1:2005 M2 mortar (N/mm^2)	
		f_{xk1} parallel	f_{kx2} perp.	f_{xk1} parallel	f_{kx2} perp.
Low	50	0.15	0.82	0.4	1.2
Medium	35	0.16	1.16	0.35	1.0
High	30	0.07	0.37	0.25	0.8

(b) Wall test results vs design characteristic strengths in British Standard (N/mm^2)

The NHBC Foundation guide, although based on limited experimental tests, provides a basis for NHL mortared masonry design. Mortar compressive classes are categorised equivalent to various NHL: sand mix proportions and their mortar compressive strengths at 91 days. Characteristic compressive strength of masonry is given for few combinations, 6.0, 5.0 and 3.5 N/mm^2 respectively for brick with compressive strength 30 N/mm^2 and classes M5, M2.5 and M1 mortar; and 8.0 N/mm^2 for brick strength 75 N/mm^2 and M 2.5 mortar. Characteristic flexural strength values are provided as follows (Table 2.2):

Table 2.2 Characteristic flexural strengths of NHL mortared masonry

Brick water absorption	Mortar strength class: M 2.5 and M 1	
	Plane of failure parallel to bed joints (N/mm^2)	Plane of failure perpendicular to bed joints (N/mm^2)
less than 12%	0.20	0.50
Over 12%	0.10	0.40

2.5 Summary and conclusions

In the literature a number of investigations have been completed. Many variables affecting on bond formation have been identified and examined. In this chapter, previous research on the mechanical properties of lime based mortars, cement mortared masonry and lime mortared masonry are reviewed. Main conclusions are summarised as follows:

1. Binder type and mix proportion play an important role in mortar properties and the resultant masonry bond characteristics. In general the strengths of mortar and masonry bond increase with binder hydraulicity and content. The inclusion on hydrated lime in cement based mortars generally improves workability and bond development.

2. A suitable grain size distribution of aggregate enables higher mortar strength. Chemical composition shows significant contribution to the strength development, for instance, mortar with limestone aggregates exhibit high strength. Round-shaped aggregate causes poor cohesion in mortar mix and a strength reduction in hardened mortar.

3. Water absorption property of masonry unit is a crucial factor affecting bond development in masonry. Initial rate of absorption (IRA) and total water absorption (TWA) are two common indicators having been recognised and analysed. There is no universal acceptance of brick water characteristics in relation to bond development: water absorption is used in the UK (Eurocode 6) whilst IRA is used in Australia. Sorptivity is a relatively new method used for measuring water capillary action in brick.

4. Brick and mortar types have a controlling influence on the brick-mortar bond. It is important to select suitable materials for the compatibility between them. For instance, high absorption brick require mortar with high water retentivity to ensure sufficient water for proper hydration of mortar.

5. Some attempts (Palmer and Parson 1934, the Structural Clay Products Institute 1961, Ritchie and Davison 1962, McGinley 1990, Lawrence and So 1994) have been made to correlate the IRA of masonry units to bond strength of masonry. Various optimum ranges of IRA were given for

achieving maximum bond strength, generally in the range of 0.25-1.55 kg/m^2/min.

6. Moisture content of masonry unit at the time of laying affects the rate of water suction and therefore bond development in masonry. The optimum moisture content of masonry unit is approximately 40~80% of the saturation value and is brick and mortar type dependent. Dry or fully saturated units result in poor bond strength. For a given combination of brick and mortar, the initial moisture in the two materials can be controlled to provide appropriate conditions for mortar hydration and to develop good bond strength.

7. In addition to the properties of mortar and masonry unit, workmanship during construction, curing conditions and age of masonry also produce significant influences on bond development.

Many researchers (Goodwin and West 1982, Lawrence and Page 1995, De Vitis et al. 1995, Groot 1997, Sugo et al. 2001) have also reviewed previous work and developed theories on bond development mechanism. The various mechanisms having been postulated for explaining the observed masonry performance can be summarized as follows:

- Bond between unit and mortar at a micro level is achieved predominantly by the locking crystallisation of mortar hydration products in the pores of masonry unit at the interface.
- The interactive water movement between unit and mortar involved with mortar hydration, brick capillary suction, transport of hydrate products, mortar moisture loss to the air and carbonation, is vital to bond formation.
- Bond formation process is the result of a complex interaction between masonry unit and fresh mortar, which reduces the effectiveness of using

brick IRA and TWA values to predict bond strength. The main methods currently used to define the water absorption of mortar (water retentivity) and unit (IRA, TWA) in isolation are not adequate to fully explain observed behaviour in masonry.

The UK NA to EC6 uses unit 5-h water absorption and mortar strength to determine characteristic flexural strength of masonry. However, it is clear from previous work that flexural bond strength is influenced by many inter-related factors. The mechanism of bond development is still not fully understood. The study on masonry bond is still in progress.

BLANK PAGE

3. Experimental Materials and Test Methodologies

3.1 Introduction

This PhD is primarily an experimental based study focusing on the mechanical flexural bond strength developed between fired clay bricks and natural hydraulic lime mortars. As outlined in chapter 2, bond in brickwork is a product of complex interactions between material properties (including binder content and grade, sand quality, and brick water absorption property), environment (curing condition and time) and human response to these factors (quality of work). In this PhD, natural hydraulic lime mortars have been combined with many different varieties of fired clay brick, although all produced by Ibstock Brick Ltd. The study has focussed on the effect of material parameters and age on bond strength development. For comparison, weak cement: hydrated lime: sand mortared brickwork have also been tested.

Testing methods have largely followed British Standard methodologies. Where this has not been possible appropriate test and analysis methods have been developed. In accordance with British Standards, different methods of strength testing have been adopted to evaluate material properties. Brickwork flexural bond strengths were examined by both wall panel testing (testing both parallel and perpendicular to bed joints) and bond wrench testing on stack bonded brick prisms. Shear bond strength of various brickwork prisms and compressive strength characteristics of one test series were also investigated.

For NHL mortared brickwork, the flexural bond strength, shear bond and compressive strength brickwork tests were generally carried out at 91 days. As lime develops strength, significantly through carbonation, at a much slower rate than cement bound materials, 91 days (3 months) has become the internationally accepted standard age for tests, taken as equivalent to 28 days (one month) for cement materials. The bond wrench test was used to examine the development of bond strength with age, with tests performed at 14, 28, 56, 91, 365 days. The comparative cement: hydrated lime: sand mortared brick prisms were tested at 28 days.

The experimental programme included six independent series of prism construction, curing and testing. Most series were completed within three months (91 days) from construction. In series I to IV, the research study on the influence of mortar constituents on brickwork properties was limited to a few bricks with different water absorption properties. The relationship between wall flexural test and bond wrench test were also examined in these series. The final two series concentrated primarily on bond wrench testing to study the influence of different brick water absorption properties.

In total 146 wall panels were constructed, including:

- 80 wall panels (two-brick wide and ten courses high) for flexural strength test parallel to bed joint.
- 60 wall panels (four-brick wide and four courses high) for flexural strength test perpendicular to bed joint.
- Six wall panels (two-brick wide and seven courses high) for compressive strength test.

In addition over 620 four-brick stack bonded specimens and 120 brick couplets were built for bond wrench testing (providing nearly 2000 individual bond test results). 90 brick triplets were built for initial shear testing. The work represents the most comprehensive study of bond strength characteristics for hydraulic lime mortared brickwork reported to date.

Together with the masonry tests, the properties of hydraulic lime mortar were investigated. Mortar specimens were cast and tested at the same time as the brickwork tests. In total 740 mortar prisms were cast and tested in three point bending, followed by nearly 1500 compressive strength tests.

This chapter introduces the materials used in the study, reporting on relevant material properties. Methodologies for mortar and brick preparation, brickwork specimen fabrication and curing after construction are also outlined. The experimental set-ups and test procedures are summarized in the final section. Test results for mortar and brickwork properties are presented later in chapters 4-7.

3.2 Experimental bricks

The influence of brick absorption characteristics on the brickwork bond strength has been a major aspect of this PhD. Brick water absorption characteristics are widely recognised as a significant determinant for the bond strength of cement: hydrated lime: sand mortars (Ritchie and Davison 1962, Sinha 1983, Gazzola et al. 1985, Lawrence and Cao 1988, McGinley 1990, Groot 1993, Lawrence and Page 1994, Venu Madhava Rao et al. 1996, Borchelt et al. 1996, 1999, Choubey et al. 1999, Sugo et al. 2001, Sarangapani et al. 2002). Early tests in this study indicated that brick properties were also very important to the bond in hydraulic lime mortared brickwork.

In total 37 different commonly used brick types were chosen, covering a wide range of water absorption values. All bricks were supplied by Ibstock Brick Limited, produced in a variety of Ibstock plants such as Aldridge, Cattybrook, Tannochside, West Hoathly, Throckley, Roughdales, Atlas, South Holmwood, and Nostell. All bricks were fired clay bricks; the majority were extruded perforated wire-cut bricks (with a range of finishes), although a small numbers of pressed stock and handmade bricks were also included in the study. Nominal dimensions of the bricks were mostly 215×102.5×65mm, except that a few bricks which were nominally 75 mm high. Perforation patterns included three oval holes, three round holes, quasi- rectangular holes, ten small round holes, ten small rectangular holes and five slots. Four types of single-frogged bricks and one type of solid low absorption brick were also used. Figure 3.1 illustrates representative specimens.

3.2.1 Brick water absorption tests

The UK National Annex to Euro Code 6 (NA to BS EN 1996-1:2005), in common with the standard it replaced, BS 5628 (withdrawn in April, 2010), uses total water absorption of fired clay bricks as the primary design parameter to determine characteristic bond strength. Some researchers (Ritchie et al. 1962, Boynton and Gutschick 1964, Goodwin and West 1982, Gazzola et al. 1985, McGinley 1990, Lawrence and So 1994, Borchelt et al. 1996, 1999) prefer to use initial rate of absorption (also known as suction rate). In this study the initial rate of absorption (IRA), total water absorption (using two test methods) and sorptivity of all bricks were determined. In total over 600 IRA, total absorption and sorptivity tests were completed.

Initial rate of absorption (IRA)

The IRA was determined in accordance with BS EN 772-11:2011. IRA is defined as the mass of water absorbed by one brick bed face when placed in water for one minute. In preparation the bricks were oven dried at 105^{o}C ± 5^{o}C for a minimum of 24 hours and then allowed to cool to constant mass in a

Type 1 (10 test series)

Three round hole perforation (17% voids)

Type 2 (9 test series)

Three oval hole perforation (18% voids)

Type 3 (7 test series)

Three quasi-rectangular hole perforation (22% voids)

Type 4 (5 test series)

Frogged

Type 5 (2 test series)

Ten rectangular-hole perforation (23% voids)

Type 6 (2 test series)

Ten round hole perforation (21% voids)

Type 7 (1 test series)

Five slot perforation (12% voids)

Figure 3.1 Test brick formats

conditioning room set at 20 ± 2^{o}C and 65% ± 5% RH. The bricks were placed face down in a pool of water to a depth of 5mm ± 1mm for a period of 60 seconds ± 2 seconds. The water absorbed was expressed as a function of net brick bed face area, kg/m^{2}/min.

Total water absorption (TWA)

At present two alternative methods for determining brick total water absorption are permitted by BSI. Both methods were used in this study to compare performance. One used 24 hour cold water immersion (referred to hereafter as the 24-hour immersion test) and in the other test water absorption was measured following 5 hours in boiling water (5-hour boil test)

The 24-hour immersion tests for total water absorption tests were conducted in accordance with BS EN 771-1:2011. Bricks were initially immersed in water (set at 20^{o}C ± 2^{o}C) for 24 hours. Thereafter, the saturated bricks were weighed, and oven dried (at 105^{o}C ± 5^{o}C) to constant mass, and then re-weighed. Total water absorption is expressed as a percentage of initial brick dry mass (%).

The 5-hour boil test was undertaken in accordance with BS EN 772-7:1998. Bricks were placed in boiling water for 5 hours, and then allowed to cool. The saturated bricks were weighed, and oven dried (at 105^{o}C ± 5^{o}C) to constant mass, and then re-weighed. Total water absorption is also expressed as a percentage of brick dry mass (%). The reported water absorption values by 5-hour boiling test are generally greater (32% on average from a range between 4% and 44% by McGinley 1990, 46% on average from a range between 22% and 93% by Wilson et al. 1999) than that by 24-hour cold water value (Wilson et al. 1999).

The ratio of 24-hour cold water immersion to 5-hour boiling test (also called saturation coefficient in ASTM C 67) is also used as an indicator of brick freeze/thaw resistance and almost always less than 1.0. In NA to BS EN 1996, the flexural strength of the masonry f_{xk} of different bricks is classified by brick water absorption in three categories, less than 7%, 7%-12% and over 12%.

These values were originally established using the 5-hour boil test. In the main text of Eurocode 6 (BS EN 1996-1-1:2005), f_{xk1} (plane of failure parallel to bed joints) and f_{xk2} (plane of failure perpendicular to bed joints) values are designated only by masonry unit type.

Sorptivity

Sorptivity testing of bricks followed the procedure generally outlined by Hall and Hoff (2002, 2005). In this study a procedure successfully used at the University of Bradford was adopted. Plastic trays were filled with fine sand to a depth of around 50mm and carefully levelled and flattened. A layer absorbent filter paper was laid directly on top of the sand and then a sufficient quantity of water was added to ensure the surface of the filter paper was saturated (Figure 3.2). During the whole testing process water was added as necessary to maintain paper dampness. Sorptivity assumes uni-sectional flow of water. To avoid loss of moisture from the brick faces during testing, the four sides of the bricks were wrapped with heavy duty plastic ('Duck') tape. In preparation for testing, the bricks were oven dried to constant mass and then allowed to cool in the conditioning room (20^{o}C and 65%RH). The increases in brick mass were measured incrementally at 1, 2, 4, 8, 16, 32, 64, 128, 256 minutes. The sorptivity value is determined from the gradient of a plot of mass of water absorbed 'i '(per unit area of inflow surface) against square root of time ($min^{1/2}$). At least six points were required to establish the initial linear relationship. Typical graphs for the three most common bricks used in this project are presented in Figure 3.3. The sorptivity value is obtained from:

$$S = i/t^{1/2} = \Delta w/\rho A t^{1/2}$$

where

- Δw is the increase in brick weight;
- ρ is water density (1000 kg/m^3);
- A is the inflow surface area (net bed face area);
- $t^{1/2}$ is the square root of elapsed time.

Figure 3.2 Sorptivity test

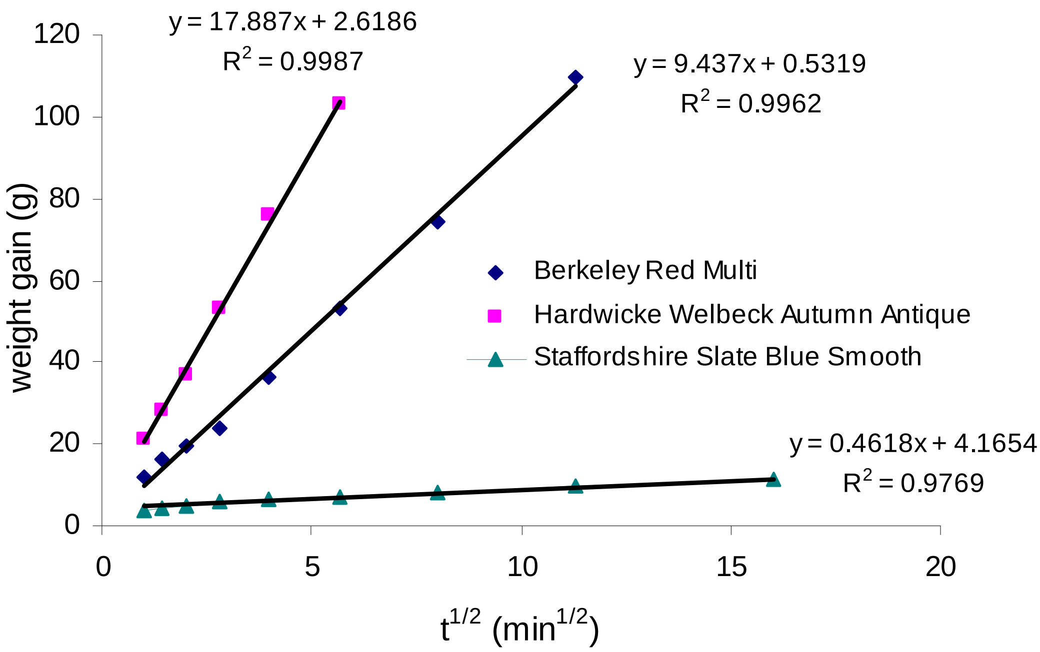


Figure 3.3 Typical experimental datasets obtained in sorptivity testing

Ten brick specimens, randomly selected from the batch of bricks supplied for testing were used to determine the values of IRA and total water absorption for each series. Due to time constraints, sorptivity tests were determined using a minimum of seven randomly selected bricks. The test results, together with other Ibstock brick data, are summarized in Table 3.1.

Table 3.1 Brick properties

Brick name	Type[2] & Texture[3]	Perforation type	IRA (kg/m^2/min)		5-hour boil water absorption (%)		24-hour immersion water absorption (%)		Sorptivity (mm min$^{1/2}$)	
			Average	CV (%)	Average	CV (%)	Average	CV (%)	Average	CV (%)
Berkeley Red Multi (Cattybrook)[1]	Wire	2	1.3	7.3	8.4	10.7	5.1	6.9	0.49	22.8
Staffordshire Slate Blue Smooth (Lodge Lane)	Wire	1	0.1	35	3.3	12.3	2.3	14.9	0.03	29.4
Hardwicke Welbeck Autumn Antique (Dorket Head)	Wire	1	2.4	7.5	16.5	11.4	14.8	3.9	2.13	6.7
Holbrook Smooth (South Holmwood)	Wire	2	1.0	11.8	8.7	12.9	7.7	6.7	0.65	20.9
Cheshire Weathered (Ravenhead)	Wire	2	1.1	13.7	8.0	6.0	6.2	12.3	0.77	29.3
Chester Blend (Roughdales)	Wire	2	1.9	10.8	9.6	3.3	8.3	6.0	1.61	3.6
Royston Cream (Nostell)	Wire-dragfaced	2	0.4	13.1	6.4	2.5	6.0	5.3	0.14	19.0
Cheddar Red (Cattybrook)	Wire-smooth	1	0.4	17.7	5.3	7.2	2.9	30.7	0.06	60.0
Cheddar Brown (Cattybrook)	Wire-rolled	1	0.5	14.4	4.7	8.8	4.5	13.5	0.17	30.6
Kenilworth Textured Multi Red (Stourbridge)	Wire-dragfaced	7	0.5	13.1	6.1	2.7	4.8	8.3	0.15	18.6

Brick name	Type & Texture	Perforation type	IRA ($kg/m^2/min$)		5-hour boil water absorption (%)		24-hour immersion water absorption (%)		Sorptivity ($mm\ min^{1/2}$)	
			Average	CV (%)	Average	CV (%)	Average	CV (%)	Average	CV (%)
Surrey Orange (South Holmwood)	Wire-rolled	2	0.6	27.1	8.6	9.3	7.2	16.2	0.42	28.9
Ruskin Red 73 (Aldridge)	Wire-smooth	3	0.7	6.3	8.8	9.3	6.1	4.4	0.48	15.4
Hadrian Buff (Throckley)	Wire-rolled	6	0.9	8.7	7.4	2.6	6.7	1.7	0.38	16.0
Himley Midland Red Sandfaced (Aldridge)	Wire-sandfaced	3	0.9	18.7	7.1	10.2	6.0	8.0	0.38	26.0
Tradesman Antique (Atlas)	Wire-rolled	5	0.9	6.7	8.2	12.5	6.7	2.5	0.37	12.6
Argyll Buff Multi Wirecut (Tannochside)	Wire-dragfaced	1	0.9	6.0	8.5	6.8	6.8	3.2	0.28	20.1
Madeley Mixture (Aldridge)	Wire-dragfaced	3	0.9	7.7	9.0	5.0	6.7	7.6	0.37	28.4
Tradesman Sandfaced (Atlas)	Wire-sandfaced	5	0.9	11.4	8.4	4.5	5.7	11.1	0.43	12.7
Brunswick Tryfan Grey (Cattybrook)	Wire-rolled	1	0.9	10.3	4.7	8.8	3.9	9.0	0.16	43.8
Colonsay Red Wirecut (Tannochside)	Wire-dragfaced	1	1.0	8.5	8.4	3.3	7.1	4.3	0.51	16.0
Medium Multi (West Hoathly)	Stock	4	1.1	26.2	14.9	6.5	8.6	14.0	0.26	79.4

Brick name	Type & Texture	Perforation type	IRA (kg/m^2/min)		5-hour boil water absorption (%)		24-hour immersion water absorption (%)		Sorptivity (mm min$^{1/2}$)	
			Average	CV (%)	Average	CV (%)	Average	CV (%)	Average	CV (%)
Parham Red Stock (Ladybrook)	Stock	4	1.1	6.1	13.2	1.8	8.5	3.4	0.53	34.9
Brunswick Red (Cattybrook)	Wire-rolled	1	1.2	9.4	7.1	3.1	5.6	13.0	0.33	18.2
Kielder Orange (Throckley)	Wire-rolled	6	1.3	7.1	6.4	22.3	6.4	4.1	0.43	24.4
Shireoak Russet (Aldridge)	Wire-rusticated	3	1.3	8.3	10.6	5.4	7.5	4.4	0.31	21.6
Lancashire Weathered (Ravenhead)	Wire-smooth	1	1.3	5.9	9.9	3.6	7.3	9.8	0.38	19.9
Colonsay Red Rustic (Tannochside)	Wire-rusticated	1	1.4	4.5	8.6	4.4	7.4	2.5	0.44	22.1
Calderstone Claret (Roughdales)	Wire-rolled	1	1.4	13.2	8.8	2.7	6.8	10.2	0.63	41.5
Cavendish Fireglow (Dorket Head)	Wire-rusticated	3	1.5	13.0	13.8	9.7	9.3	18.5	0.49	74.4
Anglian Red Multi Rustic (Aldridge)	Wire-rusticated	3	1.6	12.5	12.0	5.5	9.2	5.6	0.53	20.2
Red Multi Rustic (Roughdales)	Wire-dragfaced	1	1.6	23.1	8.8	8.0	7.9	13.1	0.86	38.2
Red Multi (Nostell)	Wire	2	1.7	15.7	10.0	10.0	8.0	10.1	1.12	20.0

Brick name	Type[2] & Texture[3]	Perforation type	IRA ($kg/m^2/min$)		5-hour boil water absorption (%)		24-hour immersion water absorption (%)		Sorptivity (mm $min^{1/2}$)	
			Average	CV (%)	Average	CV (%)	Average	CV (%)	Average	CV (%)
Handmade Multi (West Hoathly)	Handmade	4	1.9	25.6	9.7	6.0	7.4	6.3	0.45	36.4
Dorset Red Stock (Ellistown)	Stock	4	2.1	4.6	16.9	2.0	12.7	1.2	1.31	11.1
Surrey Buff Multi (South Holmwood)	Wire-rolled	2	3.7	7.7	19.6	10.3	18.2	2.7	1.90	13.0
Bradford University[4] Low Absorption Solid	Wire	Solid	0.4	16.7	3.8	7.1	2.6	11.8	0.04	23.7
Bradford University[4] High absorption Frogged	wire	4	3.0	7.4	18.5	9.6	16.9	5.8	1.78	9.8

Notes:

[1] Ibstock production plant

[2] Brick types used in this project were mainly wire-cut, with three types of pressed stock brick and one type of handmade brick. All wire-cut bricks were perforated except one solid brick while all stock and handmade bricks had a single frog on the upper surface of the brick. The information about bricks is as follow from Ibstock brochures:'

- *Wire-cut brick: Prepared clay is continuously extruded to a required size and shape and then cut into individual bricks by fine wires. They have uniform shape and consistent characteristics and are generally the cheapest facings because the manufacturing process is highly automated.*
- *Stock brick: Wetted clay is moulded to a required size and shape as people made bricks in early days. They have traditional look and slightly irregular shape. Some of the producing process is automated, and they are usually a bit more expensive than wire-cuts due to the involvement of manual labour.*
- *Handmade brick: They are made as described above for the stock brick. However the clay is not compacted firmly by machine but by hand. Usually bricks have distinctive creasing and they are expensive due to the distinctiveness in colour and texture.*

[3] *Brick texture is crucial to reflect the look and feel of brickwork. The extruded clay column leaving the die box is smooth. Texture can be added as required.*

- *Dragfaced & rolled: The clay column is light textured by using a variety of blades or rollers on the extruded bricks. Bricks with dragfaced texture have small indentations on the surface, while bricks with the rolled back texture have a rippled/wave effect.*
- *Rusticated: The column is hard textured by a series of revolving blades fitted in a machine which roughen the surface and give a bark like effect of brick.*
- *Sandfaced: The finish blasts a coating of sand onto the column of clay before firing. The adhered sand adds a light texture to an otherwise smooth brick.'*

[4] Two bricks were supplied directly from Bradford University as part of the collaborative research programme.

A wide range of water absorption of bricks was covered. The IRA values ranged from 0.1 to 3.7 kg/m^2/min; the 24-hour brick water absorption values ranged from 2.3 to 18.2%; the 5-hour brick water absorption values ranged from 3.3 to 19.6%; the sorptivity values for the bricks used ranged from 0.03 to 2.13 mm $min^{1/2}$. The IRA and total water absorption values are more consistent than the sorptivity values recorded (as indicated by the coefficients of variance). On the average coefficients of variance for the IRA, 5-hour total water absorption and 24-hour total water absorption were 12.5%, 7.0% and 8.5% respectively. The average coefficient of variance for sorptivity was 26.7%.

Sorptivity test is a measurement of brick water absorption over time and is considered the most realistic simulation of the water absorbed by a brick when in contact with fresh mortar (Hall and Hoff 2002, 2005). The test results herein showed the highest variance of water absorption characterisation. Comparatively the results of IRA and both total water absorption tests were more consistent. The variation in performance can be attributed to intrinsic variations in the bricks stemming from production and variations between different batches. However, the greater variation in the sorptivity test is also likely to result from the test set up, including inconsistencies in contact between the damp filter paper and brick face. The sorptivity test is based on the assumption that the effect of gravity on the capillary absorption can be neglected as the microstructure of the bricks is fine enough. This assumption may not be generally valid for all brick types.

3.2.2 Relationships between water absorption parameters

In this project four brick parameters (IRA, 5-hour and 24-hour total water absorption (TWAs), and brick sorptivity) have been used to characterise brick absorption properties. To correlate them, the relationships between 5-h and 24-h total water absorption, between IRA and the TWAs, between sorptivity and IRA, between brick sorptivity and TWAs, were explored and are presented in Figures 3.4-3.6. Best fit curves, including linear or power regressions were applied to test correlations between the various parameters. For brick sorptivity, power regressions provided a good fit to the data; simple linear regression models did not represent well the relationships with other water absorption variables (Figure 3.6).

Despite spread in the data there are a strong correlation between the test results for the two methods used to measure brick total water absorption (Figure 3.4). The two test methods do not yield consistent results for identical materials. It is therefore important to specify the test method when quoting total water absorption values. For the range of bricks tested here the 5-h boil test consistently attained higher values than the equivalent 24-h immersion test value. On average, the 5-h test was 23.3% higher than the 24-h test value (46% was reported by Wilson et al. 1999). The increased TWA with boiling the water is believed to be related with the effect of elevated temperature on the pore structure of the brick to allow more water to fill in more porous clay matrix through capillary network.

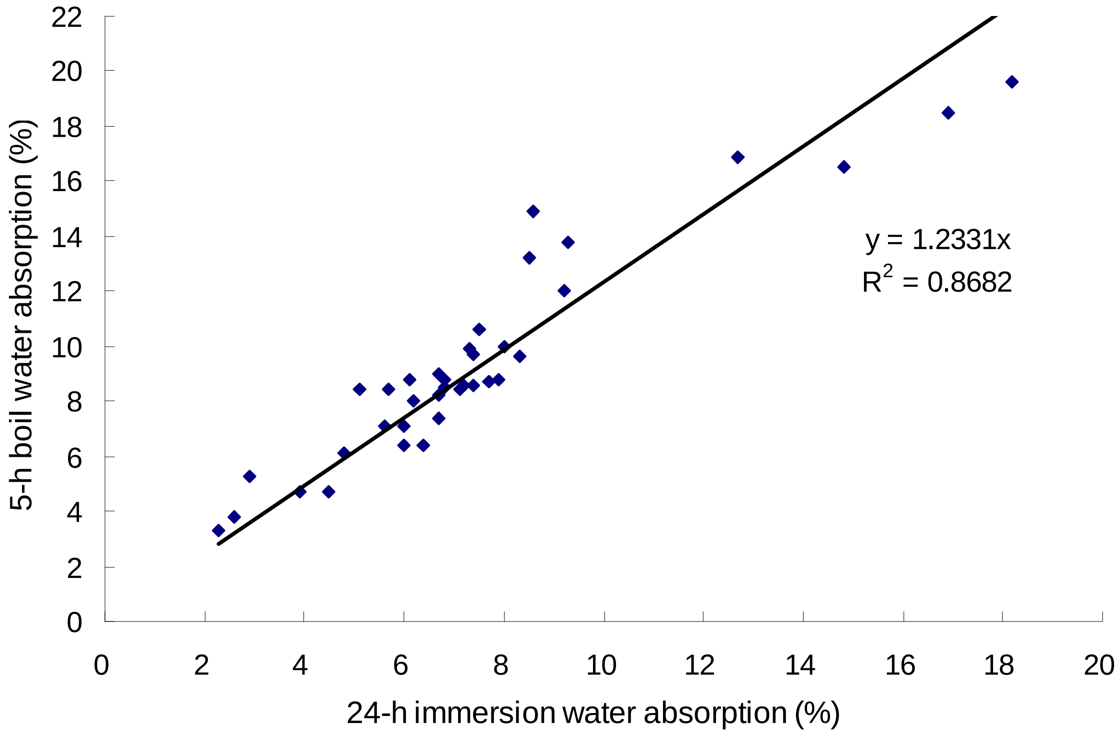
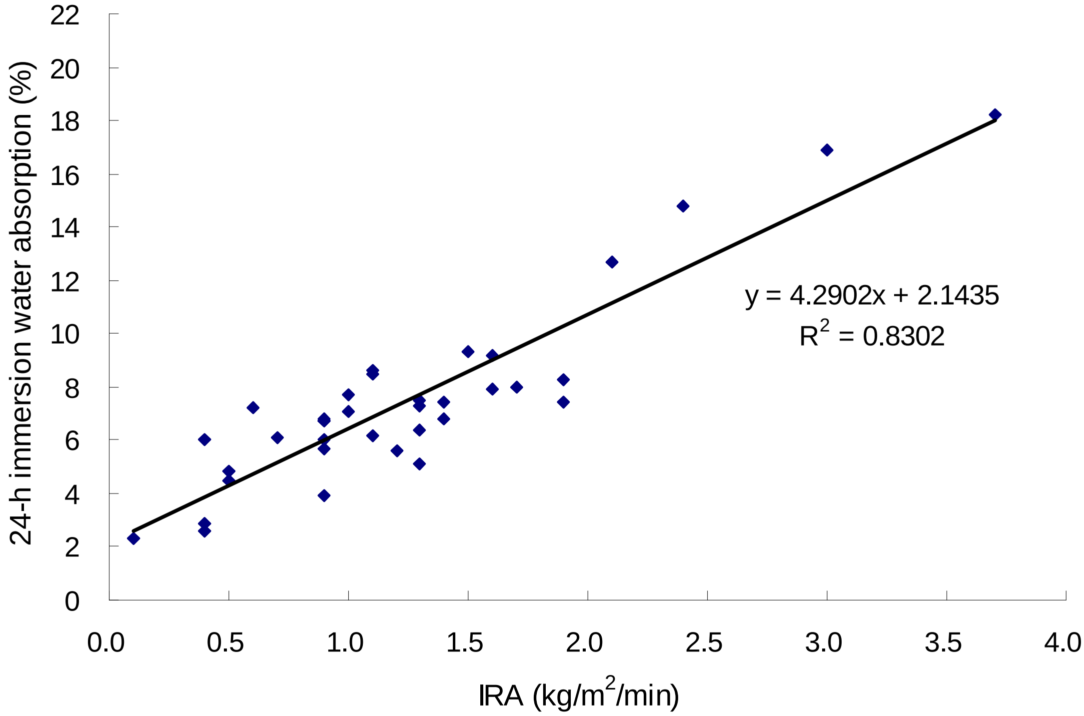
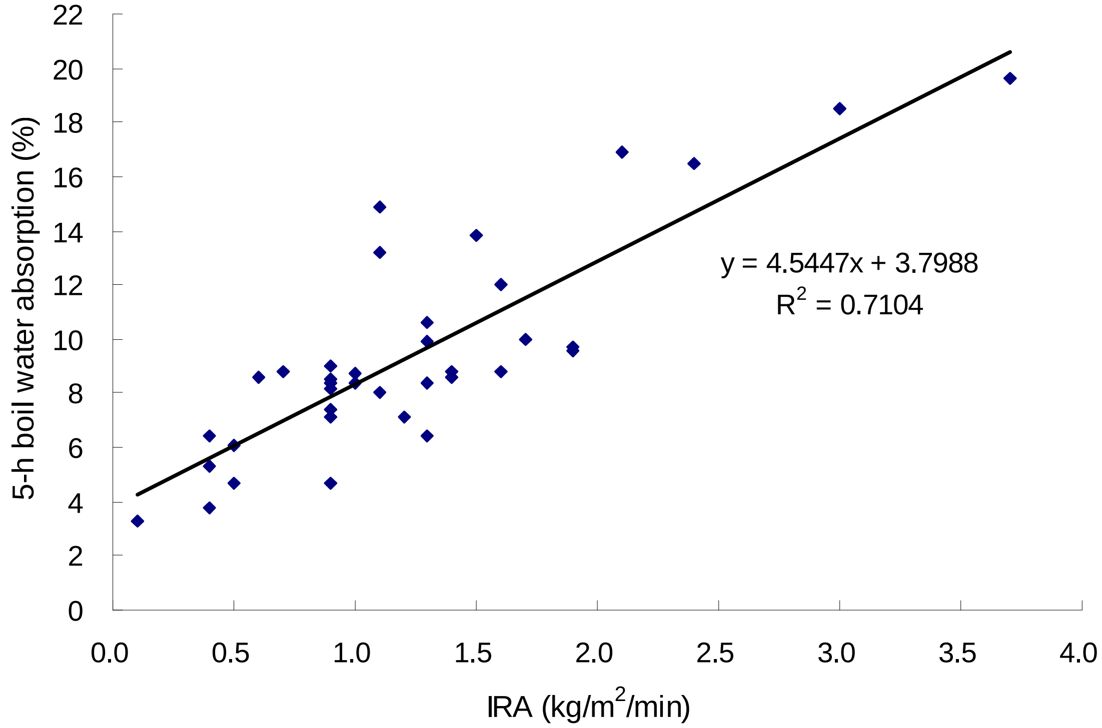


Figure 3.4 Relationship between 24-h and 5-h total water absorption

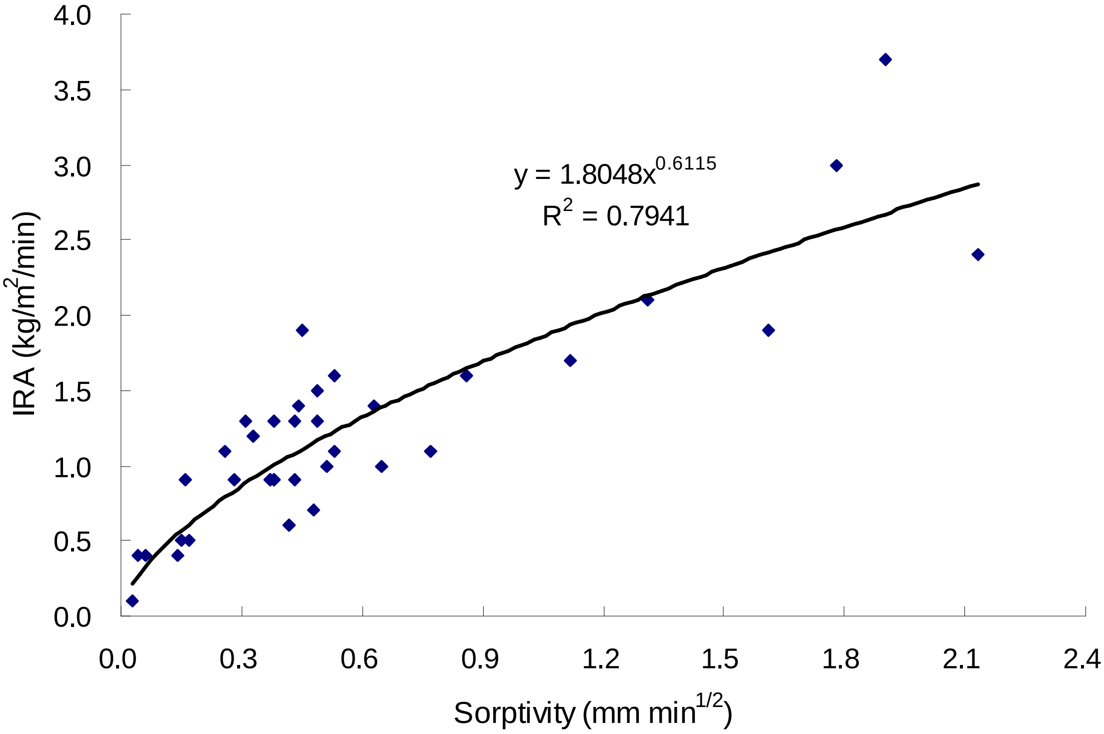


(a)



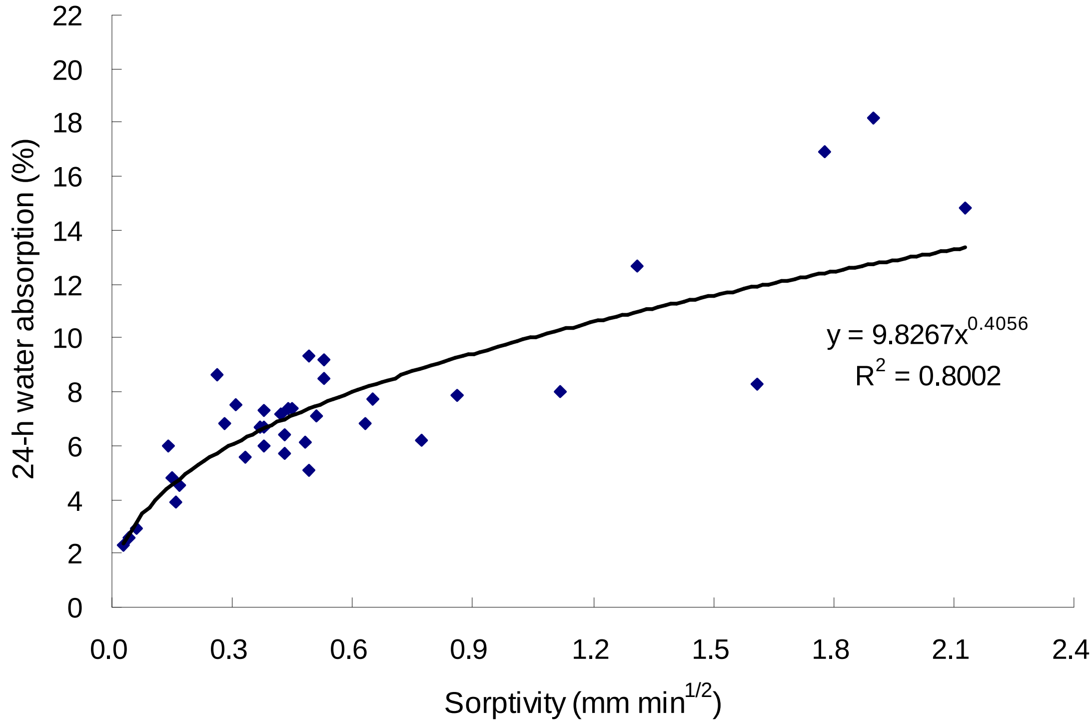
(b)

Figure 3.5 Relationship between IRA and total water absorption



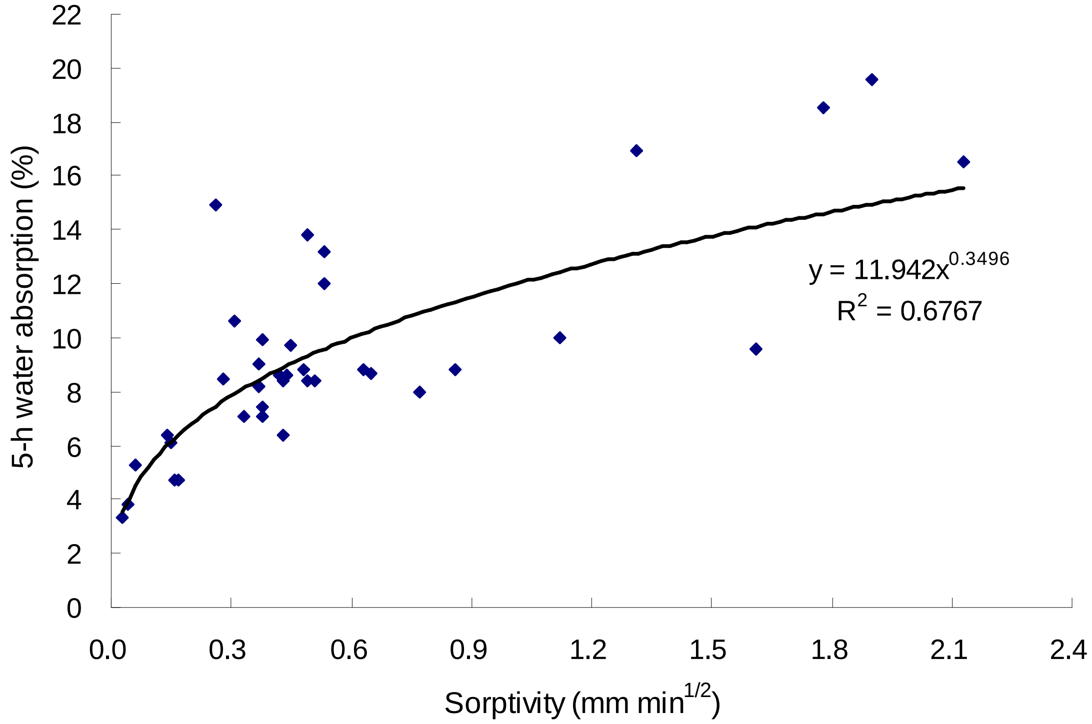
y = 1.8048x^0.6115
R^2 = 0.7941
IRA (kg/m^2/min)
Sorptivity (mm min^1/2)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4

(a)



y = 9.8267x^0.4056
R^2 = 0.8002
24-h water absorption (%)
Sorptivity (mm min^1/2)
0
2
4
6
8
10
12
14
16
18
20
22
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4

(b)



(c)

Figure 3.6 Relationship between sorptivity and IRA and total water absorption

As total water absorption is used as a key parameter in determining design values for flexural bond strength of brickwork, the original BS 5628 values (withdrawn in 2010), which are reproduced in the UK NA to BS EN 1996-1, use the 5-hour boil test. Flexural strengths are based on three ranges of TWA: <7%, 7-12% and >12%. For bricks with TWA values falling close to the limits between these ranges, the choice of TWA method of determination can have a significant effect on design strength specified by NA to EC6 for cement based mortared masonry.

Among the different relationships, the strongest correlation is between IRA and 24-h brick immersion absorption. Although as expected there were strong correlations in all three comparisons, there was also some considerable scatter where there has been greater number of similar brick tests. Figure 3.7 shows there is little correlation within the range of 6-10% water absorption. Although it looks less scattered in the values of less than 6% and over 10% water absorption, there were fewer bricks studied within these ranges. A similar scatter in data would be expected throughout the full range of brick performance. In general, there is better correlation between IRA or sorptivity and the 24-hour (R^2 values: 0.8302 and 0.8002 respectively), rather than the 5-hour (R^2 values: 0.7104 and 0.6767 respectively) total water absorption values.

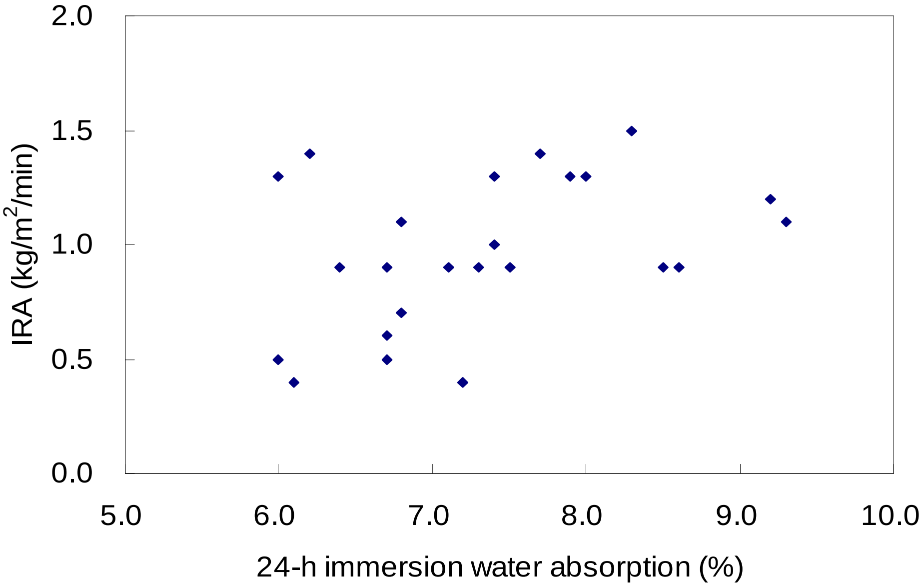


Figure 3.7 Bricks with similar water absorption properties

The scatter in performance therefore represents a significant challenge when seeking to explore correlative relationships between brick water absorption properties and brickwork bond performance. As the individual sample results for each brick are quite consistent (the coefficients of variation for IRA and water absorption in Table 3.1 are generally below 10%), the lack of strong correlation to the fundamental differences in water absorption properties of the bricks can be made by using different materials and firing processes, which gives rise to significant macro- and micro-structure differences such as surface characteristics and overall porosity. Although a more detailed exploration of brick water absorption was beyond the scope of this project, the influence of brick properties on brickwork bond is discussed in detailed in Chapter 6.

3.3 Mortars

As well as brick characteristics, the constituent materials and mix proportions of the mortars have a direct and important influence on the properties of brickwork. In this section the binders and aggregates used in this study are outlined.

3.3.1 Binders

Natural Hydraulic Limes (NHLs) used for lime mortar mixes in this project were mostly manufactured by Castle Cement Ltd, supplied by Lime Technology Ltd. Three grades, NHL 2, NHL 3.5 and NHL 5, were used. The performance requirements for the binders are characterised by 28 day compressive strengths in accordance with BS EN 459-1:2010. The performance requirements for NHL 2, NHL 3.5 and NHL 5 are given in Table 3.2. There are significant overlaps between the three classifications. For example, limes producing compressive strengths between 5 and 7 N/mm^2 can be designated as either NHL 2, or NHL 3.5 or NHL 5. The significant overlap in classification reflects inconsistencies in the industrial production of natural hydraulic limes.

Table 3.2 Compressive strength performance requirements for NHLs (BS EN 459-1: 2010)

Lime type	Compressive strength (N/mm^2)	
	7 days	28 days
NHL 2	-	≥ 2 to ≤ 7
NHL 3.5	-	≥ 3.5 to ≤ 10
NHL 5	≥ 2	≥ 5 to ≤ 15

Other natural hydraulic limes used in this study were ‘hl2’, Hydraulic Lincolnshire Lime, manufactured by Singleton Birch in the UK, and ‘StA’, Manufactured by CESA (Chaux et Enduits de St. Astier), St. Astier, France. NHL 3.5 binders from each supplier were chosen as a comparison to the lime produced by Castle Cement Ltd. All NHLs are readily available from specialist suppliers and used throughout the UK.

For comparison cement: hydrated lime: sand mortars were included in this study. Lafarge Blue Circle Portland cement (CEM I 42.5) and Rugby CL 90 grade hydrated lime were used throughout the study. Premixed bagged moderately hydraulic lime mortar provided by Lime Technology Ltd was also tested for comparison. The bulk densities of all binders used in the study for mass batching, are determined in accordance with BS EN 459-2:2010, and presented in Table 3.3.

Table 3.3 Bulk densities of binders

Binder type	Bulk densities (kg/m^3)
NHL 2	564
NHL 3.5	592
NHL 5	660
Portland Cement	1352
CL 90	631

3.3.2 Aggregates

A range of silica sands were used in the study. Fine aggregates for mortars are most commonly specified by grading, although water absorption and grain strength can be specified as well. The properties of the aggregates used in a mortar will play a significant part in determining performance of mortar and brickwork. Given their significance, it is important to use materials specified and in use by lime mortar suppliers.

Four different mortar sands were used in the study. 'Binnegar' is a blended sand sourced from Hampshire. At the time of the experimental study it was widely used by Lime Technology Ltd. and was primarily used in this project. To ensure consistency the material was supplied in one six-tonne kiln dried batch. Three other sand types, 'Allerton Park' (a coarsely graded sand sourced from

Yorkshire), ‘Croxden’ (a medium-coarsely graded sand sourced from the Midlands) and ‘Yellow Pit’ (a very finely graded sand sourced from Somerset), have been used for comparison with the ‘Binnegar’ sand. Throughout the report the sands will be referred to by their trade names. ‘Binnegar’, ‘Allerton Park’ and ‘Croxden’ are widely used for lime and cement mortars. ‘Allerton Park’ was previously used by the University of Bradford, and ‘Croxden’ was used by the University of Bristol in this collaborative research project. All materials are silica sands. The bulk densities of the sands, determined in accordance with BS EN 1097-3:1998, are summarized in Table 3.4.

Table 3.4 Bulk densities of sands

Sand type	Bulk densities (kg/m^3)
Binnegar	1660
Croxden	1522
Allerton Park	1676
Yellow Pit	1568

The grading curves of the sands were determined in accordance with BS EN 933-1:1997. The resultant grading curves of the four sands, established by sieve analysis, are given in Figure 3.8. Repeat testing, especially of the ‘Binnegar’ sand during the course of the study, showed little variation from the distributions given in Figure 3.8. All four sands fit within the grading limits specified in BS EN 13139: 2002 (which replaced BS 1200: 1976). ‘Allerton Park’ was the coarsest material, whilst ‘Yellow Pit’ closely matched the finer grading limit envelope. ‘Binnegar’ generally falls within the mid-range of the BS EN 13139 grading limits.

3.3.3 Mortar Mixes

The proportions of constituent materials have great influence on the characteristics of mortar. Table 3.5 summarises the various binder: aggregate

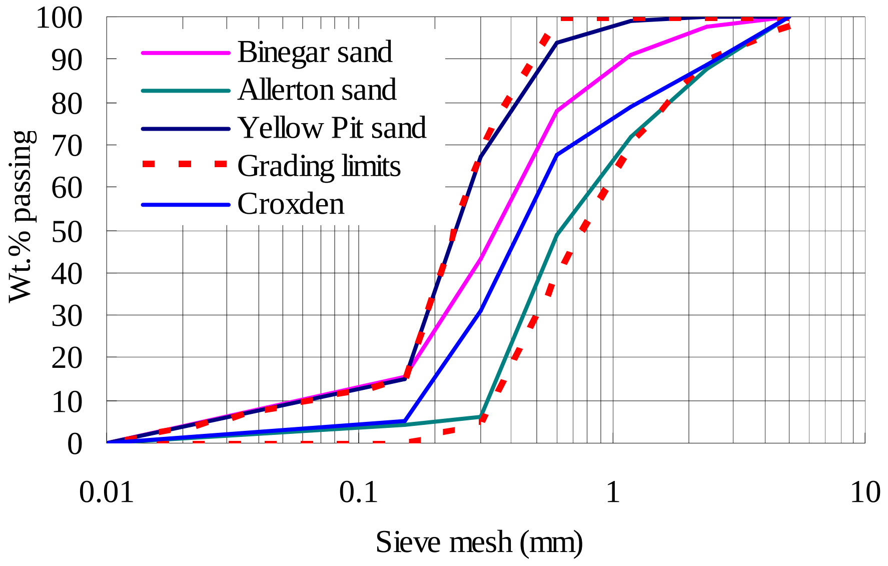


Figure 3.8 Sand grading curves

(B:Ag) mix ratios used for the experimental study, designed to investigate the influence of mortar mixes on bond properties of brickwork. The constituent material ratios were selected by volume following consultation with the industrial partners involved in the project. However, mixing materials were batched by mass using material bulk densities, in order to control the mix procedures and products more consistently than volumetrically. The proportion ratios by both volume and mass are listed in Table 3.5. Cement lime mortars 1:2:9 and 1:3:12 (Portland cement: hydrated lime: sand) were chosen for comparison. Lafarge Blue Circle Portland cement and Rugby CL 90 grade hydrated lime were used. A premixed hydraulic lime mortar, supplied by Lime Technology, was also included within the study.

3.4 Specimen Preparation

An experimental programme was designed to investigate material parameters (including brick water absorption properties, mortar mix proportions, lime grade and supplier, sand type) on properties of mortar and brickwork. Various combinations of brick and mortar were tested at selected ages from 14, 28, 56, 91 days and in a limited number of cases, 365 days after construction.

Table 3.5 Experimental Mortar Mixes

<table>
<tr><th>Mortar type</th><th>Cement</th><th>Lime grade</th><th>Lime supplier</th><th>Sand type</th><th>Mix proportion (by volume)</th><th>Mix proportion (by mass)</th></tr>
<tr><td rowspan="10">Hydraulic lime: sand</td><td rowspan="10">------</td><td rowspan="3">NHL 3.5*</td><td rowspan="5">Castle cement</td><td rowspan="5">Binnegar</td><td>1:2.25</td><td>1:6.3</td></tr>
<tr><td>1:2</td><td>1:5.6</td></tr>
<tr><td>1:2.5</td><td>1:7.0</td></tr>
<tr><td>NHL 2</td><td>1:2.25</td><td>1:6.6</td></tr>
<tr><td>NHL 5</td><td>1:2.25</td><td>1:5.7</td></tr>
<tr><td rowspan="3">NHL 3.5</td><td rowspan="3">Castle cement</td><td>Allerton Park</td><td rowspan="3">1:2.25</td><td>1:6.4</td></tr>
<tr><td>Yellow Pit</td><td>1:6.0</td></tr>
<tr><td>Croxden</td><td>1:5.8</td></tr>
<tr><td rowspan="2">NHL 3.5</td><td>Singleton Birch (hl2)</td><td rowspan="2">Binnegar</td><td rowspan="2">1:2.25</td><td>1:6.3</td></tr>
<tr><td>St Astier (StA)</td><td>1:6.3</td></tr>
<tr><td rowspan="2">Cement: lime: sand</td><td rowspan="2">CEM I 42.5</td><td rowspan="2">CL 90</td><td rowspan="2">Lafarge, Rugby</td><td rowspan="2">Binnegar</td><td>1:3:12</td><td>1:1.4:14.7</td></tr>
<tr><td>1:2:9</td><td>1:0.9:11.1</td></tr>
<tr><td>Premixed hydraulic lime mortar</td><td>------</td><td>Moderately hydraulic</td><td>Lime Technology</td><td>------</td><td>1:2.25</td><td>------</td></tr>
</table>

* **Bold** font shows the ‘Baseline mortar’ set for comparison.

Six series of specimen construction and testing were completed over two and half years. Each series had its own objectives and was generally completed within 91 days. Methodologies for the preparation of mortar mix and brick, the fabrication of brickwork and mortar specimens, and the later curing stage are outlined below. In the study different test methods were used to measure brickwork properties. The test procedures are summarised later.

3.4.1 Programme design

The brick-mortar bond characteristics were investigated by measuring the flexural bond strength of wall panels (both parallel and perpendicular to bed joints), bond wrench and initial shear strength of brickwork prisms in accordance with corresponding parts of BS EN 1052. The flexural wall test has been used in the UK for a number of years as the standard means of determining the flexural bond strength. Whereas, the alternative bond wrench test was only accepted as standard for use in the UK in 2005. The bond wrench, developed primarily in Australia and the USA, is a much simpler and more economical test when a large parametric study of materials is required. A comparison between the bond wrench test and the flexural wall test has been completed to verify its acceptance in this study.

Specimen construction and testing have been performed to study the influence of variables affecting bond properties between brick and mortar. Parameters such as brick water absorption properties, lime grade and supplier, sand type and mortar mix proportions, are investigated. For better comparison, a ‘baseline brickwork’ has been designated as a combination of ‘Berkeley Red Multi’ brick with the ‘baseline’ mortar (comprising ‘Castle cement NHL 3.5’ lime and ‘Binnegar’ sand in proportions 1:2.25 by volume).

Bond wrench strengths of the baseline samples were tested at different ages: 14, 28, 56, 91 and 365 days, in order to trace the development of bond strength with curing time. Other brickwork specimens were tested generally at 91 and/or 28 days, with some series also tested at 14 and 56 days. Flexural strengths of wall panels parallel and perpendicular to bed joints and initial shear strength of NHL lime mortared specimens were tested at 91 days, while cement: lime: sand mortared brickwork were tested at 28 days. Compressive strength of brickwork was determined only for the baseline materials at 91 days.

The flexural and compressive strengths of NHL mortars were tested at the same time as the brickwork specimens. These tests not only characterised the variation in mortar strength with the variation of constituent materials, but also mapped the strength development of the hydraulic lime mortars with time. The relationship between mortar strength and corresponding brickwork bond strength was explored. The lime mortar specimens were cast in steel moulds, in accordance with BS EN 1015-11:1999. The influence of brick dewatering on the properties of resultant mortars cannot be shown in these mortar specimens.

The whole process of research was divided into six series of specimen construction followed by testing, which were performed between May 2006 and December, 2008. Table 3.6 outlined the specimen casting time period, the corresponding testing time period and the main focus of each series.

3.4.2 Preparation of Constituent Materials

The bricks were dried within the ambient laboratory environment for at least two weeks prior to construction. Halved stretcher bond bricks for the wall panels were sawn in advance and also allowed to dry out before use. ‘Binnegar’, ‘Croxden’ and ‘Allerton Park’ sands were dried in the factory before delivery and kept dry before use, in order to maintain consistent proportions in the mortar mixes. ‘Yellow Pit’ sand was dried under low heat in the laboratory oven and allowed to cool down before use.

The bagged lime and cement were stored dry and were used within 6 months of delivery. Partially used bags were discarded after each series of specimen construction. Difficulties were experienced with a bag of NHL5 lime; the bag had become moist as many small lumps had formed and mixed in the lime

Table 3.6 Experimental programme design

Series No.	Time of specimen construction	Time of specimen testing	Test methods used	Main research focus
I	15/05/06-25/05/06 and 26/06/06-28/06/06	30/05/06-24/08/06* and 10/07/06-27/09/06	1. Bond wrench tests; 2. Flexural strength tests of wall panels for a plane of failure parallel and perpendicular to the bed joints (later abbreviated as flexural strength tests of walls); 3. Initial shear strength tests.	1. Influence of mortar mix proportion; 2. Comparison of properties between natural hydraulic lime mortared brickwork and 1:3:12 cement lime mortared brickwork
II	11/09/06-22/09/06	19/10/06-22/12/06	1. Bond wrench tests; 2. Flexural strength tests of walls; 3. Initial shear strength tests.	1. Influence of lime grade; 2. Influence of brick water absorption.
III	12/02/07-21/02/06	27/02/07-23/05/07	1. Bond wrench tests; 2. Flexural strength tests of walls; 3. Initial shear strength tests.	1. Influence of sand grading; 2. Influence of brick moisture content at laying; 3. Comparison of properties between natural hydraulic lime mortared brickwork and 1:2:9 cement mortared brickwork

IV	10/09/07-21/09/07	28/09/07-21/12/07	1. Bond wrench tests; 2. Flexural strength test of walls	1. Comparison of the tests between bond wrench and flexural strength for a plane of failure parallel to the bed joints; 2. Influence of brick type.
V	08/01/08-17/01/08	22/01/08-18/04/08	1. Bond wrench tests.	1. Influence of different lime supplier; 2. Influence of brick types.
VI	30/06/08-1/07/08; and 02/09/08-03/09/08	14/07/08-30/09/08; and 16/09/08-03/12/08	1. Bond wrench tests.	1. Comparison of properties between natural hydraulic lime mortared brickwork and 1:3:12, 1:2:9 and 1:1:6 cement lime mortared brickwork

* Some specimens were tested one year after construction.

powder prior to being supplied. The resultant test results of the brick wall panels constructed by using this bag showed that the wetted lime had developed substantial inferior bond strength. The lime was later discarded.

3.4.3 Fabrication and Curing of Mortar & Brickwork Specimens

The mortars were mixed in a rotating drum mixer (Figure 3.9). Initially the dry materials were mixed together for 60 seconds, and thereafter water was carefully added and mixing continued for 10 minutes in total. The cement mortars were used at this point, however the hydraulic lime mortars were left to stand (under cover) for 50 minutes before briefly re-mixing and use. This practice was in accordance with industry best practice for lime mortars and is believed to improve mortar workability. Cement mortars were used for two hours before discarding, whilst the hydraulic lime mortars were used for up to four hours.

Figure 3.9 Drum mixer

The water content and flow of the mortar depends on the mortar mix type and was controlled by the bricklayer to reach an appropriate consistency. The water required for achieving similar workability generally increases with sand content and decreases with lime grade, see Table 3.7. The mortar workability was occasionally varied to accommodate different water absorption bricks. Though it was desirable to minimise variation in materials for comparison, the brick with high absorption level, ‘Hardwicke Welbeck Autumn Antique’, required mortar with slightly higher level workability, whilst the low absorption brick, ‘Staffordshire Slate Blue Smooth’, required less water.

Table 3.7 Mortar mixes

Sand:lime (by volume)	Sand type	Hydraulic lime	Water:lime (by mass)
2	Binnegar	‘Castle Cement’ NHL3.5	1.40
2.5			1.49
2.25	**Binnegar**	**‘Castle Cement’ NHL3.5 (Baseline)**	**1.49**
		‘Castle Cement’ NHL2	1.58
		‘Castle Cement’ NHL5	1.31
		‘St Astier’ NHL3.5	1.71
		‘Singleton Birch’ NHL3.5	1.67
	Allerton Park	‘Castle Cement’ NHL3.5	1.43
	Croxden		1.40
	Yellow Pit		1.55
N/A	N/A	‘Limetec Technology’ Premix (Limetec moderately hydraulic mortar)	N/A

The flow table test, as specified by BS EN 1015-3:1999, was performed on each batch of mortar to quantify the workability of the fresh mortars. The desorptivity test was conducted by the research team at The University of Manchester, determining the water retaining ability of mortar. Details will be discussed in section 3.5.1.

To determine mortar flexural and compressive strengths, three identical mortar prisms were cast in 40×40×160 mm steel moulds for each batch mortar and initially were placed in plastic bags. Based on experience, the specimens were left in moulds for at least three days to gain sufficient strength for demoulding. They were kept in plastic bags after demoulding until they reached seven days old. Thereafter, the mortar prisms were cured in a climate controlled room under the conditions (20 ± 2^{o}C and RH 65 ± 5%) until testing (Figure 3.10).

Figure 3.10 Mortar specimens on shelves curing in climate room

Four-brick high stack-bonded prisms were constructed for bond wrench strength specimens, whilst three-brick stack-bonded prisms were constructed for initial shear strength specimens. Both were built on benches while wall panel specimens were built on flat horizontal surfaces of wooden pallets (Figure 3.11), which allowed convenient movement for storage and subsequent testing. The thickness of mortar joints in all cases was maintained at a nominal 10 mm by an experienced bricklayer. Table 3.8 summarises the nominal dimensions of all brickwork specimens.

All specimens were covered in plastic sheet immediately after construction to protect them from drying and pre-compressed by laying three courses of loose stacked bricks for wall panel specimens and two courses bricks for quadruplets and triplet brick prisms, meeting the BS EN 1052-3:2002 requirements of pre-compression between 0.02 and 0.05 N/mm^2. All specimens were left undisturbed for 7 days to achieve sufficient bond strength before removal to the climate room. They were stored under the same conditions as the mortar samples until testing.

Figure 3.11 Brick specimens in construction and curing

Table 3.8 Nominal dimensions of brickwork specimens

Test	Width (brick length)	Height (course)	Nominal dimensions thick × high × length (mm)
Bond wrench strength	1	4	102.5×290×215
Flexural strength (parallel to bed joints)	2 or 1+2×half	10	102.5×740×440
Flexural strength (perpendicular to bed joints)	4 or 3+2×half	4	102.5×290×890
Initial shear strength	1	3	102.5×215×215
Compressive strength	2	7	102.5×515×440

The same bricklayer was used throughout the study. He was very experienced with lime mortars, having worked on projects such as St Pancras station refurbishment, and was very meticulous in his work, typically laying around 100 bricks in a day. For all specimens mortar joints were remained flush with the brickwork. The procedure included building the specimens, allowing the mortar to dry, fixing flaws in the surface, striking the joints and brushing softly to clean the joints. Both vertical and horizontal joints were fully filled with mortar. By using the same bricklayer to fabricate all brickwork specimens the same consistent good quality of work was ensured as much as possible. All mortar mixes and specimens were prepared by the author.

3.5 Testing specimens

3.5.1 Mortar tests

Consistency of the fresh mortars was examined using the flow table test in accordance with BS EN 1015-3:1999. A standard truncated conical mould is placed centrally on the disc of the flow table and filled with fresh mortar. The flow value was taken as the mean diameter of the fresh mortar obtained by the test specimen after 15 jolts of the flow table at a frequency of one per second (Figure 3.12).

Figure 3.12 Flow table

Desorptivity test of the mortars was conducted to determine the water retaining ability for natural hydraulic lime mortars with the use of a modified version of the American Petroleum Institute pressure cell (Figure 3.13). The lower desorptivity value, the better water retaining the mortar has. The measurement is carried out using a pressure filtration technique, firstly tamping a known volume of freshly mixed mortar into the pressure cell in several layers endeavouring to eliminate voids, then sealing the cell and applying different values of gas pressure, 0.1, 0.15 and 0.2 N/mm^2. The desorbed water is collected and recorded at 10 second intervals. The desorptivity value is determined from the gradient of a graph of the cumulative volume of water per unit area, plotted against the square root of time.

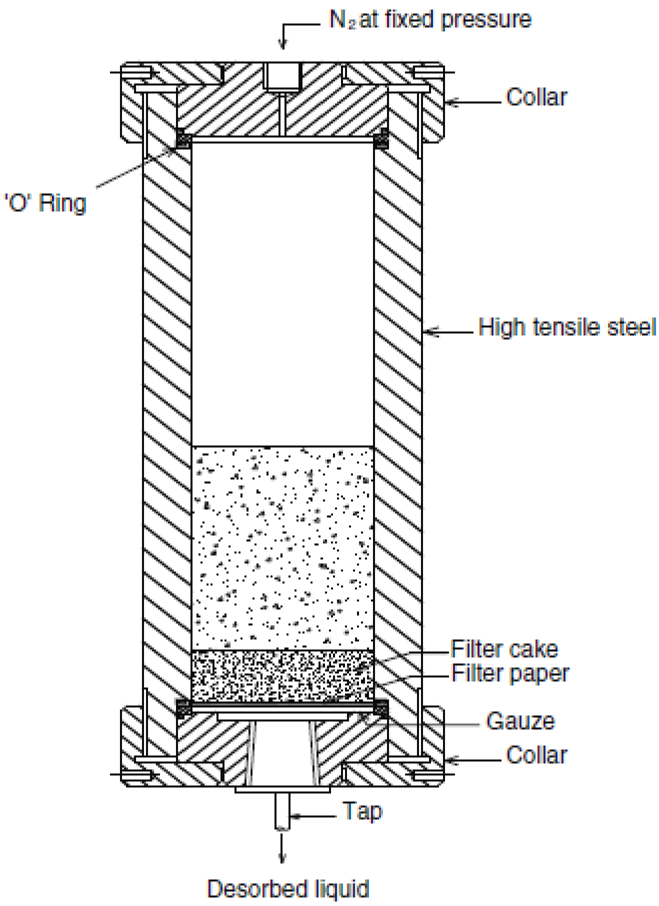


Figure 3.13 Schematic diagram of the pressure cell
(Image from Ince et al. 2011)

The hardened mortar properties were determined on the same day as the testing of the corresponding brickwork specimens (selected from ages of 14, 28, 56, 91 and 365 days). The flexural and compressive strengths of mortar were tested in accordance with BS EN 1015-11:1999 (Figure 3.14). Flexural strength was determined by three-point loading of hardened prisms to failure, which was applied under displacement control at a low loading rate of 0.3 mm/min. The compressive strength of the mortar was determined on the two parts resulting from the flexural strength test under displacement control at loading rate of 1.2 mm/min. For each batch of mortar, three specimens were tested to obtain the flexural strength value at different ages. Therefore, six half prisms were available to obtain the mean value of compressive strength.

Figure 3.14 Mortar flexural and compressive strength test

After the flexural strength test and before the compressive strength test, the carbonation of the mortar specimens was measured by spraying a 1% solution phenolphthalein on the freshly fractured surface. The uncoloured area indicates presence of the lower alkalinity calcium carbonate in the mortar mix following carbonation, whilst the pink staining indicates the presence of higher alkalinity uncarbonated calcium hydroxide remains (Figure 3.15). There is generally a clear boundary between the carbonated and uncarbonated materials.

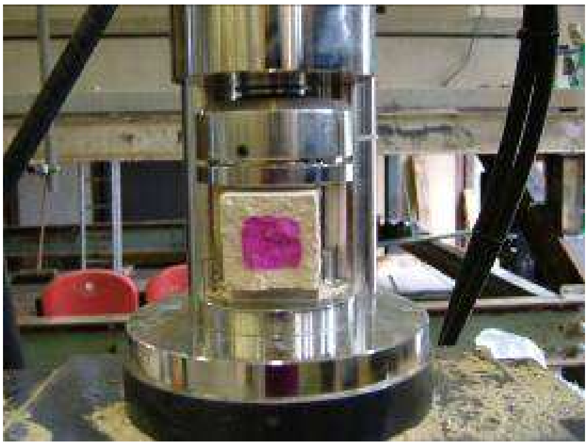


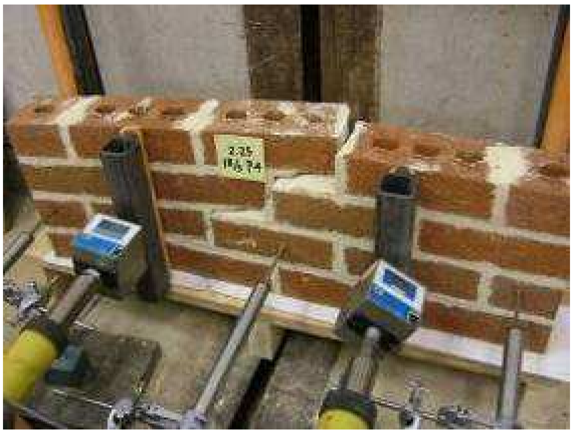
Figure 3.15 Carbonation measurement

3.5.2 Flexural strength test of brickwork

The flexural strength of brickwork was derived from the strength of wall panels tested to destruction at 91 days after construction (28 days for the cement mortared brickwork). The mean and characteristic flexural strengths for both parallel and perpendicular to bed joint testing were obtained from a sample of six specimens.

The panels were loaded under four-point bending for a plane of failure either parallel (Figure 3.16 (a)) or perpendicular (Figure 3.16 (b)) to the bed joints. The procedure of construction and tests were in accordance with BS EN 1052-2:1999. The characteristic values achieved by the specimens were considered to be the flexural strengths of the brickwork. Two layers of polytetrafluoroethylene (PTFE) were put underneath each specimen to ensure that the base is free from excessive frictional restraint. A constant displacement rate was set to ensure the maximum load can be achieved in approximately 10 minutes.

(a)



(b)

Figure 3.16 Flexural strength test apparatus
(parallel and perpendicular to bed joints)

The characteristic flexural strength f_{xk} is obtained as follows:

$$f_{xk} = anti\log_{10}(y_c)$$

$$y_c = y_{mean} - k \cdot s$$

$$y_{mean} = \sum y_n / n$$

$$y_n = \log_{10} f_{xn}$$

$$f_{xi} = \frac{3F_{i,\max}(l_1 - l_2)}{2bt_u^{\;2}}$$

where

f_{xi} is the individual flexural strength

$F_{i,\max}$ is the individual maximum load

l_1 is the distance between the two outer bearings

l_2 is the distance between the two inner bearings

s is the standard deviation for the n log values

k is a function of n

n is the number of individual specimens

b is the height or width of specimen perpendicular to the direction of span

t_u is the width of masonry unit

3.5.3 Bond wrench test of brickwork

Bond wrench strength was determined by testing quadruplet brick prisms at selected ages (14, 28, 56, 91 and 365 days). Specimens were removed from the climate room at the prearranged time and tested in accordance with BS EN 1052-5:2005. Four prisms for each brick-mortar combination were completed to give 12 mortar joints except when occasionally some weakly bonded joints failed during handling or preparation for testing.

The prism was clamped securely in the retaining frame such that the second from top brick was restrained against rotation. A bending moment is applied to the test joint through a lever-arm clamped onto the top brick. The test was under load control, and the loading rate was maintained at 0.05 N/mm^2/min. Figure 3.17 shows the details of the bond wrench test setups. Apparatus 1 was used in the first four series (series I to IV), whilst apparatus 2 was used in the last two series (series V and VI). When compared, using t-test, there was no significant statistical difference between the results obtained from the two set-ups.

Apparatus 1

Apparatus 2

Figure 3.17 Bond wrench test apparatus

In apparatus 1 loading was applied manually by continuously pouring lead shot into the bucket hung at the end of the lever until failure of the joint. The maximum load was obtained by weighing lead shot. The loading and unloading process was heavy manual work and maintaining a constant loading rate was at times difficult. Apparatus 2 was therefore developed using a pneumatic loading system. The load applied to the specimens was automatically recorded and displayed by a digital load cell. The brickwork prisms tested can be lifted up by operating the hydraulic jack beneath the specimen. Apparatus 2 improved consistency and speed of testing.

3.5.4 Initial shear strength test of brickwork

As specified in BS EN 1052-3:2002, the initial shear strength of brickwork was determined by testing triplet brick specimens to failure after curing for 91 days (28 days for the cement mortared brickwork). The specimens were subjected to three-point horizontal in-plane loading, with three levels pre-compression applied perpendicular to the bed joints. Steel plates were used to apply loads uniformly into the brickwork specimen. The load was applied on the plate at the side of the middle brick. The displacement of each brick was registered by the transducer set on the side faces of the specimen (Figure 3.18).

Figure 3.18 Initial shear strength test apparatus

In this project ten shear triplet specimens were constructed for each combination of brick and mortar. Three or four specimens were tested at each of pre-compression loads, which gave stresses at 0.2, 0.6 and 1.0 N/mm^2 respectively. The shear stress was increased at a rate of 0.2 N/mm^2/min. The whole loading process was automatically recorded and the data saved directly onto computer. The maximum load and its corresponding pre-compression load can be tracked and used to calculate on the values of individual shear strength and individual pre-compression stress. The initial shear strength and angle of internal friction for each series were determined from a plot of shear stress and pre-compression stress (Figure 3.19). The initial shear strength was determined from linear regression of the data back to zero normal stress. The characteristic value of the initial shear strength was taken as f_{vok} where f_{vok} = 0.8 $f_{vo,}$ and the characteristic angle of internal friction was obtained from $tan\ \alpha_k$ = 0.8 $tan\ \alpha$.

3.5.5 Compressive strength test of brickwork

In accordance with BS EN 1052-1:1998, the compressive strength of the

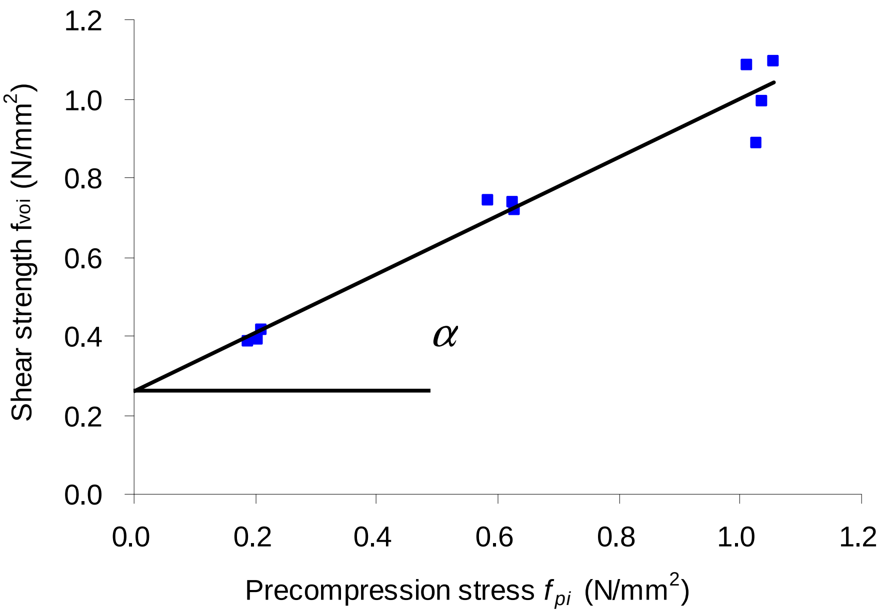


Figure 3.19 Shear strength and angle of internal friction α

baseline mortared brickwork was determined by loading wall panels in uniaxial compression to destruction at the age of 91 days (Figure 3.20). Six specimens were built and tested to obtain the average and characteristic compressive strengths. A thin layer of quick setting dental plaster was applied before testing to ensure that a uniform load distribution was applied to each specimen. A constant displacement rate was selected to ensure that the maximum load was achieved between 15 and 30 minutes.

Figure 3.20 Brickwork compressive strength test apparatus

3.6 Test results

Experimental data were processed in accordance with the corresponding British Standards. Mechanical strength results for the brickwork are generally expressed as both the average (mean) and 95% characteristic values. All the failure modes and test results of specimens are presented and discussed in Chapters 4-7. Main conclusions drawn from the experimental work are outlined in Chapter 8.

BLANK PAGE

4. Mortar properties

4.1 Introduction

Not only do the various constituents of masonry mortars have a significant influence on their fresh and hardened properties, but they also govern the resultant brickwork properties as well. Characterising the properties of hydraulic lime mortars is therefore not only important to understand the materials themselves, but it is essential to understand bond formation within brickwork, which is the main focus of this study. Although mortar characteristics are important influential factors in brickwork performance, the final properties of the mortar within brickwork joints is a result of complex dynamic moisture transfer interaction between the two materials from initial construction (Goodwin and West 1982, Lawrence and Page 1995, Groot 1997, Sugo et al. 2001).

In this chapter the fresh and hardened properties of the experimental hydraulic lime mortars mixes are reported, establishing a basis for the further investigation of hydraulic lime brickwork properties reported in later chapters. Workability of the fresh mortars was characterised primarily using the flow table test. Variations in flow table performance, in response to varying water: lime ratios, are outlined. In addition results for the fresh mortar desorptivity are also presented; this work was conducted by the University of Manchester. Following this, the test results for flexural and compressive strengths of the hardened mortars, varying with different parameters such as lime grade and supplier, mix ratios, sand type and curing time, are presented in detail. For comparison, properties of cement: lime: sand mortars (1:3:12, 1:2:9 and 1:1:6) were also tested and reported in this chapter.

4.2 Fresh mortar properties

As with cement based mortars, previous research work has reported that initial water: lime ratio influences both the fresh and final hardened properties of hydraulic lime mortars (Allen et al. 2003, Lanas et al. 2004). As with cementitious materials, increasing water content reduces the final strength of hydraulic lime mortars resulting from the changes in pore structure. In this project, the effect of water: lime ratio on the initial workability of fresh mortar was examined by testing the mortar consistency using the flow table test. The effect of water content on the strengths of hardened mortar samples was also studied and is presented later.

4.2.1 Flow table test

The mortar water content and workability for mortar mix were initially controlled by the same experienced bricklayer used throughout the study. Once water contents were set, all constituent materials were thereafter batched by mass to maintain mortar consistency. A flow table was used to measure the level of consistency (a measure of fluidity) of the freshly mixed mortars, in accordance with the test procedure in BS EN 1015-3:1999.

Flow value for each mortar mix was taken as the average diameter measurement from two repeat mortar specimens. Initially the mortar specimen is tamped inside a truncated conical mould placed centrally on a jolting metal flow table. The table is jolted 15 times by raising the flow table and allowing it to fall through a standard distance, with each cycle taking one second. The water: binder ratios and flow values of different mixes are summarized in Table 4.1.

The flow values ranged between 152 mm and 187 mm, with the majority in the range of 175±10 mm. Mortars were therefore generally in accordance with the same workability specification used in BS EN 1015-2:1999. The average values were determined from a number of repeat batches of mortar mixes; the numbers of repeat batches are indicated in parentheses in Table 4.1. The coefficients of variation for flow table testing were low; the highest was just 4.8% for the NHL mortar mixes, confirming consistency of batching, mixing, testing and materials supply. Mortar workability was deliberately varied (slightly) by the bricklayer in Series II to accommodate the extreme brick water absorptions. For the highest absorption bricks ('Hardwicke Welbeck Autumn Antique') and the lowest absorption brick ('Staffordshire Slate Blue Smooth') the water contents of the mortars were increased and reduced respectively. 'Hardwicke Welbeck Autumn Antique' required mortar with a slightly higher level workability (average flow value 173mm), whilst the 'Staffordshire Slate Blue Smooth' required lower level workability mortar (average flow value 160mm). Subsequent tests (see section 4.3.6) showed the variations in mortar compressive strength as a result of these small variations in water: lime ratio.

As shown in Table 4.1, the water required to achieve similar workability increased with sand content. The water: lime ratio increased from 1:1.43 to 1:1.69 when sand content increased from 2 parts to 2½ parts by volume. With more sand in the mix, more water is required to fill the voids between the sand particles to maintain same mortar flow.

The water required to achieve similar workability decreased (water: lime ratio decreased from 1.57 to 1.40) when the lime grade increased from NHL 3.5 to NHL 5. The average flow value decreased from 172 mm for NHL 3.5 mixes to 165 mm for NHL 2 mixes, with similar water: lime ratio. That the water required decreased with the increased lime grade may be attributed to the microstructure of different limes. In section 3.3.1, the bulk densities of NHL2, NHL 3.5 and NHL 5 were measured as 564, 592 and 660 kg/m^3 respectively. The lowest grade of lime, with lowest bulk density and highest porosity, thus required most water to fill the pores.

Table 4.1 Hydraulic lime mortar mix properties

Brick	Lime	Sand	Mix proportions (by volume)	Water:lime ratio			Flow value (mm)		
				Average	CV (%)	Range	Average (No. of Specimens)	CV (%)	Range
Berkeley Red Multi	NHL 5	**Binnegar**	1:2.25	1.40	8.1	1.28-1.54	170 (13)	4.5	155-178
	NHL 3.5		1:2	1.43	5.8	1.38-1.59	172 (7)	2.7	166-180
			1:2.25 (Baseline)*	**1.57**	**6.6**	**1.38-1.78**	**172 (31)**	**3.2**	**160-180**
			1:2.5	1.69	3.2	1.59-1.71	172 (6)	1.1	169-174
	NHL 2		1:2.25	1.58	3.6	1.49-1.62	165 (6)	1.1	162-166
	NHL 3.5	Allerton Park	1:2.25	1.43	-----	-----	137 (1)	-----	-----
		Croxden		1.40	-----	-----	164 (1)	-----	-----
		Yellow Pit		1.55	-----	-----	156 (1)	-----	-----
Staffordshire Slate Blue Smooth	NHL 3.5	Binnegar	1:2.25	1.41	4.3	1.30-1.50	160 (9)	4.3	152-173
Hardwicke Welbeck Autumn Antique				1.47	3.0	1.40-1.51	173 (8)	4.8	162-187

* **Bold** font shows the baseline mortar for comparison.

By using either the coarser-graded (‘Allerton Park’) or the finer-graded (‘Yellow Pit’) sands, instead of the well-graded ‘Binnegar’ sand, reduced flow table values. The average flow table values were 137 mm for the ‘Allerton Park’ sand and 156 mm for the ‘Yellow Pit’ sand, compared to an average of 172 mm for the ‘Binnegar’ sand. The shortage of fine particles in the coarsely-graded ‘Allerton Park’ sand will have reduced the water content required to lubricate the sand particles. Whereas the higher fine particle content in the ‘Yellow Pit’ sand increased the surface area and so required more water, although flow table reduced.

In this study the flow table provided a consistent and repeatable methodology for assessing initial workability of hydraulic lime mortar specimens using the ‘Binnegar’ sand. However, for the coarser and finer sands the flow table performance was less consistent. British Standard BS EN 1015:4 1999 specifies an alternative method for determining the consistency of freshly mixed mortar. The BS EN 1015-4 test measures the penetration depth of a plunger rod falling into the fresh mortar specimen. Normally a linear correlation between flow value and the plunger penetration value for the same type of mortar with increasing water content is expected. Others have resorted to characterising rheology of fresh hydraulic lime mortars by measuring yield shear stress and viscosity (Seabra et al. 2007). Alternative workability tests were not investigated in this study as it was not a key research aspect of this work.

4.2.2 Desorptivity test

Desorptivity tests were conducted by the University of Manchester at request of the author on behalf of this study. The novel desorptivity test developed by the University of Manchester team was used to evaluate the water retaining ability of the natural hydraulic lime mortars (Ince et al. 2010). The lower the desorptivity value a mortar obtains, the better water retaining ability it has.

Factors such as lime grade, lime supplier, mortar mix proportions and sand type on desorptivity were examined. The measurements were carried out on freshly mixed mortars. Although the various mix proportions were set by volume (1:2, 1:2.25 and 1:2.5), the materials were batched by mass.

4.2.2.1 Influence of binder hydraulicity on desorptivity

The measured desorptivity values for 1:2.25 lime:sand and 1:3:12 cement: hydrated lime mortars are presented in Table 4.2. As with all desorptivity evaluations, the tests were carried out at three different suction pressures (0.10, 0.15 and 0.20 N/mm^2). The pressures are reported to be representative of typical brick suctions (Hall and Hoff 2002, 2005). The cement: lime: sand mortar, which has greatest hydraulicity, exhibited significantly better water retaining qualities than the NHL mortars. Ince et al. (2010) previously reported an OPC mortar without hydrated lime has having higher desorptivity compared natural hydraulic lime mortars. The significantly improved water retention recorded here might therefore be reasonably attributed to the hydrated lime content rather than the use of cement. Ince et al. (2010) also reported that a CL90 air lime mortar had lowest water desorptivity.

At each of the three different applied pressures the NHL 5 mortar consistently had higher desorption values than both the NHL 2 and NHL 3.5 mortars. This observation was in line with previous tests reported by Ince et al. (2010). However, the lower desorptivity results of the NHL 3.5 compared to that of the NHL 2 mortars was unexpected. Previously Ince et al. (2010) only studied NHL 5 and NHL 2 hydraulic lime mortars, with desorptivity values of 1.65 and 1.33 mm/min^{½} respectively, significantly lower than those reported here. The influence of sand on desorptivity performance is discussed later.

Table 4.2 Mortar desorptivity values at different applied pressures

Degree of hydraulicity	Mortar	Pressure (N/mm^2)	Desorptivity (mm/min$^{1/2}$)
↓	NHL 2 (1:2.25)	0.1	3.57
	NHL 3.5 (1:2.25)		2.55
	NHL 5 (1:2.25)		4.00
	1:3:12		0.36
↓	NHL 2 (1:2.25)	0.15	3.92
	NHL 3.5 (1:2.25)		3.66
	NHL 5 (1:2.25)		4.66
	1:3:12		0.47
↓	NHL 2 (1:2.25)	0.2	4.96
	NHL 3.5 (1:2.25)		3.97
	NHL 5 (1:2.25)		5.41
	1:3:12		0.81

4.2.2.2 Influence of lime supply on desorptivity

Apart from limes supplied by Castle Cement, the desorptivity of the St Astier NHL 3.5 and Limetec Premix moderately hydraulic mortars were also examined (Table 4.3). The desorptivity values increased with the applied suction pressure and varied with lime supplier. Desorptivity of the Limetec premix mortar was more than twice that of the corresponding values for the Castle Cement mortar under various pressures. From this comparison, it seems apparent that the water retaining properties of NHL mortars differs significantly depending on source, which may account for discrepancies with values reported previously by Ince et al. (2010) and in the resultant brickwork bond performance reported later (Chapter 6).

Table 4.3 NHL mortar desorptivity values using different lime suppliers

Lime source	Pressure (N/mm^2)	Desorptivity ($mm/min^{1/2}$)
Castle Cement (NHL 3.5)	0.10	2.55
	0.15	3.66
	0.20	3.97
St Astier (NHL 3.5)	0.10	4.09
	0.15	4.75
	0.20	5.89
Limetec Premix (moderately hydraulic)	0.10	6.57
	0.15	7.09
	0.20	8.34

4.2.2.3 Influence of different binder: sand ratio on desorptivity

The influence of material mix proportions on mortar desorptivity was also examined, with three binder: sand ratios 1:2, 1:2.25 and 1:2.5 studied. Results of these tests are shown in Table 4.4. It can be seen that the desorptivity values not only increased with suction pressure, but also generally increased with the sand content. As the particle size of lime is much finer than the sand particles, the considerably higher surface area of lime (Ince et al. 2010) can help to retain more water.

4.2.2.4 Influence of sand grading on desorptivity

The effect of sand grading on the desorptivity values is outlined in Table 4.5. The well-graded 'Binnegar' sand showed better water retaining ability than the coarser graded 'Allerton Park' and 'Croxden' sand mortars. In their study Ince et al. (2010) used a 'Croxden' sand, although in a richer 1:2 (by volume) mix than reported here. Their desorptivity values for NHL2 and NHL5 mortars with 'Croxden' sand were 1.33 and 1.65 $mm/min^{½}$ respectively, significantly lower than those reported in Table 4.5. The source of this inconsistency is unclear, but may be attributed to combination of factors, including variation in lime supply (Castle Cement limes were used in both studies), variation in sand supply, and the use of richer mix proportions. The inconsistency may also point towards problems with the novel test methodology.

Table 4.4 Desorptivity values of NHL mortars with different lime/sand ratio

Lime: sand ratio	Pressure (N/mm^2)	Desorptivity ($mm/min^{1/2}$)
1:2	0.10	2.31
	0.15	2.99
	0.20	3.97
1:2.25	0.10	2.55
	0.15	3.66
	0.20	3.97
1:2.5	0.10	3.24
	0.15	3.59
	0.20	4.25

Desorption values for the finer ‘Yellow Pit’ sand mortars were not expected to be higher than the ‘Binnegar’ sand mixes. In previous studies finer sand mortars have exhibited better water retention properties (lower desorptivity values), which was explained by attributing to greater surface area provided for wetting and bonding with lime. Therefore, the ‘Yellow Pit’ sand tests were repeated but without change in performance. This is an unexpected anomaly and cannot be readily explained as both sands have good distributions of particle sizes. Further work with the University of Manchester desorption test methodology may be required.

Table 4.5 Desorptivity values of NHL mortars with different sand types

Sand	Pressure (N/mm^2)	Desorptivity ($mm/min^{1/2}$)
Allerton Park	0.10	3.67
	0.15	4.47
	0.20	5.47
Binnegar	0.10	2.55
	0.15	3.66
	0.20	3.97
Croxden	0.10	4.11
	0.15	4.84
	0.20	6.93
Yellow Pit	0.10	3.19
	0.15	3.95
	0.20	4.85

4.3 Mortar flexural and compressive strengths

Flexural and compressive strength tests are one of the main ways of characterising hardened mortar properties. 28-day compressive strengths are used to characterise and specify performance of cement: lime: sand mortars in BS EN 459-1 and BS EN 1996-1-1:2005 (Eurocode 6). In this study the flexural and compressive strengths of mortar samples were determined in accordance with BS EN 1015-11:1999. Mortar flexural strength is initially measured by three-point load testing 160 x 40 x 40 mm specimens. Thereafter, compressive strength is determined by crushing the two specimen halves resulting from the flexural strength test. In total approximately 750 mortar prism specimens were cast, corresponding to same number of flexural strength tests and 1500 compressive strength tests on the halved prisms. The test procedures were outlined in more detail in section 3.5.1.

In bending the mortar specimens fractured in a brittle manner once the flexural strength had been reached. The peak loads were automatically recorded by the data-logger. The flexural strength of mortar, f_f (N/mm^2), was calculated from:

$$f_f = 1.5 F_f \, l / b^3$$

where:

F_f is the maximum load obtained in the flexural test (N)

l is the span between two support rollers (100 mm)

b is the cross-sectional sample dimension (40 mm)

The compressive strength of mortar, f_c (N/mm^2), was calculated by the equation:

$$f_c = F_c / b^2$$

where

F_c is the maximum load obtained in the compressive test (N)

b is the breadth of specimen (40 mm)

As mentioned in the previous chapter, the whole project was divided into six series of brickwork construction and testing, performed between May 2006 and December 2008. In each new series fresh lime materials were used. Consequently slight variations in material performance were detected from series to series. As the strengths of hydraulic lime mortars were generally much lower than the cement mortars, these performance variations were considered more significant. Although this complicated comparisons across the various series' results, comparisons of the specimens made in each series were straight forward as the same batch of binders were used throughout each series. Comparisons between each series for the baseline mortar (1:2.25, Castle Cement NHL 3.5: ‘Binnegar’ sand) were performed (see 4.3.7). This approach provided some insight into the consistency of different lime production batches.

4.3.1 Influence of lime grade

Comparison of different lime grades, NHL 2, NHL 3.5 and NHL 5, were mainly conducted in series II. The flexural and compressive strength test results for these mortars at 28 and 91 days are summarized in Table 4.6 below. The average values were determined from the number of the tests shown in parentheses. The mortar strength performance of different batches was consistent, with the coefficients of variation generally below 15%.

Mortar compressive strengths were generally between two and three times higher than their corresponding flexural strengths. The influence of lime grade on compressive strengths of mortar is significant, especially comparing the NHL 2 and NHL 5 mixes. Mortar compressive strength increased with lime grade and age (Figure 4.1). At 28 and 91 days, the NHL 2 mortar developed 57% and 76% of the NHL 5 mortar strengths respectively. Initially the higher grade hydraulic lime mortar developed compressive strength at a faster rate (up to 28 days). NHL 5 at 28 days achieved 73% of its final 91 day strength, compared to 56% for the NHL 2 and 57% for the NHL 3.5 mixes. This behaviour is expected, reflecting the relative importance of the hydraulicity and carbonation components for each mortar mix strength development. The influence of lime grade on the flexural strength of mortar is insignificant and less clear. It is believed that small micro-cracks formed during the mortar drying process, explaining the lower strengths observed in the NHL 5 mortars in particular.

Table 4.6 Influence of lime grade on mortar strengths (Series II)
(Lime: sand 1:2.25)

Binder	Age (days)	Flexural strength		Compressive strength		
		Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)	Proportion to 91 day strength
NHL 2	28	0.28 (*17*)	11.5	0.54 (*33*)	7.9	56%
	91	0.40 (*18*)	6.9	0.97 (*36*)	8.9	---
NHL 3.5 (Baseline)	**28**	**0.33 (*43*)**	**12.8**	**0.64 (*86*)**	**6.9**	**57%**
	91	**0.40 (*45*)**	**13.5**	**1.12 (*90*)**	**8.7**	**---**
NHL 5	28	0.28 (*12*)	13.1	0.94 (*23*)	6.8	73%
	91	0.36 (*11*)	17.1	1.28 (*22*)	10.6	---

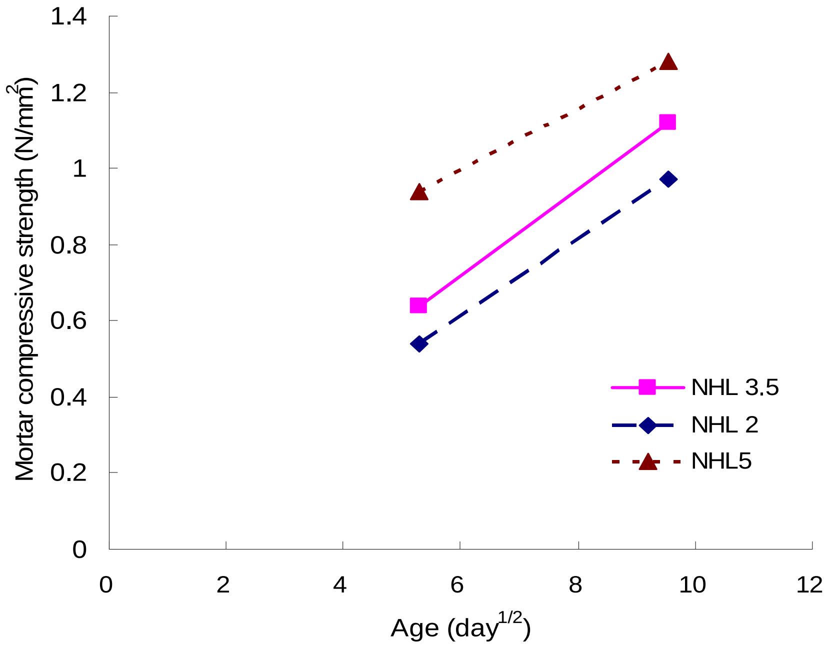


Figure 4.1 Influence of lime grade on mortar compressive strength

The mortar compressive strengths, for constant lime: sand ratio (1:2.25) at 91 days, varied between 0.97 and 1.28 N/mm^2. The hydraulic lime mortars at 91 days generally conform to M1 performance. Although increasing lime grade improved mortar compressive strengths, it was generally to a much lesser extent than the mortar grading values might imply. The improvement in compressive strength moving from NHL2 to NHL3.5 was between 15% and 19% (at 28 or 91 days), whilst the grade change might suggest a 75% improvement in strength. The 47% enhancement in compressive strength at 28 days by using NHL 5 instead of NHL 3.5 mapped closely the change implied by the grading change (43%). However, by 91 days the strength enhancement was only 14%. Thus, it is important for the construction industry not to confuse binder performance determined in accordance with BS EN 459-1, using rich mixes with standard sands, with the performance of typical masonry mortars.

4.3.2 Influence of mix proportion

Influence of the mix proportions on the development of mortar strength is summarised below in Table 4.7. Three different mixes were chosen for the comparison: 1:2 (NHL3.5:sand by volume), 1:2.25 and 1:2.5. The mixes followed current industry practice. Strength development of the three mortar mixes with age (up to 91 days) is shown in Figure 4.2.

Although the mortar flexural strength tended to increase with increasing hydraulic lime content, it was less sensitive compared to the influence of lime content on the mortar compressive strength. By 91 days the 1:2 mix had achieved 54% greater compressive strength than the weaker 1:2.5 mix. The influence of lime content on compressive strength was more apparent at the later ages (from 28 days to 91 days, see Table 4.7 and Figure 4.2). By 91 days the 1:2 mix may be classified as an M1 mortar, whilst the 1:2.25 mix (in Series I) was close to achieving M1.

Table 4.7 Influence of constituent proportions of mortar (Series I)

Binder	Binder: Aggregate ratio	Age (days)	Flexural strength		Compressive strength		
			Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)	Percentage of 91 days
NHL 3.5	1:2	28	0.36 (13)	6.3	0.68 (29)	3.7	57%
		91	0.40 (15)	4.8	1.20 (30)	8.4	---
	1:2.25 (Baseline)	**14**	**0.25 (3)**	**---**	**0.39 (6)**	**19.2**	**41%**
		28	**0.30 (22)**	**7.8**	**0.60 (45)**	**5.9**	**63%**
		56	**0.37 (6)**	**14.4**	**0.85 (12)**	**9.8**	**89%**
		91	**0.45 (23)**	**17.2**	**0.95 (50)**	**12.1**	**100%**
		365	**0.49 (3)**	**---**	**0.98 (6)**	**5.1**	**103%**
	1:2.5	28	0.32 (14)	12.2	0.55 (30)	6.0	71%
		91	0.36 (15)	16.7	0.78 (28)	4.2	---

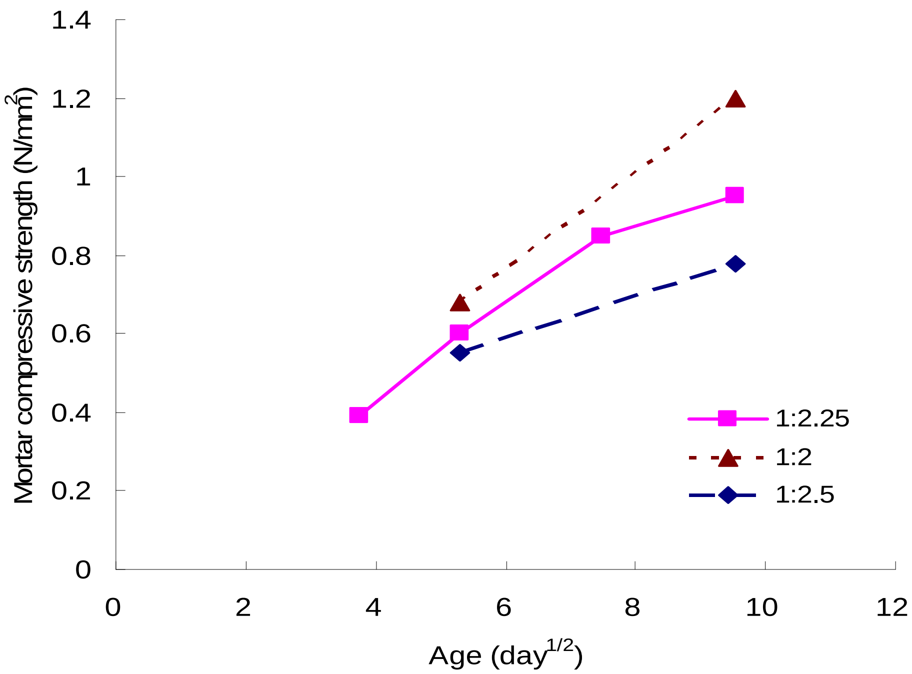


Figure 4.2 Influence of lime content on mortar compressive strength

Both flexural and compressive strengths increased with age. The increase in flexural strength was not as significant as compressive strength development, in part due to the influence of shrinkage micro-cracking on strength. The rate of strength development by 28 days was comparable although the percentage strength gain increased with reducing lime binder content, Table 4.7. Mixes 1:2, 1:2.25 and 1:2.5 developed 57%, 63% and 71% of their 91 day strengths respectively.

The mortar mixes with least lime contents gained strength more slowly after 28 days. This could be due to the process of mortar strength development at different ages. The early phase of strength increase is mainly from the lime hydration, and the later phase of strength development is mainly attributed to carbonation. At 91 days the mortar specimens have largely carbonated (more details about carbonation will be discussed in section 4.4). The mortar with the greatest lime content developed the highest strength.

The properties of the baseline mortar (1:2.25 Castle Cement NHL 3.5: 'Binnegar' sand by volume), was investigated at 14, 28, 56, 91 and 365 days. Mortar strength increased with age. At 14 days, the mortar obtained 41% of its 91 day strength and reached 63% at 28 days. After 91 days, the mortar strength still increased, but at a much slower rate. It is reasonable to assume that the strength increase after a year would eventually cease as physical and chemical changes in the mortar were complete. The baseline mortar, at 91 days, achieved 97% of its one-year compressive strength. Since indicator tests at 91 days shown that carbonation is nearly complete (section 4.4) this is perhaps not surprising.

In the Foresight project, the compressive strength developed with NHL 3.5 lime mortar was about 1.6 N/mm^2 for 1:2 mix proportion at 28 days (Allen et al. 2003), whereas, the result herein was 0.68 N/mm^2. However, the use of small cylindrical specimens by the Foresight project makes direct comparison complicated. Further, differences in curing conditions also contribute to the difference in strengths. The Foresight project stored specimens at 85% relative humidity; whereas all specimens herein were stored at 65% RH (lower humidity reduces hydration). Sand grading and type is also known to influence mortar properties and is therefore further attributed as another cause for the difference in performance.

Lanas et al. (2004) conducted tests on mechanical properties of NHL5 mortars using four types of sand. Their results for compressive strength of 1:2 NHL5 mortars varied from 4.4-6 N/mm^2. These are six to eight times higher than the values measured herein. However, one main reason for the improved performance reported by Lanas et al. can be ascribed to the calcium carbonate aggregates used in their study. In general, calcium carbonate aggregates develop stronger mortars than those using mainly silicate sands. Another reason could be attributed to the difference of testing procedures, which were not presented in detail in the paper.

Our collaborative research partner in the wider EPSRC project, the University of Bristol (Ball et al. 2009), examined mortar compressive strength in their study, using same source Castle cement NHL 3.5 combined with 'Croxden' sand. The mortar samples achieved higher strength, 1.5, 1.8 and 1.9 N/mm^2 at 7, 39 and 63 days respectively, than the 1:2 mortar mix in Table 4.7. As the different 'Croxden' sand used had little influence on mortar strength (see 4.3.3), the variation of mortar mixing and curing procedures followed might be the reason.

4.3.3 Influence of sand grading

Four types of sand with different particle size distributions (see Chapter 3), 'Binnegar', 'Allerton Park', 'Croxden' and 'Yellow Pit' sands, were used for comparison. Their flexural and compressive strengths at 28 and 91 days are summarised in Table 4.8. The influence of sand types on flexural strength was not significant, although there was a trend for mortars with finer sand to develop lower flexural strength. The trends of compressive strength development are plotted in Figure 4.3. Mortar compressive strength increased with age, enhancing between 35% and 73% from 28 days to 91 days.

Table 4.8 Influence of sand type (Series III)

Binder: Aggregate ratio	Sand type	Age (days)	Flexural strength		Compressive strength		
			Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)	Percentage of 91 days
1:2.25	**Binnegar (Baseline)**	**28**	**0.33 (6)**	**9.5**	**0.64 (12)**	**10.7**	**66%**
		91	**0.40 (12)**	**7.9**	**0.98 (24)**	**13.1**	-----
	Allerton Park	28	0.34 (3)	---	1.13 (6)	9.6	74%
		91	0.34 (3)	---	1.52 (6)	10.8	-----
	Croxden	28	0.27 (3)	---	0.59 (6)	1.8	53%
		91	0.35 (3)	---	1.02(6)	4.8	-----
	Yellow Pit	28	0.27 (3)	---	0.50 (6)	9.0	66%
		91	0.27 (3)	---	0.76 (6)	4.4	-----

Mortar compressive strengths varied significantly with sand grading and age. By 91 days, the coarser sand ‘Allerton Park’ developed 55% higher final strength than the baseline mix. ‘Croxden’ sand reached slightly higher compressive strength than the finer sand baseline mortar at 91 days, although the specimens had lower strength than the baseline at 28 days. The mortar with the finest sand, ‘Yellow Pit’, developed the lowest compressive strength, just 50% of the compressive strength of the mortar using ‘Allerton Park’ sand. This compressive strength reduction can be attributed to the increased lime: water ratio as well as aggregate characteristics such as shape, interlock and particle strength. Compared to compressive strengths, flexural strengths of the mortars were much less affected by the change in sand grading, although the ‘Yellow Pit’ sand mortar consistently exhibited lowest flexural strength.

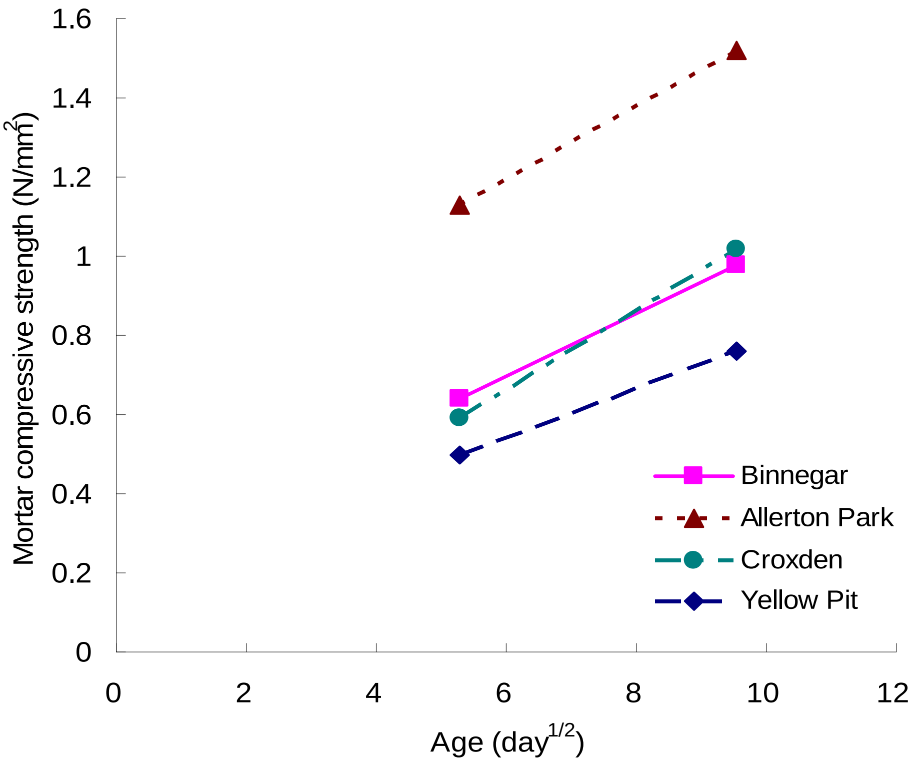


Figure 4.3 Influence of sand type on mortar compressive strength

4.3.4 Influence of lime supplier

Hydraulic limes are now available throughout the UK from various suppliers, although most materials are imported. Hydraulic Lincolnshire Lime, hl2, is the only British hydraulic lime, manufactured by Singleton Birch at Melton Ross Quarries, Barnetby, North Lincolnshire. StA is manufactured by CESA, St. Astier, France. Most raw materials of Castle Cement (now owned by Heidelberger Cement) and the Limetec Premix originated from France. Castle Cement provided a range of NHL 2 (feebly), NHL 3.5 (moderately) and NHL 5 (eminently) hydraulic limes in the research project. Only NHL 3.5 lime was used for comparing with other NHL 3.5 binders provided by other suppliers (and the moderately hydraulic mortar for the Limetec premix). The results were outlined below in Table 4.9 and Figure 4.4.

Table 4.9 Influence of lime supplier on mortar strengths (series V)

Lime supplier	Binder: Aggregate ratio	Age (days)	Flexural strength		Compressive strength		
			Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)	Percent age of 91 days
Castle Cement (NHL 3.5)	**1:2.25 (Baseline)**	**28**	**0.35 (24)**	**11.2**	**0.67 (47)**	**5.8**	**58%**
		91	**0.48 (20)**	**8.3**	**1.16 (41)**	**4.1**	
hl2 (NHL 3.5)		28	0.35 (3)	---	0.73 (6)	13.3	57%
		91	0.51 (3)	---	1.29 (6)	7.6	---
St Astier (NHL 3.5)		28	0.20 (3)	---	0.45 (6)	2.6	90%
		91	0.26 (3)	---	0.50 (6)	1.9	---
Moderately hydraulic Limetec premix		28	0.49 (3)	---	1.26 (6)	4.2	83%
		91	0.61 (3)	---	1.51 (6)	3.4	---

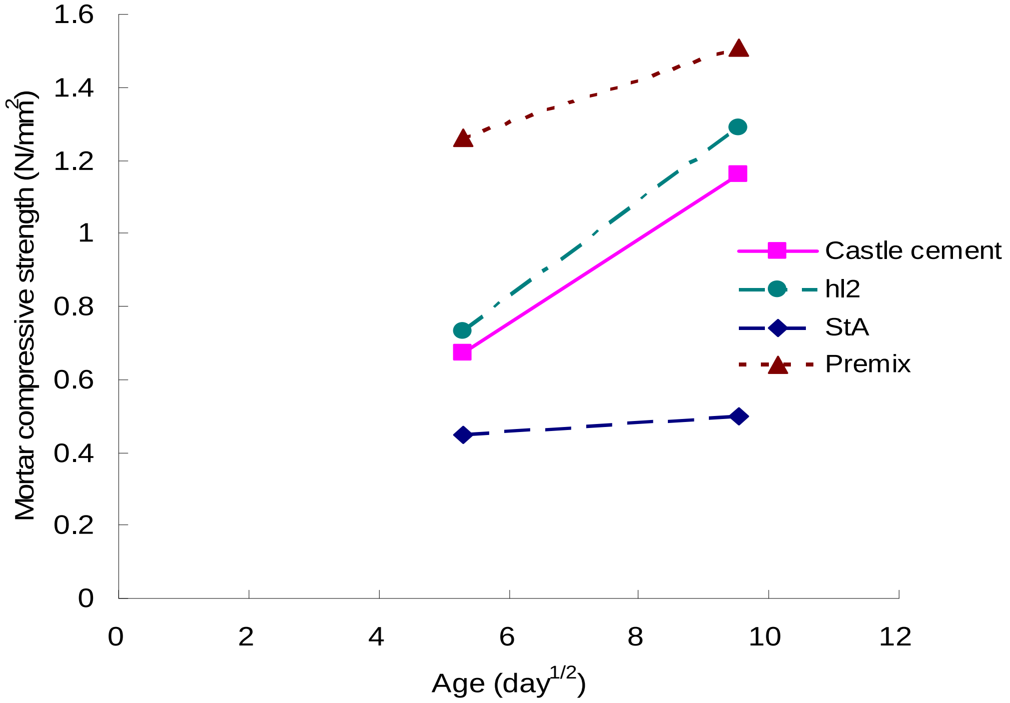


Figure 4.4 Influence of lime supplier on mortar compressive strength

Performance of products provided by the different lime supplier was inconsistent. Lime produced by St Astier developed the lowest flexural and compressive strengths (up to 91 days), whilst the Limetec premix mortar developed the highest strengths, 2-3 times the strengths produced by the St Astier lime mortar. The other two lime mortars, Castle Cement and hl2, were comparable in performance. The strengths of hl2 mortar were slightly higher than the Castle Cement material.

St Astier and Limetec premix mortar developed strengths at a faster rate (90% and 83% respectively) up to 28 days. In comparison, both the Castle Cement and hl2 lime mortars developed similar percentages of their 91 day strengths after 28 days, around 60%. Performance of similar specification hydraulic limes was inconsistent. Likely reasons for the difference in mortar performance might be attributed to variations in composition of the raw materials and the manufacturing processes. All hydraulic lime binders were supplied in the understanding that they conformed to BS EN 459-1:2010 performance specifications. This was not independently checked during this work. As previously discussed there is considerable tolerance in the performance of specification lime binders.

Given the low strength of the lime mortars this variation in performance is potentially more significant than similar variations in higher strength (cement) binders. The research in this project was limited to NHL 3.5 grade from different manufacturers. Further investigation on other lime grades and more lime suppliers needs to be conducted. Even for the same grade lime (NHL 3.5) produced from the same supplier (Castle Cement Ltd.), slight variations from batch to batch were detected during the experimental work. The consistency of the lime was investigated in the project and summarised in section 4.3.7.

4.3.5 Comparison of hydraulic lime and cement lime mortars

Previous research on bond properties of brickwork has generally been undertaken using cement mortars (Chapter 2). It is therefore of interest to understand the strength differences between hydraulic lime and cement mortars. The experimental comparisons are presented below (Table 4.10). Three of the leanest cement: lime: sand mortars (1:3:12, 1:2:9 and 1:1:6) were compared with the baseline hydraulic lime mortar performance. Strength development with age of the four mortars is compared in Figure 4.5.

Table 4.10 Comparison between hydraulic lime mortar and cement mortar (Series IV, VI)

Binder	Mix proportions	Age (days)	Flexural strength		Compressive strength		
			Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)	Percentage of 91 day strength
NHL 3.5	**1:2.25 (Baseline)** Series VI	**14**	**0.27 (6)**	**7.7**	**0.51 (10)**	**5.2**	**52%**
		28	**0.30 (8)**	**15.2**	**0.56 (16)**	**3.3**	**57%**
		91	**0.38 (9)**	**11.3**	**0.99 (18)**	**6.1**	**100%**
Cement and hydrated lime	1:3:12 Series IV	14	0.40 (6)	12.7	1.12 (12)	15.6	83%
		28	0.42 (37)	10.3	1.08 (78)	9.3	80%
		91	0.44 (39)	9.4	1.35 (75)	6.1	100%
	1:2:9 Series IV	14	0.58 (7)	10.3	1.75 (18)	9.0	75%
		28	0.71 (20)	8.8	2.30 (41)	12.1	98%
		56	0.72 (6)	5.9	2.16 (12)	4.0	92%
		91	0.75 (18)	12.8	2.34 (36)	11.9	100%
	1:1:6 Series VI	14	1.97 (3)	---	6.06 (6)	5.8	88%
		28	1.76 (3)	---	6.64 (6)	6.6	97%
		91	2.03 (3)	---	6.86 (6)	9.9	100%

Both the flexural and compressive strengths of the baseline NHL 3.5 hydraulic lime mortar were lower than that of cement: lime: sand mortars; it was closest to the leanest cement mortar 1:3:12 mix. The 28 day strengths of the cement: lime: sand mortars used in this study conform to the requirements for class M1 (1:3:12), M2 (1:2:9) and M4 (1:1:6) specified in UK NA to BS EN 1996-1-1. The strength of NHL 3.5 mortar mix is very close to achieving M1 at 91 days.

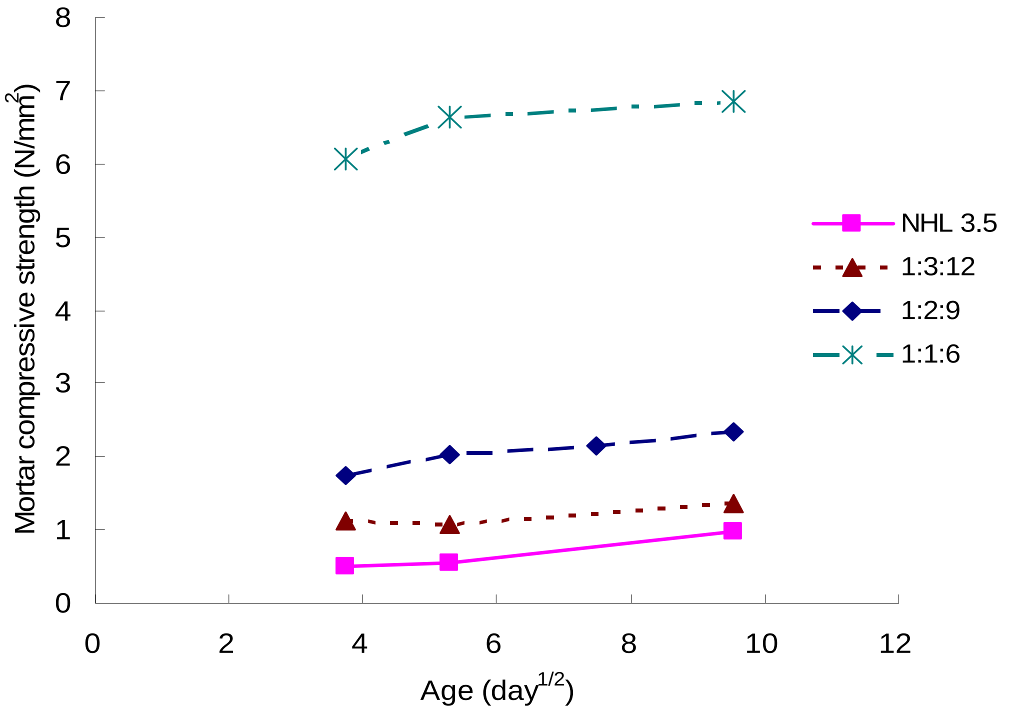


Figure 4.5 Comparison between hydraulic lime mortar and cement mortar

The flexural and compressive strengths of both hydraulic lime mortar and cement: lime: sand mortars tended to increase with age. Combining all test results previously reported in this chapter, hydraulic lime mortars, except for the St Astier and Limetec Premix mortars, at 28 days developed proportionally less of their 91 day compressive strengths than the cement: lime: mortars. The strengths of cement lime mortars increased at a faster rate at early ages. The 1:3:12, 1:2:9 and 1:1:6 mortars in the initial 14 days achieved 83%, 75% and 88% of their 91 day strengths respectively, whilst the baseline hydraulic lime mortar only reached 52% (as low as 41% in series I tests reported in 4.3.2).

By 28 days the 1:3:12, 1:2:9 and 1:1:6 cement: lime: sand mortars reached 80%, 98% and 97% of their corresponding 91 day strengths, whilst the mortar only achieved between 57% and 66% (all series results combined). The other hydraulic lime mortars developed higher early strengths at 28 days. The NHL 5 mortar achieved 73%, the 1:2.5 mix achieved 71% and the Allerton Park sand mortar achieved 74% of their 91 day strengths, although these are all still proportionally lower than the strengths attained by the cement mortars at the same age.

Reviewing the test results shown in this chapter, the mortar compressive strengths of the hydraulic lime mortars are typically between 1.5 and 4 times greater than their corresponding flexural strengths. Hydraulic lime mortar developed compressive strength much slower than similar performance cement: lime: sand mortars at early ages (up to 28 days). All series mortar mixes, using Castle Cement NHLs, achieved 53-74% of their corresponding 91-d strengths. The longer-term 91 day strength best reflects the gradual strength development of hydraulic lime mortars, rather than the 28 day strengths widely used for cement mortars. This mainly attributes to the different phase compositions between NHL and cement. C_2S is the major hydraulic phase in NHL, whilst in cement it is mainly C_3S. Compared to C_2S, the hydration rate of C_3S is much faster and makes early contribution to mortar strength.

4.3.6 Influence of water:lime ratio

As discussed earlier mortar workability was varied slightly by the bricklayer to accommodate both the high water absorption brick ('Hardwicke Welbeck Autumn Antique') and the low absorption brick ('Staffordshire Slate Blue Smooth') during series II. Although as expected both the flexural and compressive strengths decreased with the increase of water content, the experimental variation in the water: lime ratio had relatively little effect on the final baseline mortar strengths (Figure 4.6).

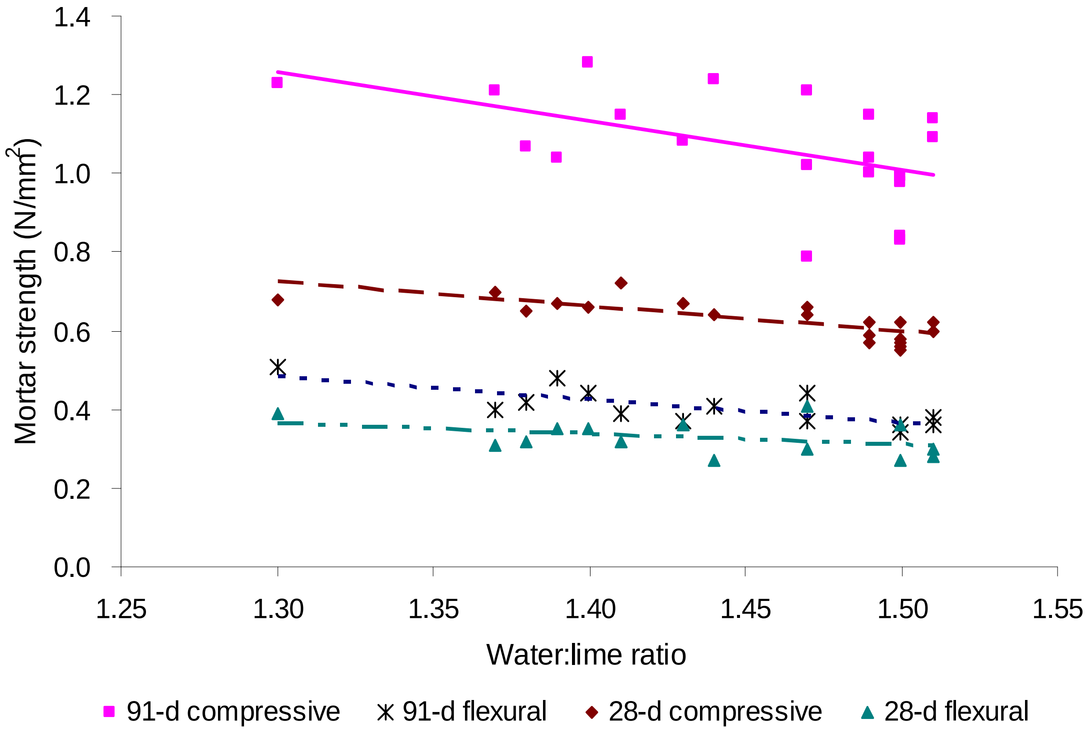


Figure 4.6 Influence of water: lime ratio on mortar strength

Allen et al (2003) reported that flexural and compressive strengths decreased with increasing water: lime ratio, although they reported non-linear regression curves. In their study the water: lime ratios covered a much wider range, roughly from 0.7 to 2.9, than herein. In this project the water: lime ratio only varied between 1.30 and 1.52. Over this narrow range relationship between strength and water: lime ratio can be approximated as linear (see Figure 4.6).

4.3.7 Consistency of lime supply

As previously discussed, variation in performance of the baseline mortar was detected during the research. To better understand any discrepancies, strength performance of the baseline mortar (1:2.25 Castle Cement NHL 3.5: 'Binnegar' sand) are summarised for all test series in Table 4.11.

Table 4.11 Comparisons between different batches of lime production

Mortar	Age (days)	Series of testing	Flexural strength		Compressive strength	
			Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)
1:2.25 Baseline	14	I	0.25 (3)	---	0.39 (6)	19.2
		III	0.30 (5)	7.1	0.53 (11)	8.9
		IV	0.18 (9)	16.1	0.39 (18)	3.9
		VI	0.27 (6)	7.7	0.51 (10)	5.2
	28	I	0.30 (22)	7.8	0.60 (45)	5.9
		II	0.33 (43)	12.8	0.64 (86)	6.9
		III	0.33 (6)	9.5	0.64 (12)	10.7
		IV	0.25 (14)	17.2	0.52 (35)	15.2
		V	0.35 (24)	11.2	0.67 (47)	5.8
		VI	0.30 (8)	15.2	0.56 (16)	3.3
	56	I	0.37 (6)	14.4	0.85 (12)	9.8
		III	0.42 (3)	---	1.08 (6)	8.1
	91	I	0.45 (23)	17.2	0.95 (50)	12.1
		II	0.40 (45)	13.5	1.12 (90)	8.7
		III	0.40 (12)	7.9	0.98 (24)	13.1
		IV	0.35 (24)	9.3	0.93 (50)	9.3
		V	0.48 (20)	8.3	1.16 (41)	4.1
		VI	0.38 (9)	11.3	0.99 (18)	6.1
	365	I	0.49 (3)	---	0.98 (6)	5.1
		IV	0.34 (6)	16.2	0.82 (12)	8.2

The compressive strength achieved by the baseline mortar mix at 28 days varied between 0.52 and 0.67 N/mm^2 and at 91 days varied between 0.93 and 1.16 N/mm^2. The overall coefficients of variation for compressive strengths of all baseline specimens at both 28 and 91 days were below 10% (Table 4.12).

Table 4.12 Averaged performance of the baseline mortar mixes

Mortar	Age (days)	Flexural strength		Compressive strength	
		Average (N/mm^2) (No. of tests)	CV (%)	Average (N/mm^2) (No. of tests)	CV (%)
1:2.25 NHL 3.5:'Binnegar' sand	28	0.31 (117)	11.4	0.60 (241)	9.2
	91	0.41 (133)	11.5	1.02 (273)	9.7

Reasons for the variation in performance might generally be attributed to changes in mortar mix materials, workmanship and environmental conditions during hardening. However, to minimise variation the 'Binnegar' sand used in the baseline mortar was factory-dried and from the same batch of production. However, new batches of natural hydraulic limes were always used in each series over the two and half year period of the study.

The same experienced meticulous bricklayer was used throughout the project. All series of mortar mixes were made by the bricklayer and the author, and all mortar specimens were prepared and tested by the author. The workmanship was as consistent as reasonably possible. All specimens were built following the procedure specified in British Standards and were cured following the same procedure outlined in Chapter 3.

During the process of specimen preparation, variation in the factors outlined above has been limited as far as practically possible. Performance variation of mortar properties is therefore primarily attributed to the variation of the different production batches of the lime binders.

4.4 Mortar carbonation

It is widely accepted that strength of hydraulic lime mortar increases initially through the process of hydration and thereafter primarily through the slower process of carbonation, which is believed to be more important to lime mortars than to cement mortars (Boynton 1980, Scholfield 1997, Allen et al. 2003, Lanas et al. 2004, Cizer et al. 2010). Rate of carbonation depends on the atmospheric CO_2 level, temperature and the relative humidity level in the environment. Tests using phenolphthalein solution were performed to evaluate the degree of mortar carbonation during material testing. Representative photos in Figure 4.7 show the partially carbonated mortar specimen cross-sections at 14, 28, 56 and 91 days. The bright pink regions indicate those areas of mortar that have not yet carbonated. The depth of mortar carbonation was determined by measuring the average distance from the outer edge to the uncarbonated area.

The carbonated areas in the specimens mostly displayed regular shape like those shown in Figure 4.7, showing that carbonation had generally progressed evenly through the specimens. The carbonated depths increased with age. At 14 days only a small depth of mortar, close to the edges of the cross section, about 2-4mm deep, had carbonated. The higher moisture content of the mortar at early age blocks pores and prevents calcium hydroxide from reacting with CO_2 in the air. Carbonation reached about 4-9 mm deep at 28 days and about 10-14 mm deep at 56 days, increasing as the mortar dried. By 91 days most mortar specimens had fully carbonated, although for a few mortar specimens small sections of uncarbonated material remained (‘91days’ in Figure 4.7). Although there was some little variation in the carbonated depths for different mortar mixes, these were not significant.

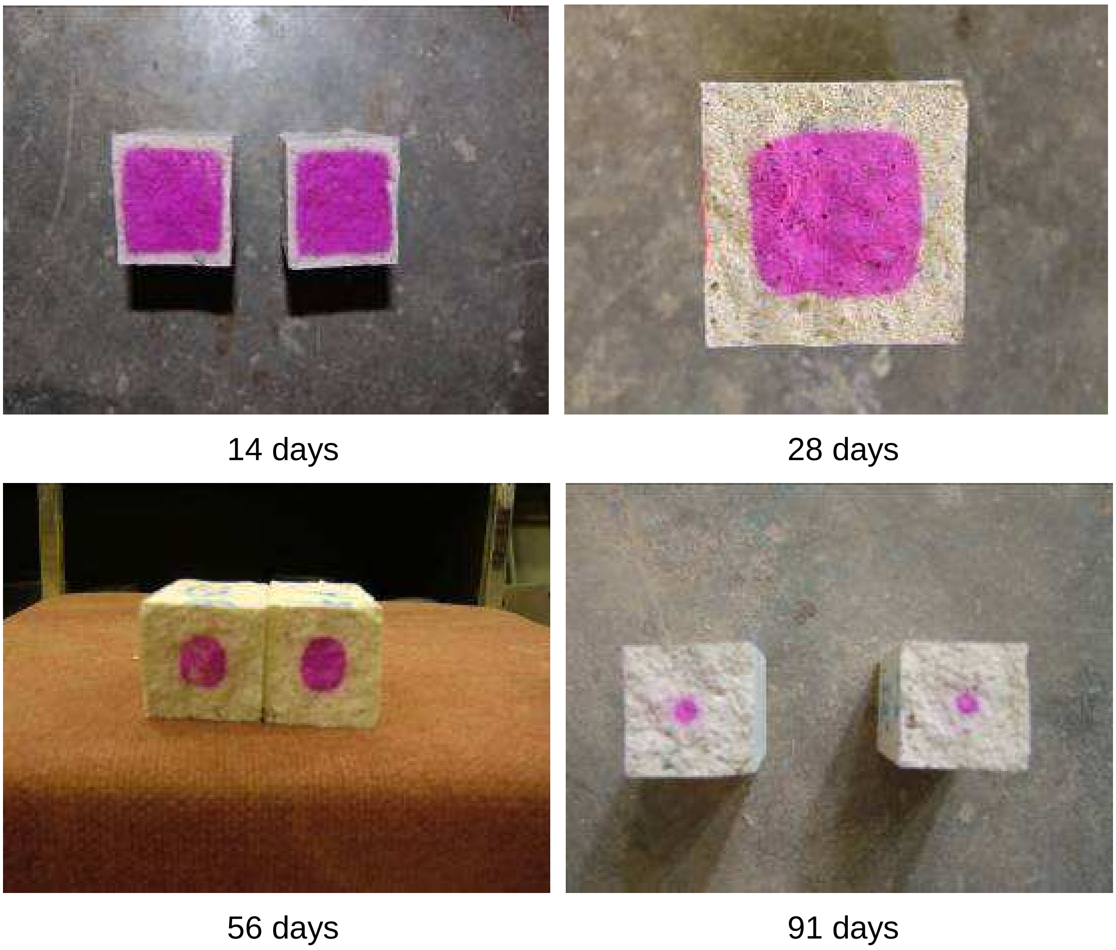


Figure 4.7 Carbonation indicator test at different ages

Figure 4.8 shows the median depths of mortar carbonation at different ages. The almost linear relationship indicates that the carbonation is proportional to $t^{1/2}$ and confirms the general proposition on the progression of carbonation (Page et al. 1982). This conclusion is also in agreement with the study by El-Turki et al. in 2009. The average rate of carbonation was approximately 0.22 mm per day. Therefore mortar joints in 100 mm thick brickwork specimens might be fully carbonated after 227 days following construction, assuming the mortar in brickwork joints carbonates at the same rate. However, the study later on the carbonation of brickwork specimens showed mortar joints were still far less than fully carbonated after 365 days, which has proved that the carbonation state of mortar changed when mortar was applied on bricks. This will be discussed in detail in Chapter 6.

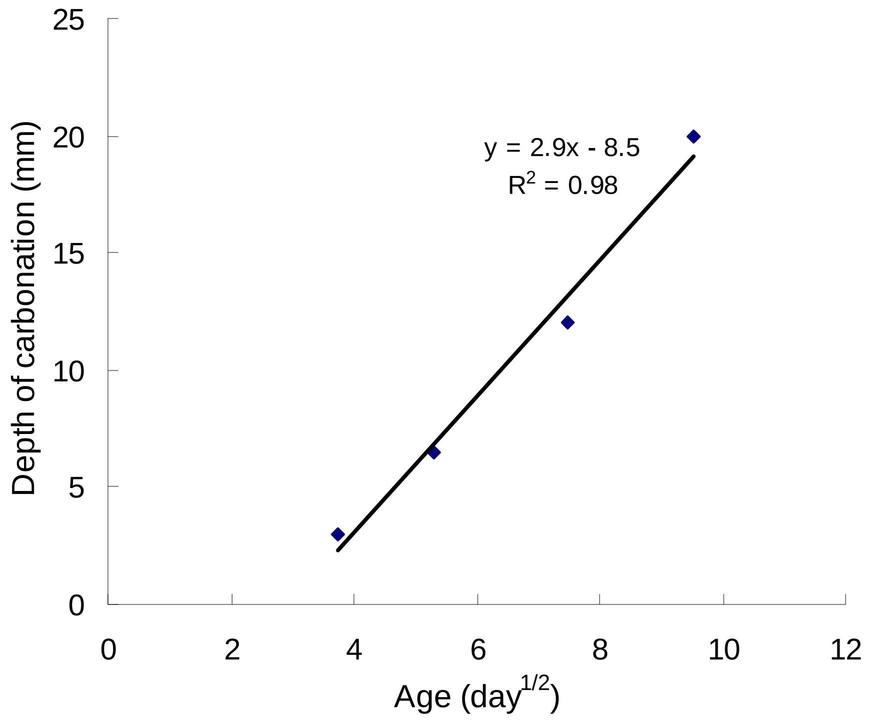


Figure 4.8 Mortar carbonation with age

4.5 Summary and conclusions

The following conclusions have been drawn from the work presented in this chapter:

1. The water required to maintain mortar workability increased with sand content and sand fineness but decreased with lime hydraulicity. The flow table provided a consistent measure for workability using the Binnegar sand, but proved less consistent using either fine or coarse sands.

2. The novel desorptivity test developed by University of Manchester on behalf of this project provided an indication of water retention performance of the experimental mortars. In general desorptivity was higher than previously reported and some inconsistencies in trends were noted.

3. Depending on mix details, mortar strength increased with hydraulic lime hydraulicity and lime binder content. The performance of lime mortars prepared using binders sourced from different lime suppliers varied significantly.

4. Sand grading had a significant influence on compressive strength of hydraulic lime mortars. The coarser graded sand mortar mixes were generally stronger, whilst the finer sand impaired mortar compressive strength.

5. Mortar flexural and compressive strengths increased with age, but initially at slower rate than cement: lime: sand mortars. The strength initially mainly comes from hydraulic set and later mainly through carbonation. At 28 days all hydraulic lime mortars tested have reached above 50% of their 91-day compressive strengths. Performance of hydraulic lime mortars should be based on 91-day strengths.

6. Mortar flexural strengths were generally low and were a less consistent indicator of relative material performance than compressive strength. The occurrence of micro-cracks caused by drying shrinkage is suspected to have impaired flexural strength. The mortar test specimens were also prone to damage during early age demoulding and handling, which may also have contributed to the inconsistent performance in bending.

7. Most of the NHL3.5 and NHL 5 mortars conformed to the performance requirements of class M1 mortars after 91 days.

8. Mortar strengths decreased with the increasing of water content.

Based on the above, the properties of hydraulic lime mortars can be affected by many variables in mix details. The influence of these mortar variations on brickwork properties are discussed in Chapter 5, 6 and 7.

BLANK PAGE

5. Flexural strength of hydraulic lime mortared brickwork: comparison of wall panel and bond wrench tests

5.1 Introduction

Until the 1930s, brickwork was mostly built with thick solid walls in which soft, flexible and low strength lime mortars were used. The heavy, sturdy structures provided sufficient resistance to vertical and lateral loads (Lynch 1994, BDA 2001). From WWII onwards, thin-walled cavity construction has been widely developing by reason of economising on materials and the popularisation of cheap, consistent and high strength cement. However, the capability of thin walling to accommodate stresses, especially flexural stress becomes a main concern in structural design. As lime mortar is generally much weaker than cement:lime:sand mortar, in this research investigating the flexural bond strength developed in brickwork has been the main focus.

Both the current and previous UK structural design codes for masonry, BS 5628 (withdrawn in April 2010) and the UK National Annex to EC6 that replaced it, do not currently include design data for hydraulic lime mortared masonry. This has no doubt impeded modern development in the structural use of hydraulic lime mortared masonry in the UK. Although researchers have begun to investigate the performance of hydraulic limes (English Heritage 1997, Cowper 1998, Holmes 2002, Allen et al. 2003, Lanas et al. 2004), as outlined in Chapter 2, comparatively little research work has been reported on the structural properties of hydraulic lime brickwork.

Nearly three years after this study commenced, in December 2008, a guide for hydraulic lime mortar brickwork design was published by the NHBC Foundation, following research work undertaken at BRE in conjunction with the Building Limes Forum. However, this design guidance is based on significantly fewer tests than completed by this study.

In this chapter, test results for the flexural strength of wall panels subject to bending with the plane of failure either 'parallel to the bed joint' or 'perpendicular to the bed joint' are reported. Initially tests focussed on using wall panels, but as confidence developed in the bond wrench tests this test became the preferred method for parametric studies (presented in Chapter 6). Results from initial bond wrench testing on quadruplet brickwork prisms are presented in this chapter. The results for flexural bond strength obtained from the two test procedures and identical materials are compared.

Many material variables, including brick water absorption, lime binder type and mortar mix proportions have been previously reported to influence brickwork bond strength (Boynton and Gutschick 1964, Sinha 1983, Lawrence and Cao 1988, McGinley 1990, Groot 1993, Lawrence and Page 1994, Borchelt et al. 1996, 1999, Sugo et al 2001, Sarangapani et al. 2002, Venkatarama Reddy and Gupta 2006) and they have also been investigated here. For comparison the property of cement: lime: sand mortared brickwork was also studied and is reported in this chapter. The chapter begins by presenting the wall panel test results, followed by bond wrench test findings. The majority of bond wrench tests studied in this project will be discussed in the next chapter.

Brick water absorption characteristics were investigated during this study. The properties of the five different perforated extruded bricks included in this part of the study are summarised in Table 5.1 below. During discussion of test results bricks will be referred to by their Ibstock product name.

Table 5.1 Brick properties

Brick	Staffordshire Slate Blue Smooth	Berkeley Red Multi	Holbrook Smooth	Chester Blend	Hardwicke Welbeck Autumn Antique
Net dry density (kg/m^3)	2209	2127	2124	2040	1685
Proportion of holes	18%	17%	22%	24%	17%
24h water absorption (%)					
Average	2.3	5.1	7.7	8.3	16.0
Coefficient of Variation	14.9%	6.9%	6.7%	6.0%	5.0%
5h water absorption (%)					
Average	3.3	8.4	8.7	9.6	N/A
Coefficient of Variation	12.3%	10.7%	12.9%	3.3%	N/A
IRA (kg/m^2.min)					
Average	0.1	1.3	1.0	1.9	2.4
Coefficient of Variation	35.0%	7.3%	11.8%	10.8%	8.9%
Sorptivity (mm.min$^{1/2}$)					
Average	0.03	0.49	0.65	1.61	2.13
Coefficient of Variation	18.5%	24.6%	19.6%	3.6%	4.5%

The characteristic flexural strength properties of panels built using five different perforated types of brick used are outlined in section 5.3.1. The brick water absorption characteristics were examined by four methods: total water absorption (24 hour immersion and 5 hour boil tests), initial rate of absorption and sorptivity. The engineering ‘Staffordshire Slate Blue Smooth’ brick had the lowest water absorption properties of those tested, whilst the ‘Hardwicke Welbeck Autumn Antique’ brick had the highest water absorption values of this series. The ‘Berkeley Red Multi’ and ‘Holbrook Smooth’ bricks have similar water absorption properties. The ‘Chester Blend’ has high IRA and sorptivity, but comparatively lower total water absorption.

5.2 Wall panel test results

5.2.1 Summary of tests

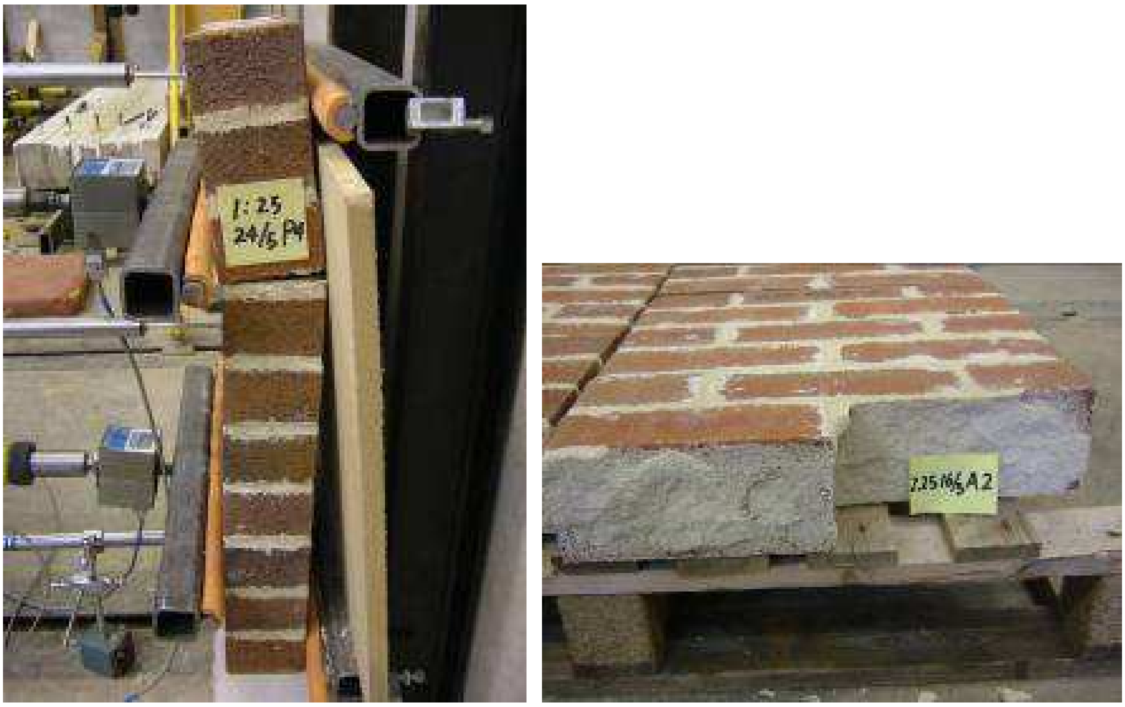
Brickwork flexural strengths were initially established from tests on wall panels tested under four point bending to establish strengths either parallel or perpendicular to the bed joint directions. The test procedures followed those specified in BS EN 1052-2 (1999). Strength results for each series of brick and mortar combination were obtained from a sample of six identical wall specimens. In total 80 'parallel to bed joint' walls (with some repeated tests) and 60 'perpendicular to bed joint' walls were tested. As discussed in the previous chapter, the flexural bond strength of the hydraulic lime mortared walls were designed to be tested 91 days after their construction, whereas the 1:3:12 and 1:2:9 cement lime mortared wall panels were tested after 28 days. Material variables studied in this programme include:

- Natural Hydraulic Lime grade (NHL 2, 3.5 and 5);
- Lime mortar mix proportions (1:2, 1:2.25 and 1:2.5 lime: sand by volume);
- Cement mortar mix proportions (1:3:12 and 1:2:9 cement: lime: sand);
- Brick water absorption properties (Table 5.1).

Test performance and failure modes are discussed below with the corresponding strength performance following in section 5.3.

5.2.2 Failure modes for plane of failure 'parallel to bed joint' panels

The wall panel tests displayed different failure modes depending on the direction of flexural stress with respect to the bed joints. In the 'parallel to bed joint' tests (vertical spanning), the horizontal joints presented an obvious plane of weakness. Principal tensile stresses developed normal to the bed joints, causing the weakest plane of the six mortar joints within the constant moment zone to suddenly fracture (Figure 5.1). The plane of failure in general occurred along one of the bed joints across the section of the test panel (Figure 5.1(a), 5.2 and 5.3), although occasionally the failure plane stepped along the bed joints (Figure 5.1(b)), which may have been encouraged by the weaker perpend joints between the two horizontal fracture planes.



(a) (b)

Figure 5.1 Fracture patterns from ‘parallel to bed joint’ tests

Three distinct failure modes along the fracture interface were observed (Figure 5.2). The most common fracture planes (about 70% of the 80 wall ‘parallel to bed joint’ panel tests) occurred directly along the interface between the mortar and either the upper or lower brick bed face (Figure 5.2 (a)). In brickwork using the lowest or highest absorption bricks (‘Staffordshire Slate Blue Smooth’, ‘Hardwicke Welbeck Autumn Antique’) all fracture surfaces belonged to this mode (Figure 5.3). This is symptomatic of the very weak bond generally developed in this brickwork. The fracture surfaces were cleaner than the

(a) Interface failure (b) Combined interface and mortar failure

(c) Mortar joint failure

Figure 5.2 Post failure fracture surfaces

Figure 5.3 Failure modes using low (left: ‘Staffordshire Slate Blue Smooth’) and high (right: ‘Hardwicke Welbeck Autumn Antique’) absorption bricks

interface failure that occurred in the brickwork using the bricks with total water absorption between 5.1% and 8.3% (Figure 5.2 (a)). Roughly 20% of failures were a combined fracture along the brick-mortar interface combined with fracture within the depth of the mortar bed joints (Figure 5.2 (b)). In around 10% of cases, fracture occurred entirely within the mortar joint (Figure 5.2 (c)). There was no obvious correlation between medium absorption brick (‘Berkeley Red Multi’, ‘Holbrook Smooth’ and ‘Chester Blend’) panel failure modes and flexural strength.

5.2.3 Failure modes for plane of failure ‘perpendicular to bed joint’ panels

In the flexural ‘perpendicular to bed joint’ tests the failure plane either stepped around the bricks (75% of cases), or less frequently induced fracture of the bricks, when the bond strength was sufficient to enable this. In the ‘perpendicular to bed joint’ test panels the principal tensile stresses are oriented parallel to the bed joints and normal to the perpend joints. At failure fracture started within the constant moment zone but sometimes extended into the shear span beyond the load points.

The fracture modes in the ‘perpendicular to bed joint’ were more varied and complicated than the ‘parallel to bed joint’ tests. Around 50% of the 60 wall tests developed fracture planes that stepped up diagonally, (Figure 5.4 (a) and (b)). In around 25% of cases a combined fracture across both diagonals was observed (Figure 5.4 (c)). In the remaining 25% of tests tensile fracture was not confined to the mortar joints. Figure 5.5 shows combined cracking within the mortar joints and bricks. As expected this failure mode only occurred in the stronger bond strength tests. No brick failures were observed in the weaker ‘parallel to bed joints’ wall tests or the bond wrench brick prism tests; bond strengths were relatively much lower than brick strength.

(a) Diagonal fracture

(b) Diagonal fracture

(c) Combined diagonal failure planes

Figure 5.4 Diagonal fracture planes

(a)

(b)

(c) (d)

Figure 5.5 Combined mortar joint and brick splitting fracture patterns

In the ‘perpendicular to bed joint’ tests fracture planes were never entirely confined to the mortar joints. The typical failure mode, where the fracture stepped around the stronger bricks, is represented in Figure 5.6. Two fracture surface types were observed at the failure planes.

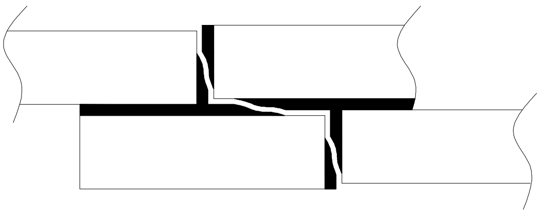


Figure 5.6 Typical fracture interface detail between brick and mortar

In panels using the brick with total water absorption between 5.1% and 8.3%, a combined failure at the interface and within mortar joints was often observed (Figure 5.7(a)). For the weakest panels, using ‘Staffordshire Slate Blue Smooth’ and ‘Hardwicke Welbeck Autumn Antique’ bricks, the failure plane occurred at the interface between brick and mortar (Figure 5.7(b), (c)), as with the ‘parallel to bed joint’ tests.

(a) Combined failure in medium absorption ‘Berkeley Red Multi’ walls

(b) Interface failure in low absorption ‘Staffordshire Slate Blue Smooth’ walls

(c) Interface failure for high absorption ‘Hardwicke Welbeck Autumn Antique’ walls

Figure 5.7 Failure modes with different brick types

The mode of failure was more dependent on brick type than the mortar strength. The brickwork tests built with both the low (‘Staffordshire Slate Blue Smooth’) and high (‘Hardwicke Welbeck Autumn Antique’) absorption bricks developed low flexural bond strengths (both parallel and perpendicular to bed joint directions) and exhibited interface failure. However, there was no apparent correlation between failure mode and mortar mix.

An interface fracture surface in both the low and high absorption brickwork has occurred for different reasons. The very low absorption ‘Staffordshire Slate Blue Smooth’ brick absorbed very little water from the mortar during construction, leading to slower setting as the bricks tended to ‘float’ on the mortar beds, thus resulting in very low bond. In contrast, the high absorption ‘Hardwicke Welbeck Autumn Antique’ brick rapidly dewatered the mortar, starving the mortar of sufficient water required for complete hydration. The mortar developed poor strength and was easily broken into pieces after testing (Figure 5.8).

Figure 5.8 Mortar splitting in brickwork using
‘Hardwicke Welbeck Autumn Antique’ brick

5.2.4 Mortar joint carbonation

As discussed in Chapter 4, most of the 40 x 40 mm cross-section mortar specimens had fully carbonated across the depth of the section by 91 days. The carbonation rate approximated to 0.22 mm/day in the 20^{o}C and 60%RH storage conditions. If the mortar in the brickwork specimens carbonates at this rate the 102.5mm thick wall panels would also have carbonated to around 20 mm deep by 91 days. However, carbonation indicator tests on the fractured interfaces of the brickwork mortar joints showed that in most walls (built with the ‘Berkeley Red Multi’ bricks and differing mortar mixes) carbonation only reached an average depth of around 11 mm (Figure 5.9). The influence of lime content and lime grade on measured carbonation rates of differing mixes mortars was negligible.

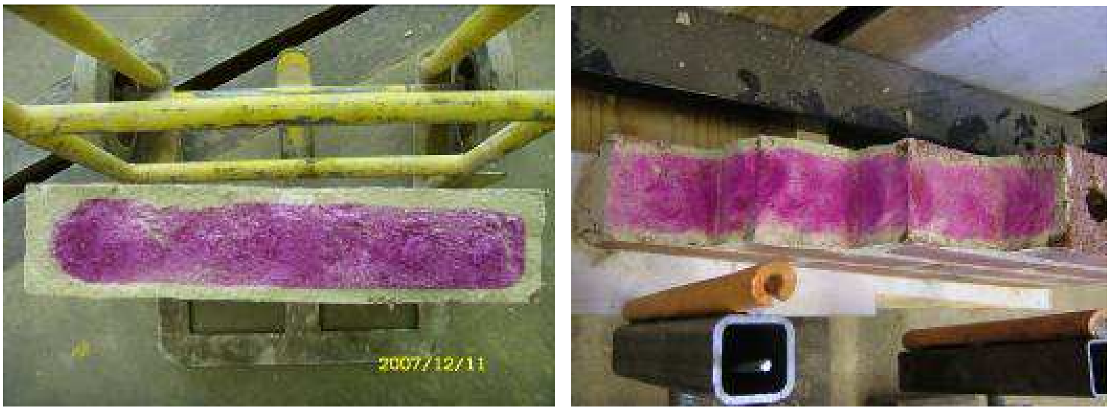
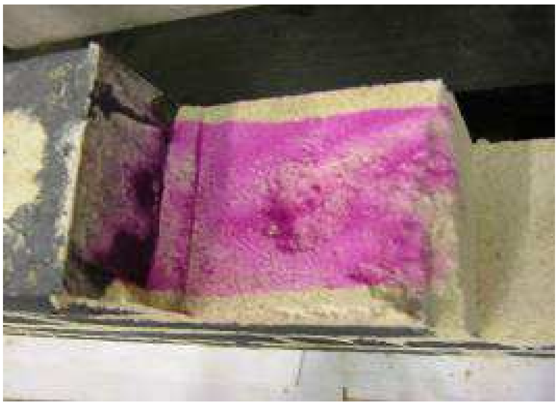


Figure 5.9 Carbonation indicator patterns
in ‘Berkeley Red Multi’ brickwork mortar joints

The carbonation rates were most influenced by brick type (Table 5.2 and Figure 5.10). Similar to the ‘Berkeley Red Multi’ brick specimens, both the ‘Staffordshire Slate Blue Smooth’ and ‘Holbrook Smooth’ brick specimens had regular carbonation outlines, although carbonation depths varied. The low water absorption ‘Staffordshire Slate Blue Smooth’ brick specimens were slightly less carbonated, around 9-11 mm on average, compared to the ‘Berkeley Red Multi’ brick walls. In contrast mortar carbonation of the higher water absorption ‘Holbrook Smooth’ brick walls had extended further, to around 15 mm on average by 91 days (Figure 5.10).

Table 5.2 Mortar carbonation rates of brickworks

Wall series	Carbonation depth at 91 days (mm)	
	average	range
‘Berkeley Red Multi’	11	8~15
‘Staffordshire Slate Blue Smooth’	10	9~11
‘Holbrook Smooth’	15	8~18
‘Hardwicke Welbeck Autumn Antique’	16	9~20
‘Chester Blend’	17	9~20



‘Staffordshire Slate Blue Smooth’

‘Holbrook Smooth’

‘Chester Blend’

‘Hardwicke Welbeck Autumn Antique’

Figure 5.10 Carbonation indicator patterns with various bricks

The differences in carbonation rates may be attributed to two main mortar parameters: porosity and moisture conditions. Whilst dewatering of the mortar by brick suction might have expected to densify the mortar (reducing porosity and so slowing carbonation rates), the experimental evidence does not support this, as carbonation has progressed faster in the high water absorption (‘Hardwicke Welbeck Autumn Antique’) brick walls. Therefore, in contrast, it is more likely that rapid dewatering of the mortars by the higher absorption bricks has impaired binder hydration resulting in higher porosity and lower strength. Although there is little direct evidence from the indicator tests, carbonation in the weaker jointed brickwork may have preferentially developed through micro-shrinkage cracks along the interface between the mortar and brick. The uneven carbonation rates observed in some series supports this suggestion.

Carbonation rates are also dependent on moisture conditions, which may have been influenced by the surrounding brick properties, especially during the initial drying period. Longer initial drying of the mortar joints in the ‘Staffordshire Slate Blue Smooth’ brick walls would support this proposal, resulting in apparently slower carbonation rates over the 91 days (Figure 5.10). In contrast the higher absorption ‘Hardwicke Welbeck Autumn Antique’ brick dries the mortar to a greater extent, enabling carbonation to commence earlier. Following initial setting, mortar within the brick joints is likely to dry out more slowly than the mortar specimens, as the bricks inhibit mortar drying and so prevent early carbonation.

The carbonation indicator patterns for both ‘Hardwicke Welbeck Autumn Antique’ and ‘Chester Blend’ brick series were more irregular (Figure 5.10). The depth of carbonation was around 20 mm in some areas, whilst elsewhere the carbonation depth was only 9 mm. However, the mortar carbonation depths in all wall panels were below the 20 mm depth observed in the mortar specimens. This irregularity may have been as a result of micro-cracking forming in the weaker mortar joints. The presence of perforations within the bricks and possibly the increased porosity (reflected by the increased brick water absorption characteristics) may have also led to this observation.

The variation in carbonation depths for walls with different bricks is a clear indication that varying dewatering rates influenced mortar properties and physical structure. Consequently, it is highly likely that the hardened mortar within the wall joints will not have the same final properties as the corresponding 40x40x160 mm mortar specimens cast within the steel moulds. However, despite some efforts to recover and test specimens of 10 mm mortar from the joints, it was not possible to confirm this experimentally.

5.3 *Wall panel flexural strengths*

5.3.1 Overview of tests

The results summarised in Table 5.3 for the flexural strength in both parallel and perpendicular directions were established from testing six identical wall panel specimens for each series, in accordance with BS EN 1052-2: 1999. The influence of brick water absorption properties, mortar mix proportions (1:2, 1:2.25 and 1:2.5) and lime grade (NHL 2, 3.5 and 5) on the flexural strength of wall panels were investigated. Cement: lime: sand mortar brickwork wall panels were also tested for comparison.

The characteristic flexural strength for hydraulic lime mortared brickwork at 91 days in the 'parallel to bed joint' (f_{xk1}) direction ranged from 0.05 to 0.39 N/mm^2. The characteristic strengths are the 5% fractile values, determined in accordance with BS EN 1052-2. The characteristic flexural strength in the 'perpendicular to bed joint' (f_{xk2}) direction ranged from 0.24 to 1.34 N/mm^2. The 'perpendicular to bed joint' strength was consistently higher than the 'parallel to bed joint' strength due to the stepping fracture surface around the bricks as discussed above.

The ratio of flexural strength 'parallel to bed joint' and 'perpendicular to bed joint' directions is known as the orthogonal ratio (f_{xk1}/f_{xk2}). The experimental orthogonal ratios varied between 0.21 and 0.46. In two series the ratio was less than the ⅓ value used by the UK National Annex to EC6 for fired clay brickwork, although the average experimental orthogonal ratio of 0.34 (coefficient of variation equal to 26%) showed good agreement with the value taken for cement:lime:sand mortared brickwork (0.26).

Table 5.3 Wall panel flexural strength test data

Brick type	Mortar mix proportion (by volume)	Lime grade	Age (days)	'Parallel to bed joint' flexural strength (f_{xk1})				'Perpendicular to bed joint' flexural strength (f_{xk2})				Orthogonality ratio (f_{xk1}/f_{xk2})
				Average (N/mm^2)	Range (N/mm^2)	CV (%)	Char. (N/mm^2)	Average (N/mm^2)	Range (N/mm^2)	CV (%)	Char. (N/mm^2)	
Berkeley Red Multi	**1:2.25**	NHL 2	**91**	0.25	0.22-0.30	13.5	0.19	0.79	0.55-0.99	20.0	0.49	0.39
		NHL 3.5 (baseline–series III)①		---	---	---	---	**1.09**	**0.86-1.51**	**23.0**	**0.66**	-----
		NHL 5		0.48(8)②	0.41-0.53	13.3	0.39	1.35	0.91-1.64	18.7	0.85	0.46
	1:2	**NHL 3.5**		0.54	0.46-0.66	15.5	0.39	1.53	1.23-1.80	15.1	1.08	0.34
	1:2.25 (baseline-series I)①			**0.48**	**0.41-0.54**	**9.6**	**0.38**	**1.26**	**1.03-1.63**	**18.0**	**0.84**	**0.45**
	1:2.5			0.46	0.43-0.50	7.1	0.31	1.32	0.84-1.66	25.0	0.84	0.37
	1:3:12	-----	28	0.41	0.37-0.51	12.8	0.31	1.49	1.27-1.62	9.0	1.21	0.26
	1:2:9			0.45	0.39-0.50	10.5	0.35	1.73	1.45-2.01	11.5	1.34	0.26

Staffordshire Slate Blue Smooth	1:2.25	NHL 3.5	91	0.21	0.18-0.25	12.6	0.16	0.82	0.63-0.97	19.8	0.52	0.31
Hardwicke Welbeck Autumn Antique				0.09	0.06-0.11	33.4	0.05	0.43	0.31-0.64	28.2	0.24	0.21
Chester Blend				0.15[3]	0.09, 0.10, 0.25[3]							
Holbrook Smooth				0.33	0.10-0.54	59.2	0.06					
Holbrook Smooth	1:2.25	NHL 5	91	0.24	0.16-0.36	30.0	0.12					

(1) Baseline mortared masonry properties varied at different construction and testing stages (discussed in details in the main text).
(2) Eight wall panel specimens were carried out for the results.
(3) Only three results of wall panels were obtained as another three specimens failed accidentally.

The experimental variation in flexural strength was generally in line with expectations. The coefficients of variation ranged between 7.1% and 25.0% for all except two brick series: 'Hardwicke Welbeck Autumn Antique' and 'Holbrook Smooth'. The variation in performance of these two series was greater than the others, which impaired their corresponding characteristic strength values. Explanation for this variation is not clear, but it is possible that panels may have been damaged during initial movement for storage or during preparation for testing. This is discussed further following bond wrench test results.

5.3.2 Influence of mortar properties

Table 5.4 summarises the influence of mortar properties on the wall panel flexural strength results. As previously noted there was some variation in mortar performance for the baseline 1:2.25 Castle Cement NHL 3.5: Binnegar sand mortar, due to variations in lime supply, baseline mortared masonry properties were carried out at I & III construction and testing series. Hydraulic lime mortar brickwork performance is compared with 1:3:12 and 1:2:9 cement: lime: sand mortared brickwork.

Table 5.4 Influence of mortar properties

<table>
<tr><th colspan="2" rowspan="2">Mortar mix</th><th rowspan="2">Age (days)</th><th colspan="2">Mortar compressive strength (N/mm^2)</th><th colspan="4">Characteristic flexural wall strengths (N/mm^2)</th></tr>
<tr><th>Average</th><th>Relative to baseline</th><th>f_{xk1}</th><th>Relative to baseline</th><th>f_{xk2}</th><th>Relative to baseline</th></tr>
<tr><td colspan="2">1:2 (NHL 3.5)</td><td rowspan="3">91</td><td>1.20</td><td>126%</td><td>0.39</td><td>103%</td><td>1.08</td><td>129%</td></tr>
<tr><td colspan="2">1:2.25 (NHL 3.5) (baseline-Series I)</td><td>0.95</td><td>100%</td><td>0.38</td><td>100%</td><td>0.84</td><td>100%</td></tr>
<tr><td colspan="2">1:2.5 (NHL 3.5)</td><td>0.78</td><td>82%</td><td>0.31</td><td>82%</td><td>0.84</td><td>100%</td></tr>
<tr><td colspan="2">1:2:9</td><td rowspan="2">28</td><td>2.03</td><td>214%</td><td>0.35</td><td>92%</td><td>1.34</td><td>160%</td></tr>
<tr><td colspan="2">1:3:12</td><td>1.08</td><td>114%</td><td>0.31</td><td>82%</td><td>1.21</td><td>144%</td></tr>
<tr><td rowspan="3">1:2.25</td><td>NHL 5</td><td rowspan="3">91</td><td>1.28</td><td>114%</td><td>0.39</td><td>---</td><td>0.85</td><td>129%</td></tr>
<tr><td>NHL 3.5 (baseline-Series III)</td><td>1.12</td><td>100%</td><td>---</td><td>---</td><td>0.66</td><td>100%</td></tr>
<tr><td>NHL 2</td><td>0.97</td><td>87%</td><td>0.19</td><td>---</td><td>0.49</td><td>74%</td></tr>
</table>

The wall panel flexural strengths both ‘parallel to bed joint’ (f_{xk1}) and ‘perpendicular to bed joint’ (f_{xk2}) broadly increased with increasing lime mortar strength (as a result of increased binder content and higher lime grade). This is in keeping with behaviour for cement: lime: sand mortars (Chapter 2). However, the brickwork bond strength increase often did not match corresponding increase in lime mortar compressive strength (Table 5.4). In those higher strength series, in which the mortar joints fractured, the ‘parallel to bed joint’ average flexural strengths (Table 5.3) are comparable with the corresponding mortar prism flexural strengths reported in Chapter 4. Perhaps this is to be expected, although this would also indicate that dewatering by some bricks at least has had little change in mortar flexural strength. The flexural strength of brickwork joints (f_{xk1}) is limited by the resultant mortar flexural strength.

When lime content increased from 1:2.25 to 1:2 the characteristic wall panel flexural strength ‘perpendicular to bed joint’ direction increased by 129%, which was in keeping with the average mortar strength increase of 126%. However, the ‘parallel to bed joint’ flexural strength only increased by 103%. In response to a reduction in lime content from 1:2.25 to 1:2.5 the flexural strength ‘parallel to bed joint’ decreased by 18% in keeping with the mortar strength decrease (18%), whilst the flexural strength ‘perpendicular to bed joint’ was unchanged. In this limited test series the correlation between brickwork flexural strength and mortar strength was variable.

The ‘parallel to bed joint’ flexural strengths of both cement: lime: sand mortared wall panels were lower than the 1:2.25 baseline NHL lime mortar series although the mortar strengths of both cement mortars were higher than the lime mortar. However, the ‘perpendicular to bed joint’ strengths for the cement: lime: sand panels were significantly higher than the lime mortar test results. The explanation for this, given that on average the orthogonal ratio for the lime mortared series is similar to that assumed for cement: lime: sand mortars, is not clear and perhaps, given the relatively limited number of test data, is not that significant either.

Mortar strength consistently increased with increasing lime grade (Chapter 4).

In the ‘perpendicular to bed joint’ tests the flexural strength of wall panels consistently increased with lime grade, Table 5.3. However, in the ‘parallel to bed joint’ direction the NHL 3.5 mortared wall panel f_{xk1} was twice that achieved by the lower grade NHL 2 mortared wall. The NHL 5 mortared wall panel developed similar ‘parallel to bed joint’ strength to that achieved by the NHL 3.5 mortared wall panels. As water retention properties of different grade NHL binders varied (Chapter 4), it is not surprising that variation in brickwork bond strength did not directly match changes in mortar strength.

The NHBC Foundation guide (2008), including the draft for development standard ‘The structural use of unreinforced masonry made with natural hydraulic lime mortars – technical annex for use with BS5628-1:2005’, provides characteristic flexural strengths of masonry for different combinations of brick total water absorption and lime mortar grades. These values are based on comparatively few tests undertaken at BRE. For brick total water absorption less than 12% the ‘parallel to bed joint’ and ‘perpendicular to bed joint’ characteristic flexural strengths for M1 mortars are 0.20 and 0.50 N/mm^2 respectively (orthogonal ratio 0.4). The brickwork built with the various natural hydraulic lime mortar mixes, combined with the ‘Berkeley Red Multi’ brick (total water absorption = 8.4% in series I or 0.66 N/mm^2 in series III), achieved higher values (f_{xk1} = 0.38 N/mm^2, f_{xk2} = 0.84 N/mm^2), although both the 1:2.25 and 1:2.5 mortars did not attain M1 performance. On this basis the provisions of the guide would seem conservative. However, a much wider comparison is provided in Chapter 6.

Although mortar strength is clearly a determinant to bond strength, the response of brickwork performance to these changes is complex. The effect of mortar properties on bond strength is also discussed further in Chapter 6.

5.3.3 Influence of brick properties

From Table 5.5 it is clear that brick water absorption characteristics had a significant influence on the resultant flexural bond of lime mortared brickwork. The highest water absorption brick, ‘Hardwicke Welbeck Autumn Antique’, developed the lowest flexural strength. Brick total water absorption (initially based on 5 hour boil test data) is used as a design parameter for brickwork flexural strengths in UK National Annex to EC6 and previously in BS 5628.

In current design guidance bond strengths improve with reducing brick water absorption properties. Herein the very low water absorption engineering 'Staffordshire Slate Blue Smooth' brick achieved higher flexural strength than the more absorbent 'Hardwicke Welbeck Autumn Antique' brick, but significantly lower than 'Berkeley Red Multi' brick. Dewatering of the mortar by the brick absorption has significantly influenced the strength of the interface formed in the brickwork. Both very low and high absorption bricks were found to have reduced the flexural strengths. Effect of brick desorption is more significant than the variations in mortar properties discussed previously.

Table 5.5 Influence brick type on wall strengths
(using NHL 3.5 1:2.25 baseline mortar)

Direction	Characteristic flexural bond strength (N/mm^2)							
	Staffordshire Slate Blue Smooth		Berkeley Red Multi		Holbrook Smooth		Hardwicke Welbeck Autumn Antique	
	Expt.	NHBC guide	Expt.	NHBC guide	Expt.	NHBC guide	Expt.	NHBC guide
'Parallel to bed joint' f_{xk1}	0.16	0.20	0.38	0.20	0.06	0.20	0.05	0.10
'Perpendicular to bed joint' f_{xk2}	0.52	0.50	0.84	0.50	-		0.24	0.40
Orthogonality ratio (f_{xk1}/f_{xk2})	0.31	0.4	0.45	0.4	-		0.21	0.25

The failure modes of both the low and high water absorption bricks were interface fractures (Figure 5.3, 5.7). However, for the low and high absorption bricks, the very weak bond at the interface might be attributed to different reasons. Whilst high absorption rapidly dewaters mortar and impairs bond development, the low absorption engineering brick absorbs very little water from the mortar. Brick-mortar bond is recognised as primarily a mechanical interlocking developed through the transport of mortar products into the porous brick face. Whilst the hydration products for the highly absorbent bricks are weak, in the low absorbent brick relatively little mortar products penetrate into the dense impermeable brick face, also resulting in poor bond development.

Due to accidental damage only three specimens for ‘parallel to bed joint’ wall panels for the ‘Chester Blend’ brick series were tested (and so characteristic strength is not given in Table 5.3). The values obtained were 0.09, 0.10 and 0.25 N/mm^2 respectively and slightly higher than the strength values of the brickwork using ‘Hardwicke Welbeck Autumn Antique’ brick, but much lower than the values of ‘Berkeley Red Multi’ brickwork. The water absorption values of ‘Chester Blend’ brick were lower than the corresponding values of the highly absorbent ‘Hardwicke Welbeck Autumn Antique’ brick, resulting in improved flexural strength (Table 5.3). The total water absorption values of the ‘Chester Blend’ brick are similar to ‘Berkeley Red Multi’, although the IRA and sorptivity values are much higher for the ‘Chester Blend’ bricks. The much lower flexural strength of the ‘Chester Blend’ brickwork suggests that total water absorption alone is not always a reliable predictor of bond performance.

With total water absorption values similar to ‘Berkeley Red Multi’ brick, the ‘Holbrook Smooth’ brick series exhibited the highest variation in performance (coefficient of variation = 59.2%, Table 5.3). The individual strengths for the six ‘Holbrook Smooth’ wall panels were 0.10, 0.15, 0.22, 0.40, 0.54 and 0.54 N/mm^2. The cause of this abnormal variation which is much greater than the corresponding bond wrench strength test (discussed later in this chapter) is unclear. It is possible that the weaker test wall panels were slightly damaged during construction, movement, storage or in preparation for testing.

Other than the work leading to the NHBC Foundation guide, there has been very little work on flexural strength of hydraulic lime mortared brickwork. Hughes et al. (2005) reported 56-73 day ‘parallel to bed joint’ flexural strengths of 0.12 N/mm^2 (Blue Lias (BL) mortar) and 0.18 N/mm^2 (Charlestown (CH) mortar) on average. The corresponding ‘perpendicular to bed joint’ flexural strengths were reported as 0.10 N/mm^2 and 0.20 N/mm^2 on average respectively. The results reported here (Table 5.3) are lower for the ‘parallel to bed joint’ flexural strengths, but much higher for the ‘perpendicular to bed joint’ flexural strengths. There are several reasons contributing to this difference. The unit used by Hughes was a Hanson London brick, which has high water absorption (20-24% water absorption). Mortar materials used here are significantly different from Hughes’ experiments. Hughes used a non-conventional hot mixing method to slake the limes, which left some quicklime unhydrated and impaired mortar performance.

In current design standards total brick water absorption is used as the parameter defining masonry flexural strength (UK National Annex to EC6 and the NHBC Foundation guide (2008)). In the EC6 UK National Annex fired clay bricks are subdivided into three groups: less than 7% water absorption, between 7 and 12% water absorption, and greater than 12% water absorption. In the NHBC Foundation guide bricks are subdivided into two groups: less than and greater than 12% total water absorption. In the current study this simplistic categorization of brick water absorption characteristics did not correlate well with observed behaviour for the low strength NHL lime mortars, and particularly for the lowest water absorption bricks. It can be seen from Figure 5.11 that the lowest water absorption brick did not develop the highest flexural strength. Further investigation on studying the correlation between brick water absorption properties and bond strength for hydraulic lime mortared brickwork has been carried out (using the bond wrench test) and is discussed in Chapter 6.

For the ‘Staffordshire Slate Blue Smooth’ brick and M2 class mortar, the equivalent characteristic flexural strength values in the UK National Annex EC6 are 0.4 and 1.2 N/mm^2 for ‘parallel to bed joint’ and ‘perpendicular to bed joint’ respectively. These values are over twice the experimental values (0.16 and 0.52 N/mm^2 respectively). For the most absorbent bricks the standard values are 0.25 and 0.8 N/mm^2 respectively, compared to 0.05 and 0.24 N/mm^2 from the experiments. The much lower strength of the lime mortar, generally M1 performance (Chapter 4), combined with differences in response of lime mortars to brick dewatering and bond development suggests that using M2 cement:lime:sand design values is not appropriate.

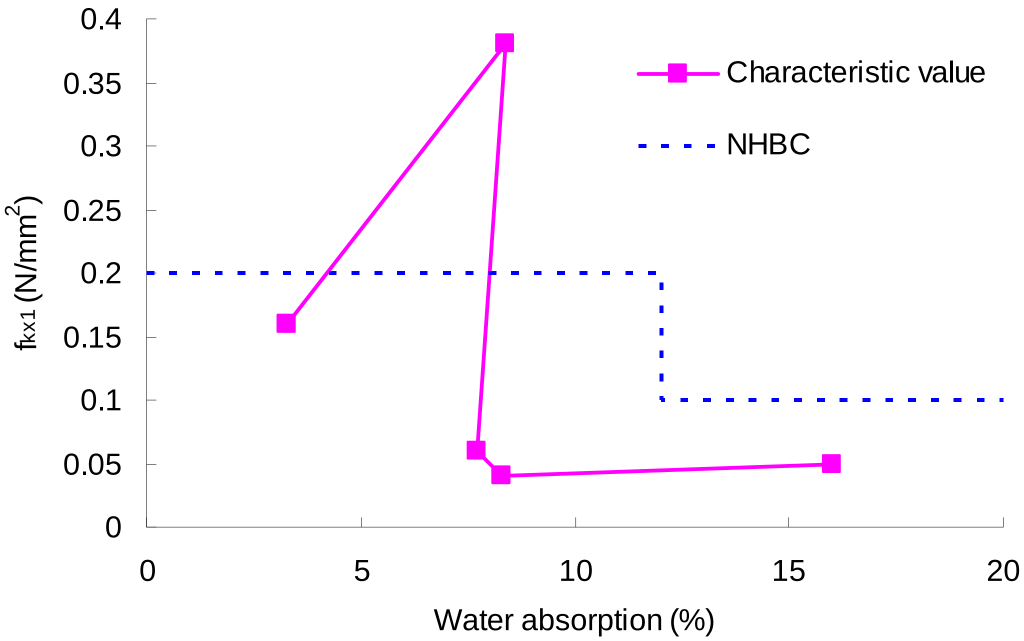


Figure 5.11 Relationship between parallel flexural strength and brick water absorption

The design flexural strengths of hydraulic lime mortared brickwork given in the NHBC Foundation guide are presented and compared against weakest test data in Table 5.6.

Table 5.6 Characteristic flexural strength of natural hydraulic lime mortared masonry, f_{xk}, (N/mm^2)

	'Parallel to bed joint' f_{xk1}	'Perpendicular to bed joint' f_{xk2}
Brick water absorption	Mortar designation, M1	
NHBC Foundation design guidance		
≤ 12%	0.20	0.50
> 12%	0.10	0.40
Weakest experimental performance		
≤ 12%	0.06	0.52
> 12%	0.05	0.24

Many of the experimentally determined values are lower than the design guidance presented in the NHBC Foundation guide, with exception of the ‘perpendicular to bed joint’ direction using brick water absorption less than 12%. The orthogonality ratios presented in the NHBC Foundation guide vary between 0.25 and 0.40, comparable with limited experimental data presented here, between 0.21 and 0.45. The guidance is discussed in further detail below.

5.3.4 Comparison with cement: lime: sand mortared brickwork

Panels built using the ‘Berkeley Red Multi’ brick, and the 1:2:9 cement: lime: sand mortar developed similar flexural strength (f_{xk1}) at 28 days to the NHL 3.5 lime mortared brickwork at 91 days. Meanwhile the 1:3:12 mortared brickwork developed slightly lower ‘parallel to bed joint’ flexural strength (Table 5.3). However, the 1:2:9 and 1:3:12 mortared brickwork series both developed higher f_{xk2} values than baseline NHL 3.5 mortared brickwork at 91 days.

The orthogonality ratio for the NHL mortared brickwork using the ‘Berkeley Red Multi’ bricks varied between 0.34 and 0.46 (Table 5.3), significantly higher than the 0.26 for the cement: lime: sand mortared brickwork samples. These compare with the ⅓ value assumed in the UK National Annex to EC6. The reduction in orthogonality ratio for the cement: lime: sand samples is in line with the relative increase in flexural strength ‘perpendicular to bed joint’ direction. However, reason for this relative improvement in ‘perpendicular to bed joint’ strength is not clear for similar strength mortars. There seems no particular reason why perpend joint flexural strengths relative to bed joint strength should significantly differ between lime and cement mortared samples. The ‘perpendicular to bed joint’ test bed joints are subject to complex combined bending, shear and torsional stresses. The difference in orthogonality ratio might indicate that cement: lime: sand mortars developed a higher torsional bond strength than the lime mortars. The flexural strengths of lime mortar wall panels, and the orthogonality ratio, were reduced with the low and high water absorption bricks (‘Staffordshire Slate Blue Smooth’ and ‘Hardwicke Welbeck Autumn Antique’).

For an M2 mortar (achieved by 1:2:9 mortar at 28 days) and the ‘Berkeley Red Multi’ brick combination (brick total water absorption between 7 and 12%) the design characteristic flexural strengths specified in the UK National Annex to EC6 are 0.35 and 1.0 N/mm^2 for f_{xk1} and f_{xk2} respectively. The corresponding experimental values are 0.35 and 1.34 N/mm^2, so meeting or exceeding the current code design values. The weaker 1:3:12 cement: lime: sand mortar at 28 days can be categorised as M1. However, the UK NA to EC6 currently does not give design flexural strengths for M1 mortars.

5.3.5 Summary of wall panel tests

This section has presented results for the wall panel flexural strength tests. The characteristic flexural strengths for the natural hydraulic lime mortared brickwork, tested in ‘parallel to bed joint’ direction (f_{xk1}) varied between 0.05 and 0.39 N/mm^2. The experimental values for the hydraulic lime mortars were generally greater than the 0.10 N/mm^2, the value given in main section of EC6 (BS EN 1996-1-1:2005) for clay brick masonry. The characteristic flexural strengths of NHL brickwork tested in ‘perpendicular to bed joint’ direction (f_{xk2}) varied between 0.24 and 1.08 N/mm^2. The low strength cement: lime: sand mortared brickwork (1:3:12 and 1:2:9) developed comparable flexural strengths in the ‘parallel to bed joint’ direction, but much higher strengths in the ‘perpendicular to bed joint’ direction.

In general, the brickwork flexural strengths in both directions improved with lime content and lime grade (hydraulicity). Brick water absorption properties had a significant influence on flexural bond strength. The importance of brick properties on bond strength were subsequently studied in depth using the bond wrench test, reported in Chapter 6.

5.4 Comparative bond wrench tests

5.4.1 Summary of bond wrench tests

Compared with the wall panel tests, bond wrench test procedure takes less time to prepare and conduct and less material for construction and testing (see section 3.5.3). The bond wrench test is a convenient method to determine the bond strength between brick and mortar. Rather than six wall panels, the bond wrench test of brick prisms provides bond strength from 10-12 mortar joint tests. In this study four identical four-brick high specimens, comprising a total of 12 test joints, were built and tested in accordance with BS EN 1052-5. In very few instances, weakly bonded specimens, joints failed prematurely during handling and so the number of test joints was occasionally fewer than 12; these are indicated in the tables below.

Though the method has been used for many years elsewhere, for example in the USA and Australia, its introduction into the UK has only been relatively recent with the publication of BS EN 1052-5 in 2005. Concerns over the test method have been expressed because of potential for uneven stress distributions at the interface resulting from the clamping process and the load application using a lever arm. In this investigation on bond strength of lime mortared brickwork, a comparison between flexural testing on wall panels in parallel direction and corresponding bond wrench testing on brick prisms was conducted.

Test series to examine the influence of different mortar mixes, with varying lime grade and mix proportion, on the brickwork bond strength were studied using the 'Berkeley Red Multi' brick as the baseline (tested at 91 days). The influence of brick water absorption on flexural bond strength was also studied using the same bricks as the wall panel tests reported above. The 1:2:9 and 1:3:12 cement: lime: sand mortared brick prisms were also tested at 28 days for comparison with hydraulic lime mortared prisms (tested at 91 days).

Different brick types, with a wide range of water absorption properties, were explored with using the bond wrench test method. These results are reported in Chapter 6. The bond wrench test made it possible to study a wide range of parameters such as lime source, sand grading, brick absorption property and curing time, and to investigate the development of bond strength with age, which will also be summarised in the next chapter. Furthermore the influence of other parameters such as lime supplier, sand type and the variation of lime property with different batches, on the flexural bond strength of brickwork will be reported as well.

This section is focussed on the comparison between two testing methods: wall panel ‘parallel to bed joint’ flexural strength test and brick prism bond wrench test. The variables studied and reported herein are:

- Lime grade (NHL 2, 3.5 and 5);
- Lime mortar mix proportions (1:2, 1:2.25 and 1:2.5 lime:sand by volume);
- Cement mortar mix proportions (1:3:12 and 1:2:9 cement: lime: sand);
- Brick water absorption properties (see Table 5.1).

5.4.2 Experimental failure modes

During loading the bond wrench test develops tensile stresses at one face of the specimen normal to the test mortar joint between the two units. When the tensile capacity of the joint is reached it fails suddenly. In the 156 bond wrench tests completed (including some repeat tests), three distinctive modes of failure were observed. The majority of failures occurred at the interface between either the upper or the lower brick and the mortar joint (or occasionally both interfaces simultaneously) and made up 76% of all test failures (Figure 5.12(a)). Figure 5.12(b) shows example of where the tensile fracture occurred within the mortar joint, which accounted for around 12% of all tests. Another 12% of failures occurred as a combination of interface failure and failure within mortar joint (Figure 5.12(c)). Failure of the brick in flexure was not observed; this is not surprising given the low strength of the hydraulic lime mortar and the bond compared to the brick strength.

In the weakest joints, using either the high and low absorption bricks (‘Hardwicke Welbeck Autumn Antique’ and ‘Staffordshire Slate Blue Smooth’ respectively), only interface failure was observed. As discussed before, poor bond was developed between these bricks and the hydraulic lime mortar. In the majority of tests, using the ‘Berkeley Red Multi’ brick, all three modes of failure were observed without any apparent relationship to mortar materials, although interface failure also predominated in these tests. Varying lime grade (NHL 3.5 and NHL 5) had no noticeable effect on variation in the failure mode. No clear correlation was found between the failure mode and strength or consistency of performance. The most common failure mode (interface) was recorded irrespective of variation in materials used.

(a) Interface failure (b) Mortar failure (c) Combined failure

Figure 5.12 Failure modes

When compared with the ‘parallel to the bed joint’ wall panel tests, the observed failure modes in the bond wrench tests were similar to the corresponding wall test series. This is perhaps not surprising as in both tests similar states of tensile stress normal to bed joints are generated. A wider variety of failure modes occurred in the broader range of bond wrench tests incorporating various mortars, brick properties and test ages; these are reported and discussed in Chapter 6.

5.4.3 Mortar joint carbonation

In section 5.2.4 the cross-sectional mortar carbonation in the wall panels was discussed. Although the mortar prism specimens were almost fully-carbonated at 91 days, the carbonation indicator tests on the brickwork showed that the carbonation had progressed at a slower rate, varying depending on material properties. The carbonation investigation of the cracked mortar joints after failure is discussed in this section.

The carbonation patterns observed in the bond wrench prism mortar joints were similar to those observed in the larger wall panels (Figure 5.13). The fractured mortar joint interfaces from 'Berkeley Red Multi' brick prisms showed carbonation had penetrated to an average depth of 12 mm. There was no apparent difference in extent of carbonation for the varied mortar lime content (1:2, 1:2.25 and 1:2.5) and grade (NHL 2, NHL 3.5 and NHL 5). In section 4.4 the carbonation depth in mortar prisms cast in steel moulds was shown to be

Berkeley Red Multi

Staffordshire Slate Blue Smooth

Hardwicke Welbeck Autumn Antique

Chester blend

Holbrook Smooth

Figure 5.13 Bond wrench carbonation indicator patterns similar for the cement:lime:sand mortared brick prisms at 91 days, indicating similar carbonation depth to the NHL mortared brick prisms at same age. The progression of carbonation in the mortar joints within brickwork is discussed further in the next chapter.

As with the wall panels, the carbonation indicator test showed that brick type had a significant influence on mortar joint carbonation in the bond wrench prisms (Figure 5.13). The carbonation depths of the low water absorption ‘Staffordshire Slate Blue Smooth’ brick were about 10-11 mm, slightly less than the ‘Berkeley Red Multi’ brick prisms, around 11mm on average. The high water absorption ‘Hardwicke Welbeck Autumn Antique’ and ‘Chester Blend’ bricks had irregular carbonation outlines and the greater depths, around 15mm on average. The medium water absorption brick ‘Holbrook Smooth’ had similar carbonation depth with the ‘Berkeley Red Multi’ brick prisms.

The observed variation in carbonation depths in the bond wrench prisms confirmed that brick type influences carbonation rates of the mortar. Carbonation rates are closely correlated with brick water absorption properties. Compared to the medium absorption ‘Berkeley Red Multi’ brick, the high IRA ‘Hardwicke Welbeck Autumn Antique’ brick absorbed the water from the fresh mortar more rapidly, making the mortar joint structure more porous and then speeding up the carbonation progress. In contrast, the carbonation rate of low absorption ‘Staffordshire Slate Blue Smooth’ brick prism mortar joint was initially hindered as water within mortar pores delayed onset and progression of carbonation.

All tests confirmed that the mortar joint carbonation depths were less than the corresponding hardened mortar specimens cast in steel moulds. Water transport between the mortar and brick delayed mortar joint drying and so slowed the carbonation process.

The carbonation indicator patterns at the fractured surfaces are related to the failure modes outlined previously (Figure 5.13). Carbonation patterns corresponding to interface failure or failure within mortar joint were very regular along brick edges. In the combined interface and mortar failures the carbonation patterns were more irregular. Carbonation may have occurred at a faster rate along the interface between brick and mortar in some specimens due to increased drying and contraction of the mortar and presence of small shrinkage cracks. Therefore the mortar joint was carbonated deeper in the interface failure zone than the part in the mortar failure zone.

5.4.4 Bond wrench flexural strength

Results from the comparative bond wrench strength tests are summarised in Table 5.7. The influence of mortar properties such as mortar mix proportions (1:2, 1:2.25 and 1:2.5) and lime grade (NHL 2, 3.5 and 5), and brick types on the bond wrench strength were investigated and are also compared with the previous corresponding wall panel test results. Both 1:3:12 and 1:2:9 cement:lime:sand mortar brickwork were also tested at 28 days for comparison.

The characteristic bond wrench strength (f_{wk}), determined in accordance with BS EN 1052-5, for hydraulic lime mortared brickwork at 91 days ranged from 0.03 to 0.45 N/mm^2. This range is similar to the characteristic flexural strength of corresponding walls in the 'parallel to bed joint' direction, which ranged from 0.05 to 0.39 N/mm^2.

The variation (coefficients of variations) in bond strength for the 'Berkeley Red Multi' brick and the very low absorption 'Staffordshire Slate Blue Smooth' brick prisms were all below 18% ('The variability of bond strength recorded by many researchers is generally in the order of 30 percent for laboratory conditions' by Gazzola et al. 1985, '*The variability higher than 25% has been observed in many experimental investigations*' by Lawrence and Page 1994). Variation in performance of the very high absorption 'Hardwicke Welbeck Autumn Antique' brick series was the highest of all tested (coefficient of variation 52.8%); this was much higher than the variation in corresponding 'parallel to bed joint' wall panel test (33.4%). As the mean value of the bond wrench strength was low, 0.09 N/mm^2, it is possible that the bond was so weak that it was partly damaged during handling.

Table 5.7 Comparison bond wrench strength test data

Brick type	Mortar mix proportion (by volume)	Lime grade	Age (days)	Bond wrench strength				'Parallel to bed joint' wall panel strength (f_{xk1})	
				Average (N/mm^2)	Range (N/mm^2)	CV (%)	Char. (N/mm^2)	CV (%)	Char. (N/mm^2)
Berkeley Red Multi	1:2.25	NHL 2	91	0.29	0.22-0.39	18.0	0.21	13.5	0.19
		NHL 3.5 (baseline–Series III)		**0.51**	**0.38-0.64**	**16.0**	**0.37**	**---**	**---**
		NHL 5		0.63	0.40-0.80	16.3	0.45	13.3	0.39
	1:2	NHL 3.5		0.61	0.43-0.75	15.1	0.45	15.5	0.39
	1:2.25 (baseline–series I)			**0.46**	**0.36-0.52**	**12.2**	**0.36**	**9.6**	**0.38**
	1:2.5			0.38	0.30-0.47	11.1	0.31	7.1	0.31
	1:3:12	---	28	0.35	0.30-0.40	8.1	0.30	12.8	0.31
	1:2:9			0.47	0.33-0.55	14.0	0.35	10.5	0.35
Staffordshire Slate Blue Smooth	1:2.25	NHL 3.5	91	0.23	0.18-0.28	14.2	0.15	12.6	0.16
Hardwicke Welbeck Autumn Antique				0.09	0.05-0.12	52.8	0.03	33.4	0.05
Chester Blend				0.33	0.15-0.54	31.4	0.17	---	---
Holbrook Smooth				0.44	0.13-0.68	35.6	0.17	59.2	0.06
Holbrook Smooth	1:2.25	NHL 5	91	0.44	0.23-0.73	34.7	0.21	30.0	0.12

The coefficients of variation of the other two brick series ('Chester Blend' and 'Holbrook Smooth') were both higher than the 'Berkeley Red Multi' and 'Staffordshire Slate Blue Smooth' brick series, 31.4% and 35.6% respectively. This variation in performance impaired the resultant characteristic bond wrench strengths. Although reasons for the higher variations are unclear, the higher proportions of holes in these two bricks (Table 5.1) might have influenced performance. In the 'Holbrook Smooth' brick wall panel series the variation was even higher (59.2%) than in the bond wrench test. This has been attributed to the possible damage to weak wall panels during movement before testing.

As with the wall panel tests, lime grades, lime: sand proportions and brick characteristics have had a significant influence on the bond strength development. These are analysed and discussed in this section. In general the characteristic bond wrench strengths of the brick prisms were similar to the corresponding characteristic flexural strength of the wall panels in the 'parallel to bed joint' direction. The correlation between the two methods of bond strength testing is analysed in depth later.

5.4.4.1 Influence of mortar properties

The influence of mortar properties on bond wrench strength was examined and the results are summarised in Table 5.8. The influence of lime content (mix proportions) and lime grade were studied. Mortar mixes followed industry practice. NHL 2, 3.5 and 5 were supplied by 'Castle Cement Ltd'. 'Binnegar' sand was used in all mixes for these series of tests. As noted before, there was some variation in mortar performance for the baseline 1:2.25 NHL 3.5: sand mortar due to variation in lime supplied in different batches over the course of the research. The test results of the baseline brickwork were presented separately as both series I and III for direct comparison with the performance of corresponding series.

As seen in Table 5.8 the 91 day characteristic (95% fractile) bond strengths of lime mortared brickwork ranged 0.21-0.45 N/mm^2. The 1:2:9 cement:lime:sand mortared brickwork at 28 days developed similar bond strength to the baseline lime mortared brickwork at 91 days, whilst the 1:3:12 C:L:S mortared brickwork at 28 days developed similar strength to 1:2.5 lime brickwork at 91 days. The coefficients of variation were all below 18% demonstrating consistency in performance in bond strength and bond wrench testing. As expected, the bond wrench strength of hydraulic lime mortared brickwork improved with increased mortar strength. The trend was same as the results from the wall panel flexural strength tests and in keeping with the general performance reported in previous research (Chapter 2).

Table 5.8 Influence of lime content and grade

Mortar		Age (days)	Mortar compressive strength (N/mm^2)		Bond wrench strength (N/mm^2)			
			Average	Relative to baseline	Average	CV %	Char.	Relative to baseline
1:2		91	1.20	126%	0.61	15.1	0.45	125%
1:2.25 (baseline–Series I)		**91**	**0.95**	**100%**	**0.46**	**12.2**	**0.36**	**100%**
1:2.5		91	0.78	82%	0.38	11.1	0.31	86%
1:2:9		28	2.03	214%	0.47	14.0	0.35	97%
1:3:12		28	1.08	114%	0.35	8.1	0.30	83%
1:2.25	NHL 5	**91**	1.28	114%	0.63	16.3	0.45	122%
1:2.25	**NHL 3.5 (baseline–Series III)**	**91**	**1.12**	**100%**	**0.51**	**16.0**	**0.37**	**100%**
1:2.25	NHL 2	**91**	0.97	87%	0.29	18.0	0.21	57%

Relative to the baseline results the bond strength variations, caused by variations in lime: sand mix proportions, matched corresponding changes in mortar compressive strength. However, variations in the lime grade did not match as well, with the bond wrench strength more sensitive to variations than the corresponding mortar prism strengths. The bond strengths of both the 1:2:9 and 1:3:12 cement: lime: sand mortared brick prisms were lower than the NHL3.5 1:2.25 baseline mortared brick prisms, even though their C:L:S mortars were stronger than the NHL mortar. Further discussions on influence of materials on bond strength will be given in Chapter 6. Compared with the two cement: lime: sand mortared brickworks, the NHL mortared brickwork developed better bond despite having lower mortar strength.

Increasing lime content and NHL grade can be specified to improve the brickwork bond strength. However, in order to optimise mortar mix design, further work is needed to establish a clearer performance relationship between materials and bond strength development.

5.4.4.2 Influence of brick properties

For the comparison between flexural strength test methods, five different brick types with the baseline NHL 3.5 mortar and two further bricks with NHL 5 mortar were studied. Results are summarised in Table 5.9. It is generally accepted that the brick water absorption characteristics play an important role in developing the brickwork bond strength.

In both BS5628 (withdrawn in April 2010) and the UK National Annex to EC6 characteristic flexural strengths are presented for fired clay brickwork. Flexural strengths are provided as a function of mortar strength and brick total water absorption. The brick water absorption figures presented (categorised into three groups: ‘less than 7%’, ‘between 7% and 12%’ and ‘over 12%) are based on brick data from the 5-hour boil test. The 24-hour cold water absorption is now preferred in BS EN 771-1:2003: Specifications for masonry units, whilst the water absorption by boiling in water is used for clay masonry damp proof course units in BS EN 772-7:1998. The experimental relationship between the 5-hour boil test and 24-hour cold water immersion test data are presented in Chapter 4. In general the 5-hour boil test yields higher value than the 24-hour immersion test, so using BS EN 771-1 may lead to a higher characteristic strength in transition regions between groupings. In this investigation four testing methods have been used to examine and characterise brick water absorption: 24-hour cold water absorption, 5-hour boiling water absorption, initial rate of absorption (IRA) and sorptivity (Chapter 4).

Table 5.9 Influence of brick absorption properties on bond strength

Brick type	Lime grade	24h cold water absorption (%)	5h boil water absorption (%)	IRA (kg/m^2.min)	Sorptivity (mm.min$^{1/2}$)	Bond wrench strength (N/mm^2)		
						Average	Char.	Relative to baseline
Berkeley Red Multi	**NHL 3.5**	**5.1**	**8.4**	**1.3**	**0.49**	**0.46**	**0.36**	**100%**
Staffordshire Slate Blue Smooth		2.3	3.3	0.1	0.03	0.23	0.15	42%
Hardwicke Welbeck Autumn Antique		16.0	N/A	2.4	2.13	0.09	0.03	8%
Chester Blend		8.3	9.6	1.9	1.61	0.33	0.17	47%
Holbrook Smooth		7.7	8.7	1.0	0.65	0.44	0.17	47%
Berkeley Red Multi	NHL 5	5.1	9.6	1.3	0.49	0.63	0.45	125%
Holbrook Smooth		7.7	8.7	1.0	0.65	0.44	0.21	58%

Of the five bricks used, the baseline ‘Berkeley Red Multi’ brick achieved the highest bond wrench strength, whilst the highest water absorption brick ‘Hardwicke Welbeck Autumn Antique’ developed the lowest bond, just 8% of the highest. Characteristic bond strengths of remaining three bricks were very similar despite differences in brick water absorption properties.

As mentioned above the UK National Annex to EC6 categorises clay bricks into three groups in accordance to 5-h total water absorption, in which the lowest water absorption bricks (below 7%) provides the highest characteristic flexural strength. However, the test results herein showed the very low water absorption bricks do not always present the highest bond strength. The effects of brick properties on bond strength are studied in greater depth in Chapter 6.

Compared to the baseline NHL 3.5 mortar, NHL 5 mortar brickwork using Berkeley Red Multi brick improved bond by around 125%. Increasing lime grade and thereby mortar strength improves brickwork bond strength. The Holbrook Smooth brick prisms produced only 47-58% of the corresponding Berkeley Red Multi brickwork bond strength, but the NHL 5 mortar developed 124% bond strength of the NHL 3.5 mortar nevertheless.

5.4.5 Discussions

For comparison with the wall panel flexural tests (‘parallel to bed joint’) the corresponding bond wrench tests were conducted and the results have been presented in this section. The bond wrench test results varied between 0.03 N/mm^2 and 0.45 N/mm^2. Comparison between the two testing methods, wall panel test and brick prism bond wrench test, is reported in section 5.5. The 1:2:9 cement:lime:sand mortared brickwork developed comparable bond wrench strength to the baseline lime mortared brickwork, even though its mortar strength was higher than the NHL mortar strength. The 1:3:12 mortared brickwork achieved lower bond strength than the baseline brickwork although its mortar strength was higher than the lime mortar.

The bond wrench strength of lime mortared brickwork generally improved with lime content and lime grade. Brick water absorption properties exhibited significant influence on the bond strength developed. Further study using the bond wrench to study effects of lime supplier, sand type, curing time and brick water absorption ability will be summarised in Chapter 6.

5.5 Comparison of wall panel and bond wrench test results

Table 5.10 summarises the test results from both testing methods: the bond wrench test and 'parallel to bed joint' wall panel flexural strength test. These data (characteristic performance), are also presented together in Figure 5.14. Despite variation in performance for relatively small test populations the overall correlation confirms earlier work (IS277 by PCA (Portland Cement Association) and ASTM C 1072) that the bond wrench is a reliable alternative to the panel test. In addition to the overall correlation presented in Figure 5.14, individual student's t-tests were undertaken, and no significant differences were found with confidence levels of 95%.

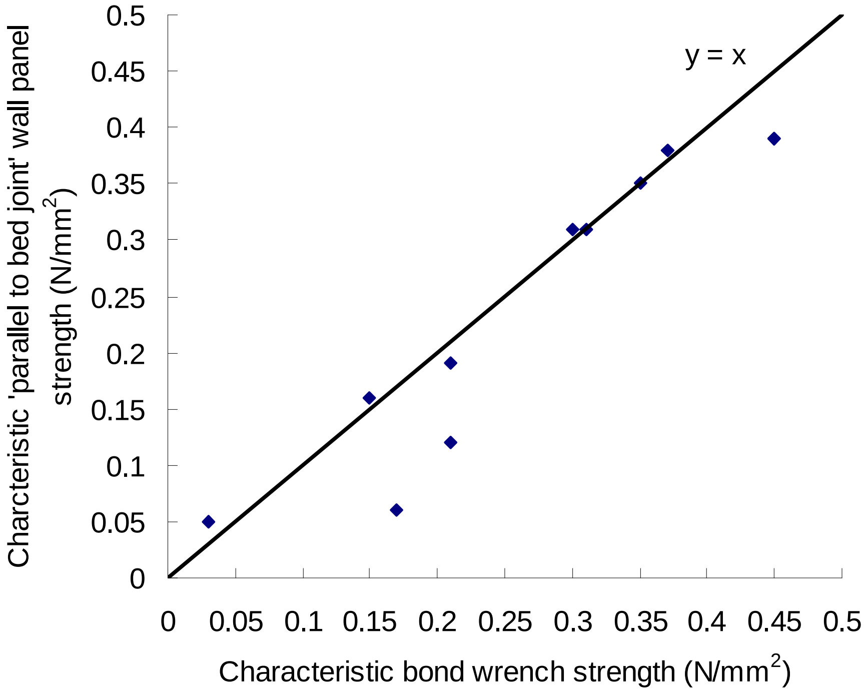


Figure 5.14 Testing methods comparison

Table 5.10 Result comparison of the two test methods

<table>
<tr><th>Brick type</th><th>Mortar mix proportion (by volume)</th><th>Lime grade</th><th>Age (days)</th><th>Mortar strength Average (N/mm^2)</th><th>Characteristic bond wrench strength (N/mm^2)</th><th>Characteristic ‘Parallel to bed joint’ flexural strength (f_{xk1}) (N/mm^2)</th></tr>
<tr><td rowspan="8">Berkeley Red Multi</td><td rowspan="3">1:2.25</td><td>NHL 2</td><td rowspan="6">91</td><td>0.97</td><td>0.21</td><td>0.19</td></tr>
<tr><td>NHL 5</td><td>1.28</td><td>0.45</td><td>0.39</td></tr>
<tr><td>NHL 3.5 (Baseline–Series III)</td><td>1.12</td><td>0.37</td><td>0.38</td></tr>
<tr><td>1:2</td><td rowspan="3">NHL 3.5</td><td>1.20</td><td>0.45</td><td>0.39</td></tr>
<tr><td>1:2.25 (Baseline–Series I)</td><td>0.95</td><td>0.36</td><td>---</td></tr>
<tr><td>1:2.5</td><td>0.78</td><td>0.31</td><td>0.31</td></tr>
<tr><td>1:3:12</td><td rowspan="2">-----</td><td rowspan="2">28</td><td>1.08</td><td>0.30</td><td>0.31</td></tr>
<tr><td>1:2:9</td><td>2.03</td><td>0.35</td><td>0.35</td></tr>
<tr><td>Staffordshire Slate Blue Smooth</td><td rowspan="4">1:2.25</td><td rowspan="4">NHL 3.5</td><td rowspan="5">91</td><td rowspan="4">0.93</td><td>0.15</td><td>0.16</td></tr>
<tr><td>Hardwicke Welbeck Autumn Antique</td><td>0.03</td><td>0.05</td></tr>
<tr><td>Chester Blend</td><td>0.17</td><td>-----</td></tr>
<tr><td>Holbrook Smooth</td><td>0.17</td><td>0.06</td></tr>
<tr><td>Holbrook Smooth</td><td>1:2.25</td><td>NHL 5</td><td>0.97</td><td>0.21</td><td>0.12</td></tr>
</table>

In Chapter 6 further bond wrench test results, exploring effects of lime content and grade, lime supplier, lime batch variation, sand grading, mix proportion and brick water absorption on brickwork bond are presented.

5.6 Summary and conclusions

This chapter has presented results from wall panel flexural tests (‘parallel to bed joint’ and ‘perpendicular to bed joint’) and the compared wall panel and brick prism bond wrench test method performance. Failure modes, mortar carbonation rates and strength results have been reported and discussed. Material factors influencing development of brickwork flexural bond, including mix proportion, lime grade and brick water absorption have been examined. Comparative cement: lime: sand mortared brickwork tests were also completed. The following conclusions can be drawn from the work:

1. Failure modes in flexural testing of brickwork walls and prisms varied depending on relative strengths and constituent material properties. In weaker joints failure was primarily along the mortar-brick interface, whilst in stronger joints failure was often partially or wholly within the mortar. In some of the stronger perpendicular to bed joint tests cracking occurred in the bricks.

2. The rates of carbonation in mortar joints were significantly influenced by brick water absorption properties. The mortar combined with high water absorption bricks carbonated much faster than with low absorption bricks.

3. The NHL mortared brickwork flexural bond strength improved with increasing mortar strength achieved through increased lime content or higher grade of lime.

4. At 91-days the NHL mortars developed bond strengths comparable with weaker cement: lime:sand (1:2:9 and 1:3:12) mortars at 28-days.

5. Brick water absorption properties have a significant effect on the formation of brickwork bond, carbonation rates and failure modes in bending. Bond strength is impaired by low and high brick water absorption.

6. There is strong correlation between flexural bond strengths derived by wall panel and bond wrench tests.

7. Current design recommendations for hydraulic lime mortared brickwork flexural bond strength did not show a good correlation with the experimental data.

6. Influence of material properties on bond strength of hydraulic lime mortared brickwork

6.1 Introduction

In the UK National Annex to EC6 the characteristic flexural strengths for masonry are based on data from wall panel tests. Where the data provided are insufficient, designers are recommended to establish performance data in accordance with panel test method outlined in BS EN 1052-2:1999. However, previous work (IS277, 1993; ASTM C1072, 2010), and confirmed in Chapter 5, the bond wrench can provide a reliable alternative method to determine f_{xk1}.

This chapter presents results from a comprehensive study of the effects of mortar and unit properties on the flexural strength of NHL mortared brickwork using the bond wrench method of testing. The work presented here builds on that presented in the previous chapter on the effects of mortar and brick properties on flexural bond strength. The study of mortar properties has been extended to include effects of sand grading and lime type. Investigation into the effects of brick properties has been broadened to include a further 32 different bricks. In addition to material parameters, this study has included the effects of curing time on bond development. The performances of NHL mortared specimens are compared with similar cement: hydrated lime: sand mortar specimens. Results from the experimental study are used to develop design guidance for flexural bond strength of NHL mortared brickwork.

6.2 Summary of bond tests

For each test sample series four identical four-brick high stack bonded prisms were constructed, providing 12 identical bond wrench test joints. Bond wrench tests were mainly undertaken at 28 and 91 days, although to map the development of bond with age some series were also tested at 14, 56 and 365 days after construction. As some variation in performance of the baseline NHL mortar was noted in the earlier tests, repeat series of the baseline brickwork materials were tested in the later series III, IV, V and VI.

The influences of various mortar mixes on bond strength were studied, including: varying lime grade (NHL 2, 3.5 and 5); lime: sand ratio (1:2.5, 1:2.25 and 1:2 (by volume)); sand grading; and NHLs sourcing from different suppliers. For comparison some limited series of 1:2:9 and 1:3:12 cement: hydrated lime: sand mortared brick prisms were also tested.

To investigate the effects of brick type on flexural bond strength, a total 37 different clay bricks, with a wide range of water absorption properties (Chapter 3) representative of current UK practice, were included in the study. In addition the effect of brick moisture content at laying was also studied using the bond wrench test.

In summary, the variables studied in the bond wrench test series were:

- Lime grade and content: three different grades (NHL 2, 3.5 and 5) and three lime: sand mix proportions (1:2.5, 1:2.25 and 1:2), tested at 28 and 91 days;
- Sand type: four different sand gradings (‘Binnegar’, ‘Allerton Park’, ‘Yellow Pit’ and ‘Croxden’), tested at 28 and 91 days;

- Lime supplier: four different suppliers (‘Castle Cement’, ‘hl2’, ‘St Astier’ and ‘Limetec’), tested at 28 and 91 days;
- Cement mortar: three different cement: lime: sand mixes (1:3:12, 1:2:9 and 1:1:6), tested at 14, 28 and 91 days;
- Age: tested at 14, 28, 56, 91, 365 days after construction;
- Bricks with a wide range of water absorption properties (tested at 91 days):
    - 24 hour cold water absorption: 2.3-18.2%;
    - 5 hour boil water absorption: 3.3%-19.6%;
    - IRA: 0.09-3.67 kg/m^2.min;
    - Sorptivity: 0.03-2.13 mm.min$^{1/2}$;
- Brick moisture content at laying: five different moisture contents (0%, 4%, 8%, 12% and saturated (15.6%)), tested at 91 days.

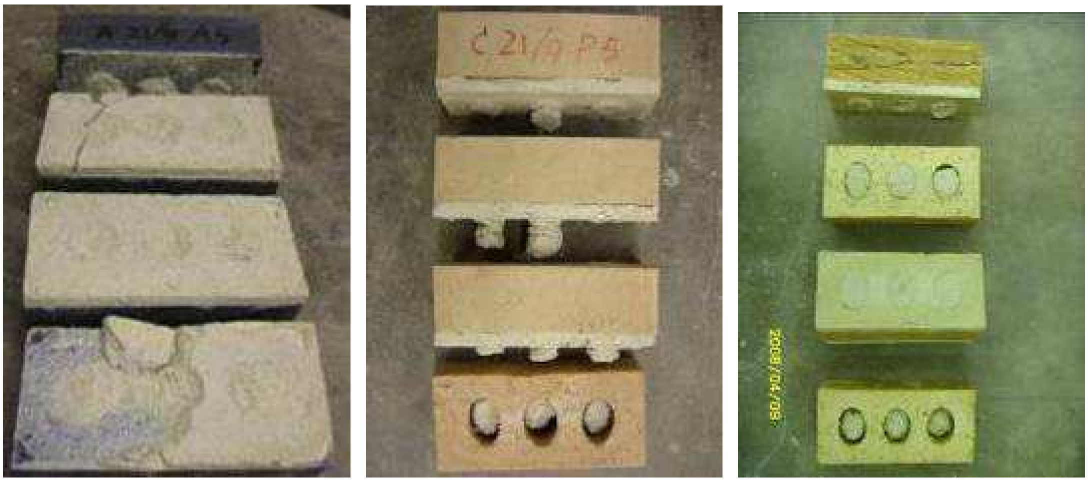
6.3 Failure modes in bond wrench testing

In total almost 2000 bond wrench joint tests have been completed as part of this PhD study, most of which are reported in this chapter. As reported in Chapter 5, three different failure modes were observed during bond wrench testing:

- Interface failure (Figure 6.1a);
- Mortar joint failure (Figure 6.1b);
- Combined failure (part interface failure with part within joint failure) (Figure 6.1c).

The most commonly observed was the interface failure, which occurred either at the top or bottom interface of the test joint, although sometimes fracture occurred partly along the top face and partly along the bottom face of the joint.

Interface failure was observed in around 70% of all tests. In other tests mortar joint failure were observed in approximately 18% of all cases with the combined failure mode observed in the remaining 12% of tests. These proportions are similar to those in the smaller series of bond wrench tests presented in chapter 5 (76%, 12% and 12% respectively). In none of the tests did the bricks fail, which is to be expected given the relative weakness of the mortars compared to the brick strengths.



(a) Examples of interface failure
(Left-to-right: ‘Staffordshire Slate Blue Smooth’, ‘Hardwicke Welbeck Autumn Antique’ and ‘Surrey Buff Multi (South Holmwood)’ bricks)

(b) Example of mortar joint failure
(‘Cheddar Red (Cattybrook)’ brick)

(c) Example of combined failure
(‘Tradesman Sandfaced (Atlas)’ brick)

Figure 6.1 Bond wrench test failure modes

Varying the lime grade, mortar mix proportion, sand grading and source of hydraulic lime had no noticeable effect on the bond wrench failure modes. The weakest joints tended to fail only at the interface whilst the combined and mortar failure modes were generally observed in the stronger joints (strength values are reported later in this chapter). Brick properties (water absorption characteristics) had the most significant influence on brickwork performance and failure mode. The very high water absorption bricks, such as 'Surrey Buff Multi (South Holmwood)' and 'Red Multi (Nostell)', as well as those already outlined in Chapter 5, all failed at the interface between the brick and mortar.

As bond strengths improved with brick type, the predominant failure mode changed to be mortar joint failure, with some combined failure mode and much fewer interface failures. Table 6.1 presents those brick types in which mortar joint failure was the main mode of failure. On average more than 80% of test joints exhibited mortar joint failure, with the remaining joints, around 20%, exhibiting combined failure mode, with almost no interface failures observed in prisms using these bricks. The test series built using brick with 5-hour boil test total absorption in the range 4.7-9.7% (Table 6.1) presented some of the highest bond strengths recorded (discuss further later in this chapter). All three failure modes were observed in prisms built using bricks with higher water absorption properties (IRA 0.5-2.1kg/m^2/min; 24-h total water absorption 3.9~12.7%; 5-h boil total water absorption 4.7~16.9 %; Sorptivity 0.14~1.31 mm min$^{1/2}$).

When investigating the effect of age on bond development, the older and generally stronger joints tended to exhibit more combined and mortar joint failures than at early ages. Brick water absorption properties still governed, as interface failure mode predominated in prism series built with either very low or high absorption bricks irrespective of age. However, in the investigation of brick moisture content on bond strength, using high water absorption brick 'Hardwicke Welbeck Autumn Antique', the failure mode and bond strength were dependent on brick moisture content at the time of construction. A greater proportion of combined or mortar joint failures were observed with the higher bond strengths.

Table 6.1 Summary of brick properties in which mortar joint failure governed

Brick type	No. of mortar failures (out of 12 joints)	IRA (kg/m^2/min)	24-h total water absorption (%)	5-h total water absorption (%)	Sorptivity (mm min$^{1/2}$)
Cheddar Brown (Cattybrook)	10	0.5	4.5	4.7	0.17
Brunswick Red (Cattybrook)	11	1.2	5.6	7.1	0.33
Cheddar Red (Cattybrook)	8	0.4	2.9	5.3	0.06
Red Multi Rustic (Roughdales)	11	1.6	7.9	8.8	0.86
Argyll Buff Multi Wirecut (Tannochside)	9	0.9	6.8	8.5	0.28
Handmade Multi (West Hoathly)	11	1.9	7.4	9.7	0.45
Berkeley Red Multi	9	1.3	5.1	8.4	0.49
Range		0.5-1.9	2.9-7.9	4.7-9.7	0.17-0.86
Total brick range		0.1-3.7	2.3-18.2	3.3-19.6	0.03-2.13

6.4 Mortar joint carbonation

6.4.1 Carbonation profiles

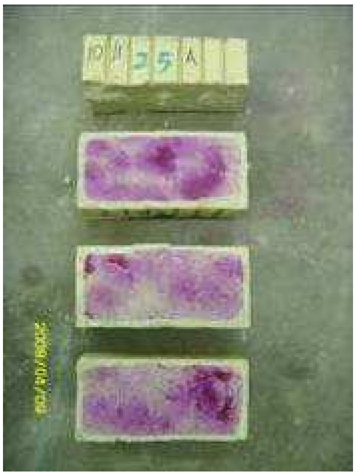
Carbonation of the mortars was mapped using indicator testing of joints immediately following bond wrench testing. In Chapter 5 it was reported that the water absorption properties of the brick had governed variation in mortar carbonation rates. This finding has been confirmed in the much broader study of brick properties. In contrast there was no significant variation in the carbonation rates as a result of variations in mortar mix, including NHL grade, lime source, lime: sand ratio and most interestingly, sand grading.

The carbonation indicator patterns, at 91 days, for different brick prisms, are presented in Figure 6.2. In general carbonation depths had progressed at a slower rate in the low and medium water absorption bricks compared to the higher absorption bricks. The carbonation indicator profiles were also generally more regular in the joints built with the lower water absorption bricks. The increased carbonation in the higher absorption bricks can be attributed to earlier drying of the mortar and the higher mortar porosity resulting from dewatering. In contrast the lower water absorption bricks dewatered the mortar less rapidly, with slower drying rates delaying the start of mortar carbonation (compare the differences in patterns in Figure 6.2). The bricks with similar water absorption values, but with very different IRA values, displayed different carbonation rates (Figure 6.2), indicating that IRA, like total water absorption, is an important brick parameter for carbonation rates.

Brick format also influenced carbonation indicator patterns. In figure 6.2 (e and f) the carbonation patterns for prisms using 'Surrey Buff Multi' (a three oval hole perforated unit) are compared with the ‘Dorset Red Stock’ brick (a frogged unit). Both bricks have very high IRA and total water absorption.

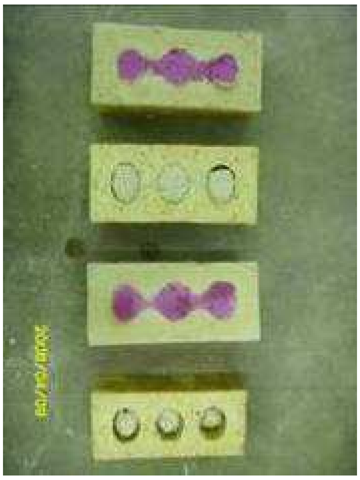
(a) Cheddar Red (Cattybrook)
24-h total water absorption: 2.9%
IRA: 0.4 kg/m^2/min

(b) Brunswick Tryfan Grey (Cattybrook)
24-h total water absorption: 3.9%
IRA: 0.9 kg/m^2/min



(c) Royston Cream (Nostell)
24-h total water absorption: 6.0%
IRA: 0.4 kg/m^2/min

(d) Kielder Orange (Throckley)
24-h total water absorption: 6.4%
IRA: 1.3 kg/m^2/min



(e) Surrey Buff Multi (South Holmwood)
24-h total water absorption: 18.2%
IRA: 3.7 kg/m^2/min

(f) Dorset Red Stock (Ellistown)
24-h total water absorption 12.7%
IRA: 2.1 kg/m^2/min

Figure 6.2 Mortar joint carbonation profiles at 91 days

The very high absorption bricks dewater the mortar joints very quickly during construction, impairing bond development but speeding up the carbonation process. At 91 days the carbonated depth for the ‘Surrey Buff Multi’ brick prisms had reached approximately 28 mm, 8 mm deeper than the carbonation of the mortar specimens (Chapter 4).

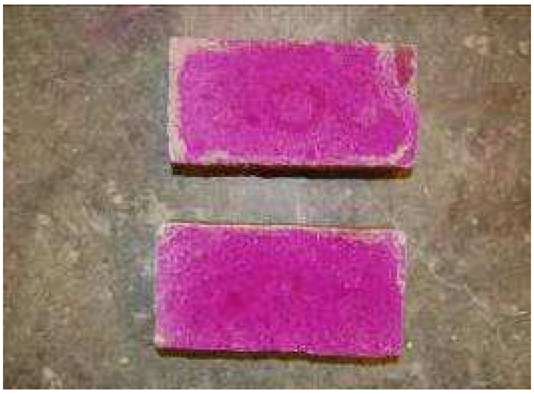
Following initial hydration, lime mortar develops further strength mainly through carbonation. Therefore, mortar joint carbonation in the brick prisms is likely to play an important role in bond development. Due to the dewatering influence of brick absorption, the properties of mortar joints in brickwork are likely to differ from the corresponding mortar specimens cast within the steel moulds.

To investigate and compare carbonation rates in the mortar specimens and mortar joints indicator testing was undertaken following testing at 14, 28, 56, 91 and 365 days in six series of bond wrench prisms and the corresponding mortar prisms. These tests were completed for the ‘Berkeley Red Multi’, ‘Staffordshire Slate Blue Smooth’, ‘Hardwicke Welbeck Autumn Antique’, ‘Holbrook Smooth’, ‘Chester Blend’ and ‘Cheshire Weathered’ series. The carbonation depths for each series, together with brick properties, are summarised in Table 6.2. The carbonation indicator tests for these different bricks showed significant variations at different ages (Figures 6.3-6.8). In general, the measured mortar joint carbonation depths increased with curing time (Table 6.2).

The average carbonated depth of mortar joint with the baseline brick ‘Berkeley Red Multi’ was approximately 1~2 mm deep at 14 days (Fig. 6.3 (a)), 3~5 mm at 28 days (Fig. 6.3(b)), 4~7 mm deep at 56 days (Fig. 6.3(c)), 8~13 mm at 91 days (Fig. 6.3(d)) and 18~32 mm deep at 365 days (Fig. 6.3(e)).

Table 6.2 Influence of brick properties and age on mortar carbonation depths

Brick	IRA (kg/m²/min)	5-h total water absorption (%)	24-h total water absorption (%)	Sorptivity (mm min$^{1/2}$)	Age (day)	Carbonation depth	
						Range (mm)	Average (mm)
Berkeley Red Multi	1.3	8.4	5.1	0.49	14	1~2	1
					28	3~5	4
					56	4~7	6
					91	8~13	11
					365	18~32	24
Staffordshire Slate Blue Smooth	0.1	3.3	2.3	0.03	14	1~2	1
					28	3~4	3
					56	5~7	6
					91	7~11	9
Hardwicke Welbeck Autumn Antique	2.4	16.5	14.8	2.13	14	9~12	11
					28	15~20	17
					56	18~28	26
					91	28~38	32
Holbrook Smooth	1.0	8.7	7.7	0.65	14	1	1
					28	4~8	7
					91	10~17	13
					365	18~28	25
Cheshire weathered	1.1	8.0	6.2	0.77	14	2~5	3
					28	3~10	6
					91	7~18	14
					365	23~44	33
Chester Blend	1.9	9.6	8.3	1.61	14	4~10	7
					28	12~17	12
					91	10~30	18
					365	37~45	40



(a)14 days

(b) 28 days

(c) 56 days

(d) 91 days

(e) 365 days

Figure 6.3 Development of mortar carbonation in ‘Berkeley Red Multi’ brick prisms

(a) 14 days

(b) 28 days

(c) 56 days

(d) 91 days

Figure 6.4 Development of mortar carbonation in ‘Staffordshire Slate Blue Smooth’ brick prisms

Compared to the baseline brick, the lower absorption ‘Staffordshire Slate Blue Smooth’ brick mortar joints carbonated at a very similar rate. The carbonation depths are shown in Table 6.2. At 14 – 56 days there was very little difference between the two series, although by 91 days the average carbonation in the ‘Staffordshire Slate Blue Smooth’ brick series was slightly less.

(a) 14 days

(b) 28 days (c) 56 days

(d) 91 days

Figure 6.5 Development of mortar carbonation in the 'Hardwicke Welbeck Autumn Antique' brick prisms

Figure 6.5 (a) compares the mortar joint carbonation between the low water absorption 'Staffordshire Slate Blue Smooth' and the higher 'Hardwicke

Welbeck Autumn Antique' brick series at 14 days (the 'Staffordshire Slate Blue Smooth' series is on the left hand side). The effect of brick water absorption properties on carbonation is clearly evident in this figure and in Table 6.2. Carbonation has progressed much faster in the higher absorption brick series due to the initial dewatering and increased porosity. In the corresponding mortar specimens cast in steel moulds (presented in Chapter 4) the carbonation progressed as follows: 3mm at 14 days; 7 mm at 28 days; 12 mm at 56 days; and, 20mm at 91 days. These carbonation depths are more than observed in the low absorption brick joints, but much less than in the corresponding 'Hardwicke Welbeck Autumn Antique' series.

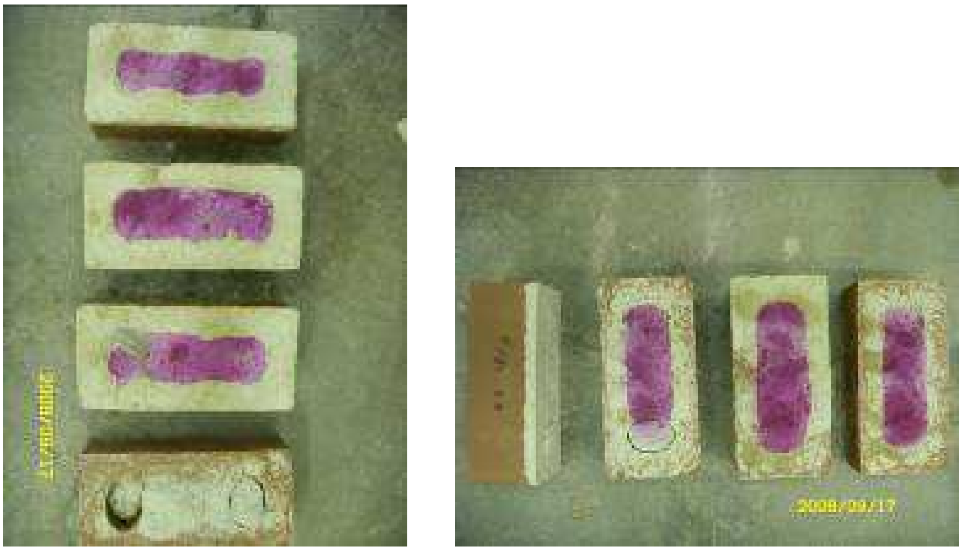
Figure 6.6 shows little difference between carbonation of 'Holbrook Smooth' brickwork and baseline brick 'Berkeley Red Multi'. The carbonation of 'Cheshire Weathered' (Figure 6.7) showed quite similar carbonation depths to the mortar specimens at early ages (14 and 28 days), but less carbonation than the mortar specimens by 91 days (Table 6.3). Initial carbonation rate in the 'Chester Blend' brickwork was faster than the mortar specimens (14 and 28 days), but also slowed down with age. However, carbonation in the high absorption 'Hardwicke Welbeck Autumn Antique' brick series progressed more than mortar specimen at all ages. The reasons behind this were discussed above.

Table 6.3 Comparative mortar carbonation depths

	Carbonation depth (mm)				
	14 day	28 day	56 day	91 day	365 day
Mortar specimen	3	7	12	20	---
'Staffordshire Slate Blue Smooth'	1	3	6	9	---
'Hardwicke Welbeck Autumn Antique'	11	17	26	32	---
'Cheshire Weathered'	3	6	---	14	33
'Chester Blend'	6	14	---	16	40

(a) 14d (b) 28d

(c) 91d



(d) 365d

Figure 6.6 Development of mortar carbonation in the 'Holbrook Smooth' brick prisms

(a) 14d

(b) 28d

(c) 91d

(d) 365d

Figure 6.7 Development of mortar carbonation in the 'Cheshire Weathered' brick prisms

(a) 14d

(b) 28d

(c) 91d

(d) 365d

Figure 6.8 Development of mortar carbonation in the 'Chester blend' brick prisms

6.4.2 Carbonation rates

The relationship between average carbonation depth and square root of curing time is shown in Figure 6.9. Depth of carbonation increased with age, and the rate of carbonation for each brick series is well represented by linear relationship with square root of time, suggesting it is governed by diffusion rates. The rates of carbonation varied between brick series. The ‘Staffordshire Slate Blue Smooth’ and ‘Berkeley Red Multi’ brick specimens carbonated at the slowest rate, whilst the ‘Hardwicke Welbeck Autumn Antique’ brickwork carbonated at a much faster rate. Other bricks in these series lie between these low and high absorption brick series.

Mortar carbonation rates (slope of lines in Figure 6.9) are strongly correlated with brick sorptivity values in polynomial regression (Figure 6.10). In general mortar between bricks with higher sorptivity carbonated faster than mortar between bricks with lower sorptivity. However, carbonation rate with brick sorptivity lower than 1.0 mm. $min^{1/2}$, varied much less significantly than the greater brick sorptivity.

Sorptivity test is a method assessing brick capillary water suction over time. The capillary water suction takes water away from the mortar pores to support carbonation, as directly previously discussed for commencement of carbonation, but also increasing brick sorptivity facilitates carbonation rate, most probably through increasing mortar porosity as a direct result of dewatering during initial construction. In addition, bricks with higher sorptivity are also more porous and therefore may directly further facilitate carbonation of the mortar joints by enabling greater carbon dioxide diffusion into the mortar. However, as carbonation of the mortar joints progresses from the edge of the brickwork face, rather than three-dimensionally through the bricks above and

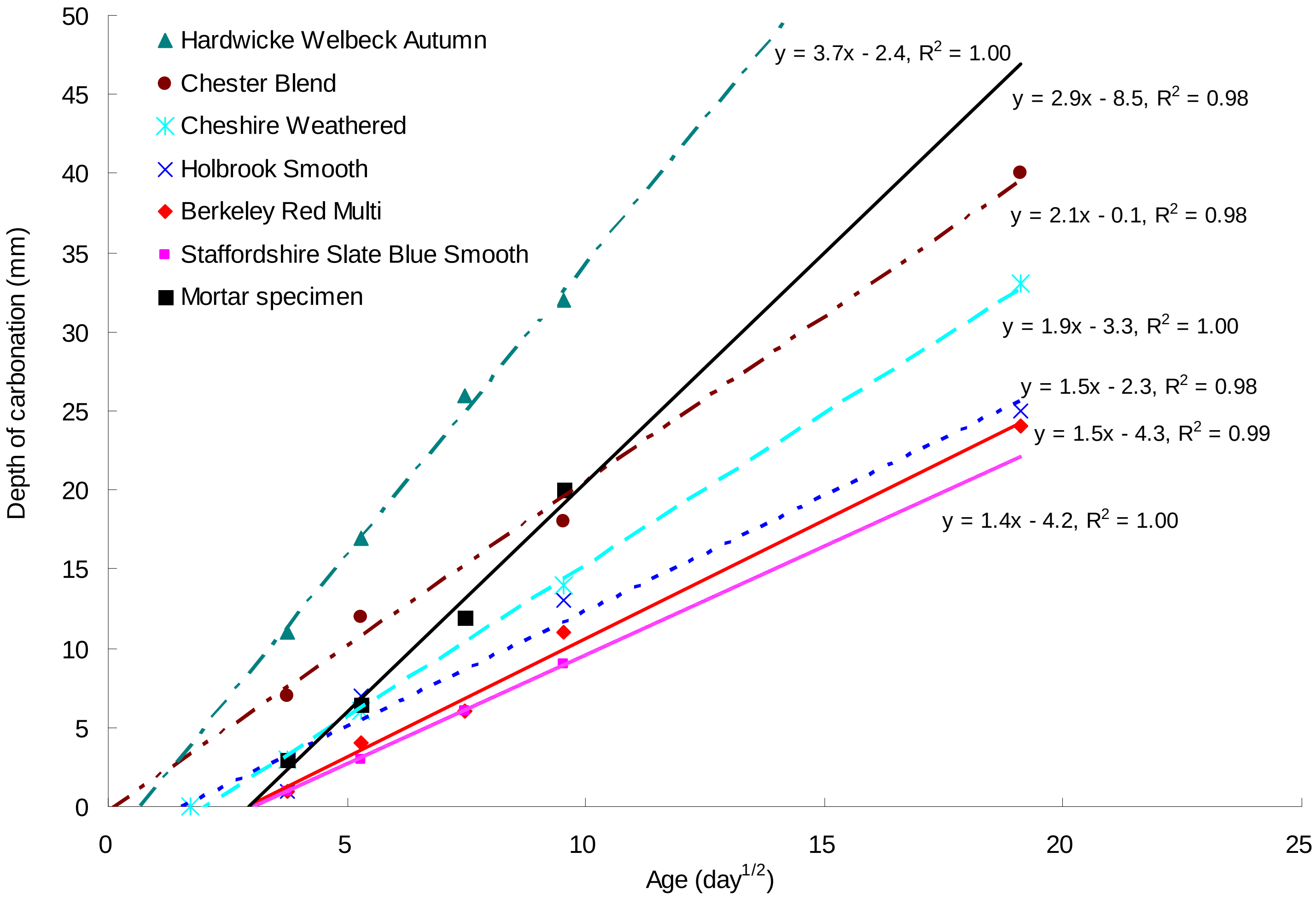


Figure 6.9 Mortar joint carbonation with age

below the bed joint, this effect is perhaps less significant compared to other actions. Carbonation commences only when mortar joint has reached adequately low moisture content to enable diffusion of carbon dioxide, which may explain why the carbonation rate only varied slightly with lower sorptivity of bricks discussed above.

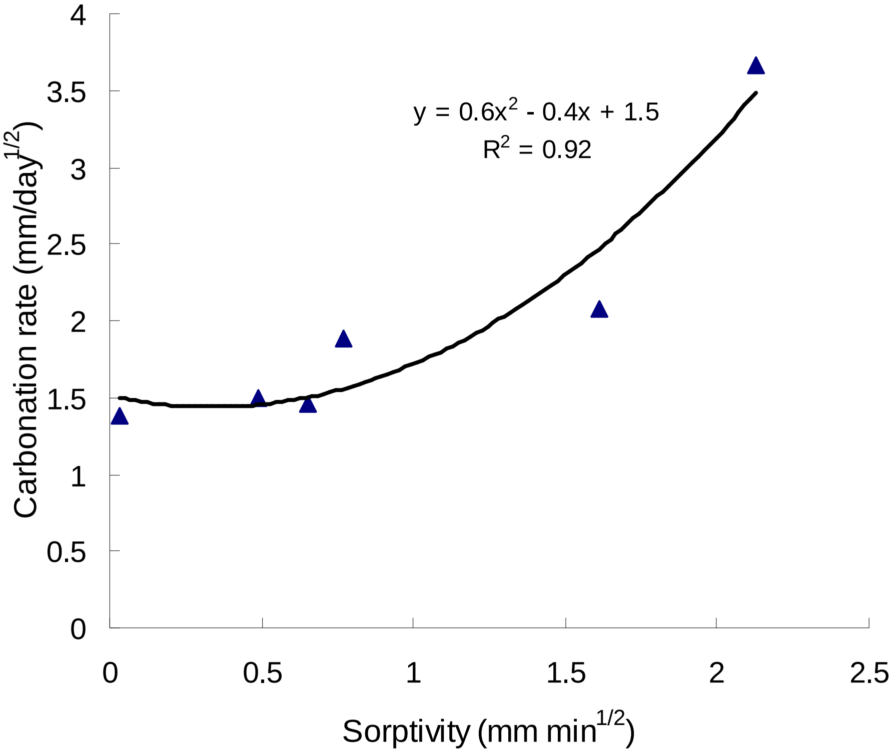


Figure 6.10 Relationship between mortar carbonation rate and brick sorptivity

By extrapolating the linear plots in Figure 6.9 backwards, it is possible to estimate age at which carbonation commenced. Interestingly these varied between brick series. It seems that the age increased with decreasing brick dewatering (water absorption) potential. The mortar joints in the ‘Chester Blend’ and ‘Hardwicke Welbeck Autumn’ brick series commenced carbonation almost at once, whilst the least absorptive brick, ‘Berkeley Red Multi’ and ‘Staffordshire Slate Blue Smooth’, did not start carbonation until approximately 8, 9 days after. Carbonation in other series commenced roughly in accordance with brick water absorption properties (Figure 6.11). Mortar carbonation can only commence once material has reached sufficiently low moisture content to enable diffusion of carbon dioxide. It is entirely expected, therefore, that commencement of carbonation is strongly aligned with the brick dewatering potential. This finding, although unsurprising, has not been reported previously in the literature.

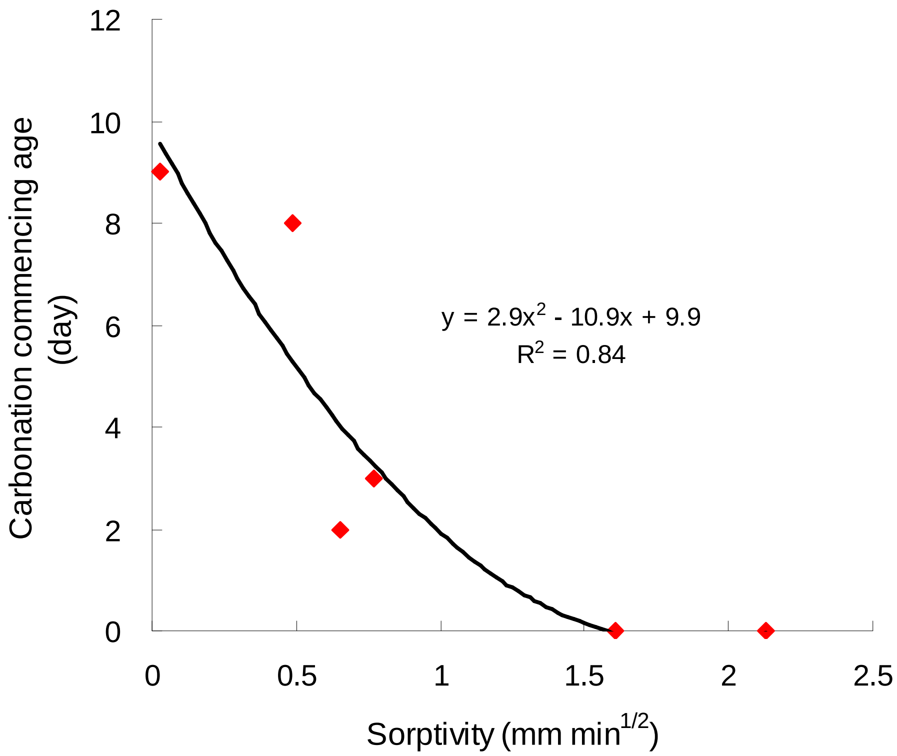


Figure 6.11 Relationship between carbonation commencing age and brick sorptivity

6.5 Influence of mortar properties on bond strength

6.5.1 Overview

The experimental investigation of mortar properties herein has studied the influence of NHL content, NHL grade, sand grading, and source of lime on bond performance in brickwork. Using the bond wrench has allowed a broader study of material parameters. The performance of NHL mortared brickwork is compared against cement: lime: sand mortared brickwork. The influence of mortar strength and development with curing time has also been studied. As this experimental study was undertaken over a period of 31 months, a study of the performance consistency in supply of NHL was also completed. The study of mortar properties was largely undertaken using one brick type, the ‘Berkeley Red Multi’. Unit water absorption is a well-known parameter controlling brickwork bond development (NA to BS EN 1996-1-1:2005). A comprehensive study on the influence of brick types is discussed later in section 6.6.

The 91 day characteristic bond strengths for the class M1 (1 N/mm^2) NHL mortars tested herein with the same baseline brick varied, as a result of sand and lime used, between 0.17 and 0.45 N/mm^2. The specification of NHL mortars by compressive strength performance alone is therefore likely to lead to conservative design guidance for many commonly used materials. Future design guidance should consider the influence of lime and aggregate properties as well. This is discussed further in the following sections.

6.5.2 Influence of lime content and lime grade

The bond wrench test results, at 28 and 91 days, using different lime grades and lime contents are summarised in Table 6.4. Three different ‘Castle Cement’ NHL grades (NHL 2, 3.5 and 5) in accordance with BS EN 459-1:2010 and three different lime: sand mortar mixes (1:2.5, 1:2.25 and 1:2 by volume) were studied. Throughout this study the same ‘Binnegar’ sand and ‘Berkeley Red Multi’ brick were used.

The characteristic (95% fractile) bond strengths ranged 0.15-0.25 N/mm^2 at 28 days and 0.21-0.45 N/mm^2 at 91 days. The coefficients of variation for the test series ranged between 11.1% and 22.2% are fairly typical of brickwork test performance. The level of bond performance maps well with the mortar performance, increasing with improved mortar strength as a result of age, NHL grade and lime content (Table 6.4). The experimental performance of bond strengths with age for varying material configurations are presented in Figures

6.12 and 6.13. The change in bond performance with mortar strength is summarised in Table 6.5.

Table 6.4 Influence of lime content and grade①

Series	Lime grade	Lime: sand (volume)	Age (days)	Mortar strength (N/mm^2)	Bond strength			
					Average (N/mm^2)	CV (%)	Char. (N/mm^2)	Range (N/mm^2)
I	NHL 3.5	1:2.5	28	0.55	0.28	13.9	0.21	0.23-0.34
			91	0.78	0.38	11.1	0.31	0.30-0.47
		1:2.25 Baseline	**28**	**0.60**	**0.30**	**18.5**	**0.21**	**0.21-0.42**
			91	**0.95**	**0.46**	**12.2**	**0.36**	**0.36-0.52**
		1:2	28	0.68	0.34	18.4	0.22	0.30-0.40
			91	1.20	0.61	15.1	0.45	0.43-0.75
II	NHL 2	**1:2.25 baseline**	28	0.54	0.24	22.2	0.15	0.15-0.34
			91	0.97	0.29	18.0	0.21	0.22-0.39
	NHL 3.5		**28**	**0.64**	**0.25**	**13.3**	**0.19**	**0.19-0.32**
			91	**1.12**	**0.51**	**16.0**	**0.37**	**0.38-0.64**
	NHL 5		28	0.94	0.35	17.0	0.25	0.27-0.47
			91	1.28	0.63	16.3	0.45	0.40-0.80

① Data derived from series I and II.

Table 6.5 Comparison of relative 91 day mortar and bond strengths

Series	Lime grade	Mortar mix	Mortar strength	Characteristic bond wrench strength
I	**NHL 3.5**	1:2.5	82%	86%
		1:2.25	**100%**	**100%**
		1:2	126%	125%
II	NHL 2	**1:2.25**	87%	57%
	NHL 3.5		**100%**	**100%**
	NHL 5		114%	122%

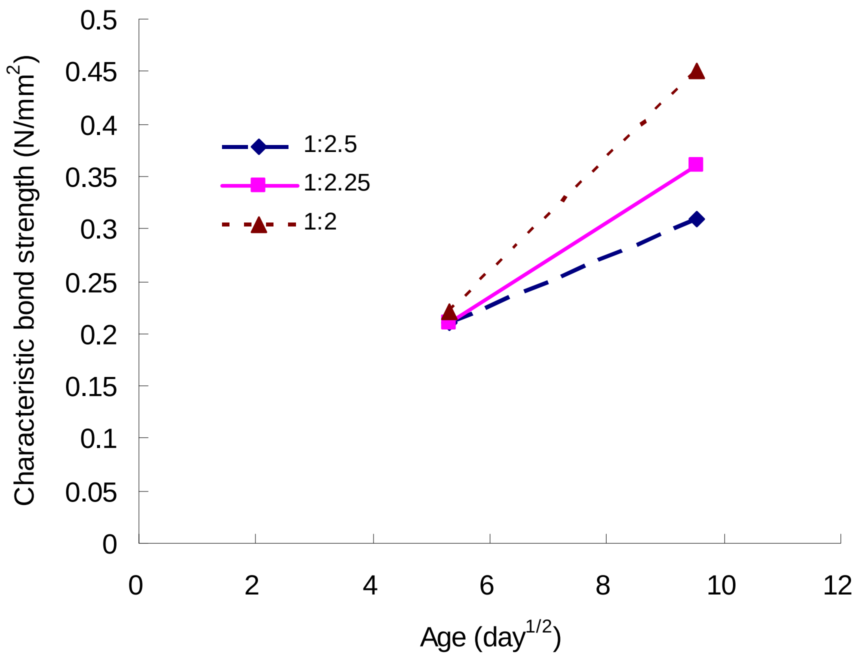


Figure 6.12 Influence of lime content on bond performance

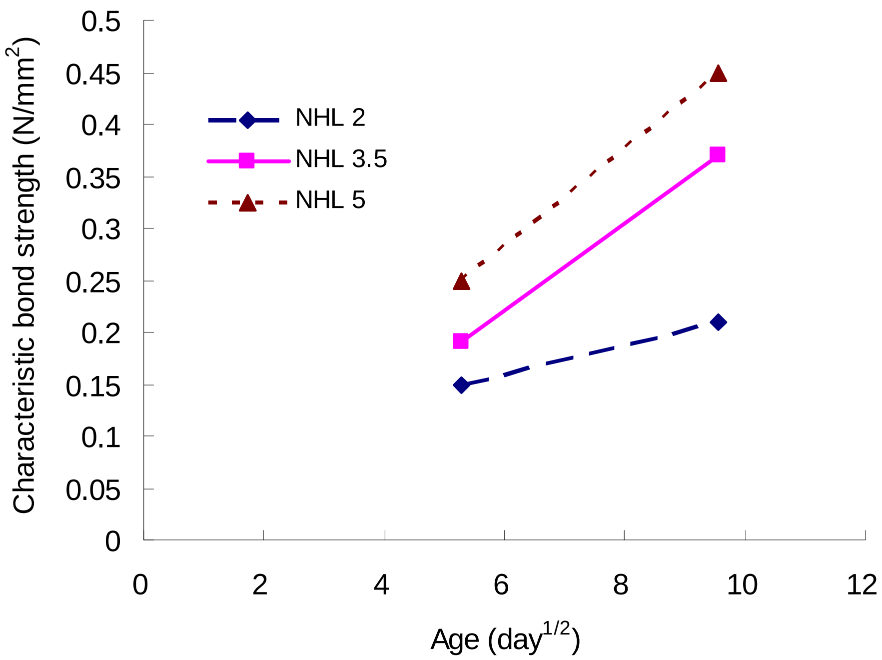


Figure 6.13 Influence of lime grade on bond performance

At 28 days from construction the characteristic bond wrench strengths for the specimens built with the three different mortar mix proportions (1:2, 1:2.25 and 1:2.5) were very similar, although average strengths showed greater variation in accordance with mortar strengths (Table 6.4). By 91 days there was more significant variation in bond strengths for the three mortar mix proportions

(Figure 6.12). The variations in bond strength were very closely aligned with the relative variation in mortar compressive strength (Table 6.5).

Bond wrench strengths varied, relatively to the NHL 3.5 baseline series, with lime grade at both 28 and 91 days (Figure 6.13). However, the variations in 91 day bond strength were not as closely aligned with corresponding changes in mortar strength as previously noted for the mortar mix (Table 6.5). In particular the NHL 2 bond strength was comparatively much lower relative to the NHL 3.5 results. Improvements in bond strength through increased NHL mortar strength, using either richer mixes or higher grade lime, can be realised. However, further work on optimising mortar mix design is required, including work to better understand the fundamental nature of the bond between mortar and brick.

All of the bond strengths in this series of tests increased from 28 to 91 days, in a process that is believed to be primarily through carbonation of the mortar. However, the gains in brickwork bond strength were not consistently in proportion with the corresponding changes in mortar compressive strength between 28 and 91 days (Table 6.6). Table 6.5 shows bond strength closely aligned with relative mortar strength changes. Table 6.6 shows that bond strength increases, corresponding to the relative mortar strength gain, also increased with lime content.

The longer term bond development in the NHL 3.5 mortared baseline brickwork was studied at 14, 28, 56, 91 and 365 days. The performance of NHL 5 brick specimens was also investigated up to 91 days (Table 6.7). Bond strengths increase with age, up to 365 days, and follows a trend similar to that previously reported for mortars (Chapter 4). Over the initial 14 days bond strength increases rapidly, during which time the binder hydration is presumed to dominate. The rate of bond strength development slows after 14 days, as carbonation becomes the more significant mortar hardening mechanism. At 14 days baseline brickwork had attained only 32% of its 365 day bond strength. From 14 days the bond strength increased gradually, reaching 40% (of the 365 day strength) at 28 days, 47% at 56 days and 68% at 91days.

Table 6.6 Relative mortar and bond strength gains between 28 and 91 days

Series	Lime grade	Mortar mix	Relative mortar strength gain	Relative increase in characteristic bond strength
I	**NHL 3.5**	1:2.5	42%	48%
		1:2.25	**58%**	**71%**
		1:2	76%	105%
II	NHL 2	**1:2.25**	75%	40%
	NHL 3.5		**70%**	**95%**
	NHL 5		36%	80%

Table 6.7 Long term bond strength development

Lime grade	Mortar mix	Age (days)	Mortar strength (N/mm^2)	Bond strength				
				Average (N/mm^2)	CV (%)	Characteristic		Range (N/mm^2)
						(N/mm^2)	Relative to 365 days	
NHL 3.5 Baseline (Series I)	1:2.25	14	0.39	0.21	10.6	0.17	32%	0.18-0.25
		28	0.60	0.30	18.5	0.21	40%	0.21-0.42
		56	0.85	0.40	19.5	0.25	47%	0.23-0.46
		91	0.95	0.46	12.2	0.36	68%	0.36-0.52
		365	0.98	0.63	8.6	0.53	100%	0.53-0.70
NHL 5 (Series II)	1:2.25	14	0.67	0.28	7.0	0.24		0.26-0.31
		28	0.94	0.35	17.0	0.25		0.27-0.47
		56	1.19	0.45	10.2	0.37		0.40-0.52
		91	1.28	0.63	16.3	0.45		0.40-0.80

The development of bond with specimen age is presented in Figure 6.14. Linear correlations between characteristic bond strength and the square root of curing time are presented for both NHL 3.5 and NHL 5 mortars and suggest mortar carbonation plays a major part in developing bond in brick prisms. It is generally assumed that the depth of carbonation is proportional to the square root of time for both concrete and cement materials (Hall and Hoff 2002, 2005, Lawrence 2006), and was confirmed for hydraulic lime mortar in Chapter 4.

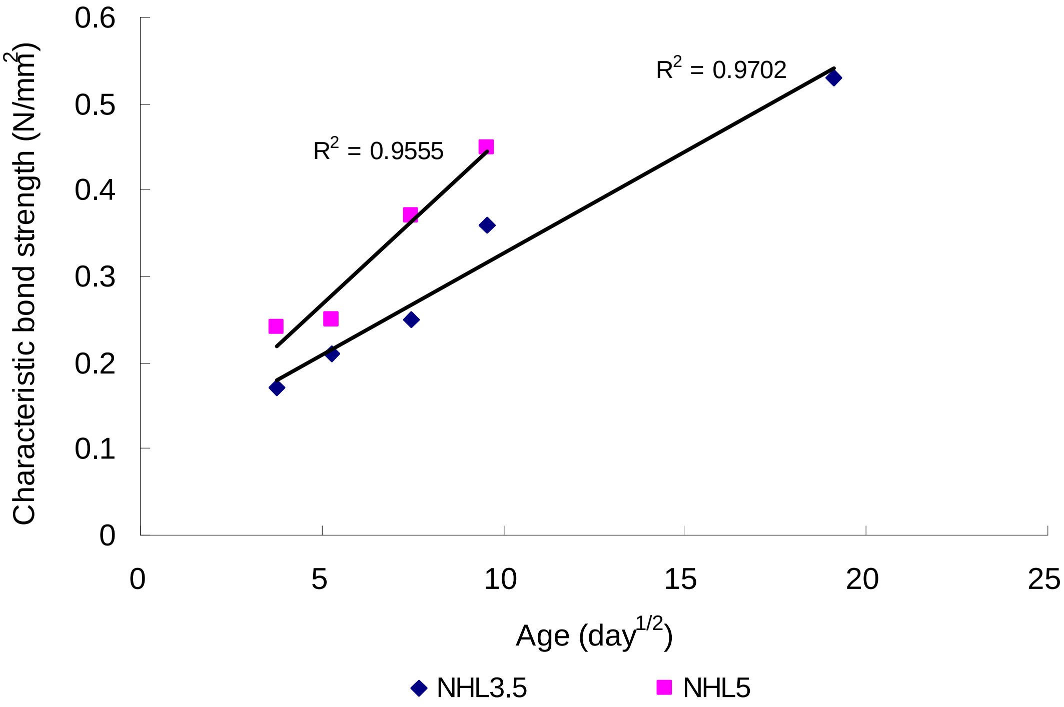


Figure 6.14 Bond strength developments with age

The NHL mortared brickwork continued to gain bond strength after 91 days. The trend in Figure 6.14 suggests that bond strength may continue to develop after one-year. The baseline brickwork bond increased by a further 47% between 91 and 365 days. The longer-term performance of NHL mortared brickwork is important and warrants further study.

6.5.3 Influence of sand grading

Four types of mortar sand were investigated in this project. The grading sequence, from coarsest to finest sand, was 'Allerton Park' (the coarsest), 'Croxden', 'Binnegar' and 'Yellow Pit' (the finest). The sand grading curves are shown in Figure 3.8. Mortar strength and bond strength were both influenced by sand grading. The test results are summarized in Table 6.8.

Table 6.8 Influence of sand type①

Sand	Age (days)	Mortar strength (N/mm^2)	Bond strength			
			Average (N/mm^2)	CV (%)	Characteristic (N/mm^2)	Range (N/mm^2)
Allerton Park	28	1.13	0.29	13.5	0.22	0.23-0.35
	91	1.52	0.42	8.8	0.34	0.34-0.48
Croxden	28	0.59	0.26	19.4	0.19	0.22-0.39
	91	1.02	0.40	15.6	0.32	0.34-0.50
Binnegar (Baseline)	**28**	**0.64**	**0.27**	**13.2**	**0.19**	**0.20-0.38**
	91	**0.98**	**0.39**	**14.0**	**0.31**	**0.28-0.43**
Yellow Pit	28	0.50	0.23	21.0	0.15	0.15-0.32
	91	0.76	0.37	17.1	0.25	0.26-0.52

① Data derived from series III.

The coarsest sand, 'Allerton Park', achieved the highest bond strength, whilst the finest sand, 'Yellow Pit', developed the lowest bond wrench strength. The three most coarsely graded sands ('Allerton Park', 'Croxden' and 'Binnegar') developed similar bond wrench strengths at 28 and 91 days, whilst the finest sand consistently developed the lowest mortar and brickwork bond strengths.

Both the 28 and 91 day bond strengths were less influenced by changes in sand grading than the corresponding mortar compressive strengths. At 91 days the relative mortar strengths (compared to the baseline 'Binnegar' sand series) varied between 80% ('Yellow Pit') and 160% ('Allerton Park'). However, in comparison, the characteristic bond strengths ranged between 81% and 110% of the baseline brickwork performance (Table 6.9). Except for the 'Allerton Park' series, the relative variation in bond strength matched well with their corresponding variation of mortar strength. The strongest bond corresponded to the strongest mortar, and the weakest bond with the 'Yellow Pit' sand mortar. It is clear that bond between brick and mortar is a complex interaction between mortar water retentivity and brick absorption (dewatering). The finer sands have better water retention characteristics, whilst the coarser sands dewater more easily, therefore, to some extent, balancing out the differences seen in mortar strength. A simple increase in mortar strength will therefore not lead to a corresponding relative improvement in bond as sand grading plays a significant role in both mortar strength and bond development.

Table 6.9 Relative changes in 91 day mortar and bond strength with varying sand grading

Sand type	Relative mortar strength	Relative characteristic bond strength
Allerton Park	160%	110%
Croxden	107%	103%
Binnegar (Baseline)	**100%**	**100%**
Yellow Pit	80%	81%

6.5.4 Influence of lime source

Mortars (1:2.25 lime: sand by volume) and bond wrench specimens were prepared using same grade NHLs sourced from different manufacturers. The test results are summarised in Table 6.10. As well as Castle Cement NHL used throughout this work, NHL3.5 lime was sourced from St Astier and Singleton Birch, as well as using a moderately hydraulic premixed mortar from Lime Technology Ltd. All mortars used ‘Binnegar’ sand and all brickwork prisms were built using the ‘Berkeley Red Multi’ unit.

Table 6.10 Influence of lime supplier on bond performance①

Lime grade/mortar	Supplier	Age (days)	Mortar strength (N/mm^2)	Bond strength			
				Average (N/mm^2)	CV (%)	Char. (N/mm^2)	Range (N/mm^2)
NHL 3.5	**Castle Cement**	**91**	**1.16**	**0.36**	**14.0**	**0.27**	**0.24-0.41**
	Single Birch	28	0.73	0.21	13.0	0.16	0.16-0.26
		91	1.29	0.37	16.9	0.27	0.28-0.47
	St Astier	28	0.45	0.14	16.0	0.10	0.10-0.17
		91	0.50	0.21	10.0	0.17	0.17-0.24
Moderately hydraulic mortar	Lime Technology Premix	28	1.26	0.36	10.7	0.30	0.30-0.43
		91	1.51	0.51	14.9	0.37	0.34-0.60

① Data derived from series V.

The 28 and 91 day flexural bond strengths for the moderately hydraulic lime (NHL3.5 and premix) mortars varied significantly depending on the source of materials. The variation in 91-day characteristic bond strength varied between 0.17 and 0.37 N/mm^2 for identical specification materials.

Despite the significant variation in bond strength for the same specification materials, the relative bond strengths in general matched the relative mortars compressive strengths (Table 6.11), confirming mortar strength performance to be a useful indicator of performance in this series. The strongest mortar (Lime

Technology Premix) provided the highest bond. The bond strength of the Singleton Birch series was comparable with the Castle Cement (baseline) series, despite having slightly higher mortar strength. This variance may perhaps be ascribed to variance in mortar water retention properties. The St Astier series presented the lowest bond strengths, only 63% of the baseline series.

Table 6.11 Relative change in 91 day mortar and bond strength for differing lime sources

Lime supplier	Mortar strength	Characteristic bond wrench strength
Castle Cement **(Baseline)**	**100%**	**100%**
Single Birch	111%	100%
St Astier	43%	63%
Lime Technology Premix	130%	137%

6.5.5 Consistency in performance of materials

The tests reported in this thesis were undertaken over 31 months. During this time the Castle Cement NHL3.5 lime was sourced in different batches to ensure fresh materials for each series. However, over the course of the work a variation in performance of both baseline mortar (Chapter 4) and corresponding bond strength was found between series during the study. The mortar variation has already been reported and discussed in Chapter 4. To monitor consistency in materials, in addition to the mortar tests, bond wrench specimens were prepared using the baseline materials (1:2.25 NHL3.5: 'Binnegar' sand and 'Berkeley Red Multi' brick). Results are summarized in Table 6.12.

Table 6.12 Consistency in material performance

Age (day)	Series of testing	Bond strength			
		Average (N/mm^2)	CV (%)	Characteristic (N/mm^2)	Range (N/mm^2)
28	I	0.30	18.5	0.21	0.21-0.42
	II	0.25	13.3	0.19	0.19-0.32
	III	0.27	13.2	0.19	0.20-0.38
91	I	0.46	12.2	0.36	0.36-0.52
	II	0.51	16.0	0.37	0.38-0.64
	III	0.39	14.0	0.31	0.28-0.43
	V	0.36	14.0	0.27	0.24-0.41

The characteristic bond strengths were similar at 28 days, with no statistically significant variation. However, by 91 days characteristic bond strength varied between 0.27 and 0.36 N/mm^2. All test results from the different series were combined into one data set to obtain the overall characteristic strength and variation in performance (Table 6.13). Although, as expected, the coefficients of variation for the combined data set reached around 20% at both 28 and 91 days, however, the characteristic bond strengths fall within values reported for the separate series.

Table 6.13 Combined performance of baseline mortared brickwork

Mortar	Brick	Age (days)	Bond strength			
			Average (N/mm^2)	SD (N/mm^2)	CV (%)	Characteristic (N/mm^2)
1:2.25 (NHL3.5: 'Binnegar' sand)	Berkeley Red Multi	28	0.27	0.05	20.0	0.19
		91	0.44	0.09	19.7	0.31

As previously discussed in Chapter 4 about the variation in performance of the baseline mortar, the reasons for the brickwork performance variation could be attributed to many factors, such as materials, workmanship, ambient environmental change and testing procedure. To reduce the effect of workmanship, all mortar mixes were prepared by the author and all brick specimens were built by the same bricklayer, experienced in lime mortared masonry, throughout the whole project. To reduce the effect of environment, all specimens were stored in temperature and humidity controlled room. The sand and bricks used were all from the same production batch. Sand was factory dried. All bricks were air dried at least two weeks before construction. All mortar mixes were made by mass batching of the constituents. All limes used in the project were delivered before each series of construction and any unused bags disposed after 6 months. Variation in NHL lime supplied is therefore attributed as the primary cause for variation in baseline series bond strengths.

6.5.6 Comparison with cement: lime: sand mortared brick prisms

As previous research has primarily focussed on the properties of cement mortared masonry, a series of 1:3:12, 1:2:9 and 1:1:6 cement: lime: sand (by volume) mortared brickwork prisms were built and tested for comparison with the NHL brickwork. The baseline ‘Berkeley Red Multi’ bricks were used for all cement mortared series. The test results are summarized in Table 6.14.

The weakest cement mortar (1:3:12) developed similar bond strengths at 91 days to the baseline NHL series, although up to 28 days it had achieved higher bond, as strength developed (as expected) at a faster rate with the cement based mortars. The other two cement mortars were stronger than the comparable NHL mortars. Although the mortar compressive strength was more than double, the 1:2:9 mortar brickwork by 28 days only achieved a characteristic bond strength similar to that attained at 91 days by the baseline

NHL mortar series. The 1:1:6 mortar (over 6 times stronger) reached similar bond strength at just 14 days. At 91 days the 1:2:9 and 1:1:6 cement lime brickwork characteristic bond strengths were just 22% and 53% higher than the baseline NHL brickwork, although the mortar strengths were more than double and seven times stronger respectively. A significant improvement in bond strength requires a proportionally much greater increase in mortar strength.

Table 6.14 Compared with cement mortared brickwork①

Mortar mix	Age (days)	Mortar strength (N/mm^2)		Bond strength				
				Average (N/mm^2)	CV (%)	Characteristic (N/mm^2)		Range (N/mm^2)
1:2.25 (Baseline) Series I	**14**	**0.39**	**41%**	**0.21**	**10.6**	**0.17**	**47%**	**0.18-0.25**
	28	**0.60**	**63%**	**0.30**	**18.5**	**0.21**	**58%**	**0.21-0.42**
	91	**0.95**	**100%**	**0.46**	**12.2**	**0.36**	**100%**	**0.36-0.52**
1:3:12 Series IV	14	1.12	83%	0.27	14.6	0.20	59%	0.21-0.32
	28	1.08	80%	0.35	8.1	0.30	88%	0.30-0.40
	91	1.35	100%	0.47	18.7	0.34	100%	0.40-0.69
1:2:9 Series IV	14	1.75	75%	0.31	11.7	0.25	57%	0.27-0.39
	28	2.30	98%	0.47	14.0	0.35	80%	0.33-0.55
	91	2.34	100%	0.56	12.1	0.44	100%	0.46-0.69
1:1:6 Series VI	14	6.06	88%	0.49	15.0	0.37	67%	0.38-0.64
	28	6.64	97%	0.59	9.0	0.50	91%	0.50-0.68
	91	6.86	100%	0.81	20.2	0.55	100%	0.57-1.15

① Data derived from series I, IV and VI.

The cement mortared brickwork gained mortar and bond strength at a much faster rate than the NHL mortars at early ages (Figure 6.15). By 28 days the cement mortared brickwork had achieved more than 80% of the 91-day bond strength, whilst the NHL mortared brickwork had only obtained 58%. The corresponding mortar strengths followed a similar trend. After 28 days the NHL mortared brickwork bond increased at a faster rate than the corresponding cement mortar series, eventually exceeding the 1:3:12 mortared brickwork at 91 days.

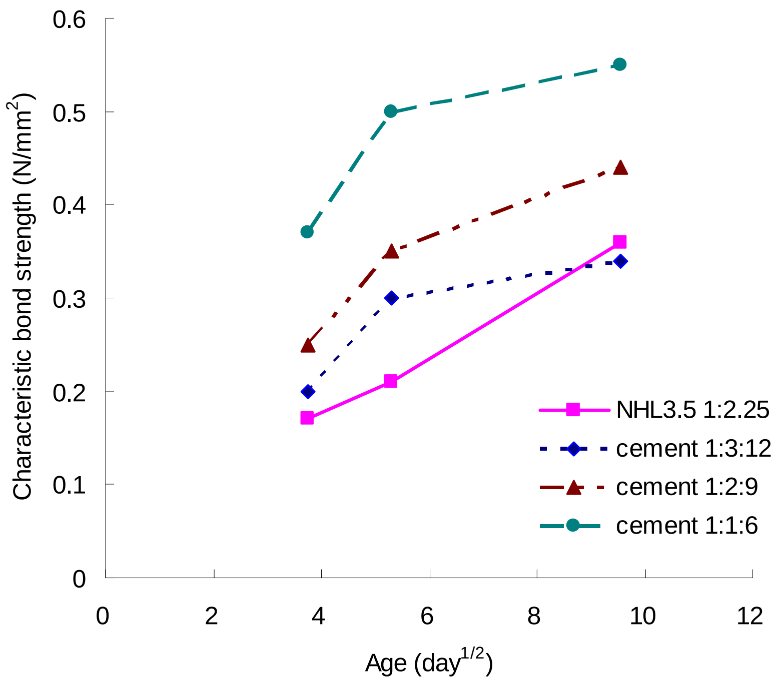


Figure 6.15 Bond strength development for the cement mortared brickwork

The three cement mortared specimens obtained 94%-153% bond strength of the baseline brickwork, whilst their mortar strengths were 42%-622% higher than the baseline mortar (Table 6.15). The NHL is capable of forming good bond with bricks, although in general the bond strengths will be lower than the bond strength achieved by the higher strength cement mortared brickwork.

Table 6.15 Relative 91 day mortar and bond strengths for cement and baseline series

Mortar mix	Mortar strength	Characteristic bond wrench strength
1:2.25 (Baseline)	**100%**	**100%**
1:3:12	142%	94%
1:2:9	246%	122%
1:1:6	722%	153%

6.5.7 Relationship between bond and mortar strength

Mortar grade (strength) is a key determinant for design flexural strengths of brickwork in both the UK National Annex to EC6 and previously in BS 5628. These data are based on evidence provided by previous research (Chapter 2).

Based on the bond wrench strength results reported in the previous sections (Table 6.4, 6.7, 6.8 and 6.10), there is an evident correlation between brickwork characteristic bond strength and mortar compressive strength. For various NHL mortar mixes, used in combination with the baseline ‘Berkeley Red Multi’ bricks, the measured bond strengths increased with mortar strength. The approximate linear relationship is shown in Figure 6.16.

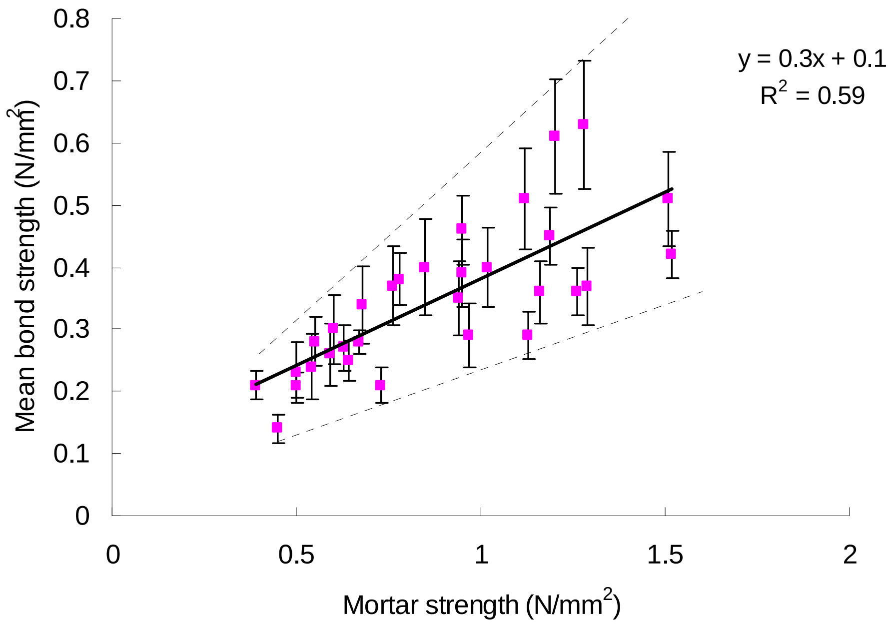


Figure 6.16 Relationship between mortar and bond strength

6.6 Influence of brick properties on bond strength

Previous work has already established that unit dewatering (water absorption) characteristics are a key determinant for bond strength of brickwork (Chapter 2). Test results presents in Chapter 5 of this work confirmed that this is also the case in the study of NHL mortared brickwork. Consequently a comprehensive study of the influence of brick properties on bond strength has been completed using the bond wrench method of testing. Brick water absorption characteristics were determined using four different methodologies:

- 24-hour cold water immersion total water absorption (expressed as percentage of dry unit mass in accordance with BS EN 771-1);
- 5-hour in boil water test (an alternative means of determining total water absorption in accordance with BS EN 772-7);
- initial rate of water absorption in accordance with BS EN 772-11 (expressed as mass of water absorbed per unit area of bed face when the face is immersed in water);
- sorptivity measuring water absorption over time in accordance in method set out in Chapter 3 (expressed as the gradient of a plot of mass of water absorbed against square root of time).

The programme therefore set out to evaluate not only the effect of brick dewatering on bond strength but assess what is the best brick characteristic to define performance. In addition, to study the effect of the practice of dipping bricks in water during construction, the moisture content of a high water absorption brick was varied to study the resultant effect on NHL mortar bond.

To investigate the effects of brick dewatering a further 31 brick types, representing the full range of engineering and facing bricks used in the UK, with a wide range of water absorption characteristics were selected for this study. The brick water absorption characteristics and the corresponding brickwork bond strengths, together with the results from Chapter 5, are summarised in Table 6.16 below. The bricks used ranged from very low absorption to very high absorption (3.3-19.6% for 5-hour boil test; 2.3-18.2% for 24-hour immersion test), with initial rate of absorption (IRA) between 0.1-3.7 $kg/m^2/min$ and sorptivity between 0.03-2.13 mm $min^{1/2}$.

Table 6.16 Effect of brick properties on 91-day bond strength
(1:2.25 NHL 3.5: 'Binnegar' sand mortar; Compressive strength 1.02 N/mm^2 (Chapter 4, Table 4.12))

Brick	Water absorption				Bond strength			
	IRA (kg/m^2/min)	5-hour boil water (%)	24-hour cold water (%)	Sorptivity (mm min$^{1/2}$)	Average (N/mm^2)	CV (%)	Characteristic (N/mm^2)	Range (N/mm^2)
Berkeley Red Multi (Cattybrook) **Baseline brick series**	1.3	8.4	5.1	0.49	0.36	14.0	0.27	0.24-0.41
Staffordshire Slate Blue Smooth	0.1	3.3	2.3	0.03	0.23	14.2	0.15	0.18-0.28
Hardwicke Welbeck Autumn Antique	2.4	16.5	14.8	2.13	0.13	53.9	0.04	0.06-0.24
Holbrook Smooth	1.0	8.7	7.7	0.65	0.44	35.6	0.17	0.13-0.68
Cheshire Weathered	1.1	8.0	6.2	0.77	0.35	22.8	0.22	0.21-0.49
Chester Blend	1.9	9.6	8.3	1.61	0.33	31.4	0.17	0.15-0.54
Royston Cream (Nostell)	0.4	6.4	6.0	0.14	0.58	13.7	0.44	0.42-0.72
Cheddar Red (Cattybrook)	0.4	5.3	2.9	0.06	0.48	31.8	0.24	0.27-0.73
Cheddar Brown (Cattybrook)	0.5	4.7	4.5	0.17	0.53	34.7	0.26	0.32-0.81
Kenilworth Textured Multi Red (Stourbridge)	0.5	6.1	4.8	0.15	0.44	15.8	0.32	0.31-0.53

Surrey Orange (South Holmwood)	0.6	8.6	7.2	0.42	0.40	28.1	0.23	0.25-0.63
Ruskin Red 73 (Aldridge)	0.7	8.8	6.1	0.48	0.52	20.1	0.35	0.36-0.68
Hadrian Buff (Throckley)	0.9	7.4	6.7	0.38	0.57	22.1	0.36	0.38-0.73
Himley Midland Red Sandfaced (Aldridge)	0.9	7.1	6.0	0.38	0.45	13.7	0.34	0.32-0.53
Tradesman Antique (Atlas)	0.9	8.2	6.7	0.37	0.46	18.4	0.32	0.36-0.64
Argyll Buff Multi Wirecut (Tannochside)	0.9	8.5	6.8	0.28	0.47	17.9	0.33	0.35-0.61
Madeley Mixture (Aldridge)	0.9	9.0	6.7	0.37	0.53	18.6	0.37	0.40-0.72
Tradesman Sandfaced (Atlas)	0.9	8.4	5.7	0.43	0.56	13.2	0.42	0.39-0.64
Brunswick Tryfan Grey (Cattybrook)	0.9	4.7	3.9	0.16	0.27	14.9	0.21	0.22-0.34
Colonsay Red Wirecut (Tannochside)	1.0	8.4	7.1	0.51	0.53	9.4	0.44	0.46-0.60
Medium Multi (West Hoathly)	1.1	14.9	8.6	0.26	0.28	20.7	0.18	0.21-0.38
Parham Red Stock (Ladybrook)	1.1	13.2	8.5	0.53	0.28	21.7	0.18	0.19-0.37
Brunswick Red (Cattybrook)	1.2	7.1	5.6	0.33	0.40	20.0	0.28	0.31-0.56
Kielder Orange (Throckley)	1.3	7.3	6.4	0.43	0.53	17.6	0.37	0.38-0.66

Shireoak Russet (Aldridge)	1.3	10.6	7.5	0.31	0.42	15.3	0.31	0.30-0.53
Lancashire Weathered (Ravenhead)	1.3	9.9	7.3	0.38	0.52	19.7	0.35	0.35-0.72
Colonsay Red Rustic (Tannochside)	1.4	8.6	7.4	0.44	0.49	28.3	0.26	0.27-0.74
Calderstone Claret (Roughdales)	1.4	8.8	6.8	0.63	0.49	27.5	0.27	0.30-0.65
Cavendish Fireglow (Dorket Head)	1.5	13.8	9.3	0.49	0.44	15.2	0.33	0.34-0.56
Anglian Red Multi Rustic (Aldridge)	1.6	12.0	9.2	0.53	0.34	17.9	0.24	0.27-0.46
Red Multi Rustic (Roughdales)	1.6	8.8	7.9	0.86	0.48	17.4	0.33	0.34-0.60
Red Multi (Nostell)	1.7	10.0	8.0	1.12	0.29	50.4	0.08	0.09-0.47
Handmade Multi (West Hoathly)	1.9	9.7	7.4	0.45	0.28	24.8	0.16	0.15-0.38
Dorset Red Stock (Ellistown)	2.1	16.9	12.7	1.31	0.34	23.3	0.21	0.23-0.46
Surrey Buff Multi (South Holmwood)	3.7	19.6	18.2	1.90	0.10	67.4	0.04	0.03-0.23
Bradford University[4] Low Absorption Solid	0.4	3.8	2.6	0.04	0.26	10.7	0.20	0.21-0.32
Bradford University[4] High absorption Frogged	3.0	18.5	16.9	1.78	0.18	36.9	0.06	0.11-0.27

The bond wrench test results for all brickwork mortar joints showed considerable variation depending on brick type, with characteristic bond strengths ranging between 0.04 N/mm^2 and 0.44 N/mm^2 (total range 0.03 N/mm^2 to 0.81 N/mm^2). It is evident that brick type has had a significant effect on brickwork bond development; the effect has been much greater than variation in NHL mortar properties.

In general the performance for each series has been consistent and in keeping with expected masonry performance. Among the 37 brick series tests, the coefficient of variation in 19 brick series was less than 20%, and in a further ten brick series the coefficient of variation was between 20% and 30%. In eight brick series the coefficients of variation were above 30%, with three brick series over 50% (corresponding to low bond strength). The much greater variation in performance for the low strength joints can be expected

6.6.1 Influence of brick total water absorption on bond strength

In the UK National Annex to EC6 (and previously in BS 5628: 2005), clay bricks are categorised into three different categories of (5-hour boil) total water absorption: less than 7%; between 7% and 12%; and over 12%. The 5-hour boil test is currently in accordance with BS EN 772-7:1998, and is primarily for the water absorption determination of clay masonry damp proof course units. BS EN 771-1:2003 Annex C outlines the alternative 24 hour cold water immersion test. The experimental relationship between two methods was given in Chapter 3; there is generally a strong correlation between two methods, with 5-hour boil test value on average 23% higher than the 24-hour immersion value.

The relationship between characteristic bond strength, determined in accordance with BS EN 1052-5, and the total water absorption values are presented in Figure 6.17 and 6.18. There is considerable scatter of data for similar total water absorption values in both cases, with the 24-h immersion absorption values displaying a slightly higher correlation coefficient with a fourth order polynomial curve. The shapes of the two curve fits are similar, with the bond strength initially increasing with total brick water absorption, peaking at around 6% for the 24-h immersion test and 8% for 5-hour boil test value. Thereafter, the bond strengths decreased with further increases in total brick absorption. Bricks with 24-h total water absorption from 2% to 6% can achieve similar bond strength as bricks with total water absorption from 6% to 12%. For very highest water absorption bricks (above 13% for 24-h test or above 18% for 5-h test), the characteristic bond strength developed was less than 0.1 N/mm^2 and lower than the bond for the very low absorption bricks.

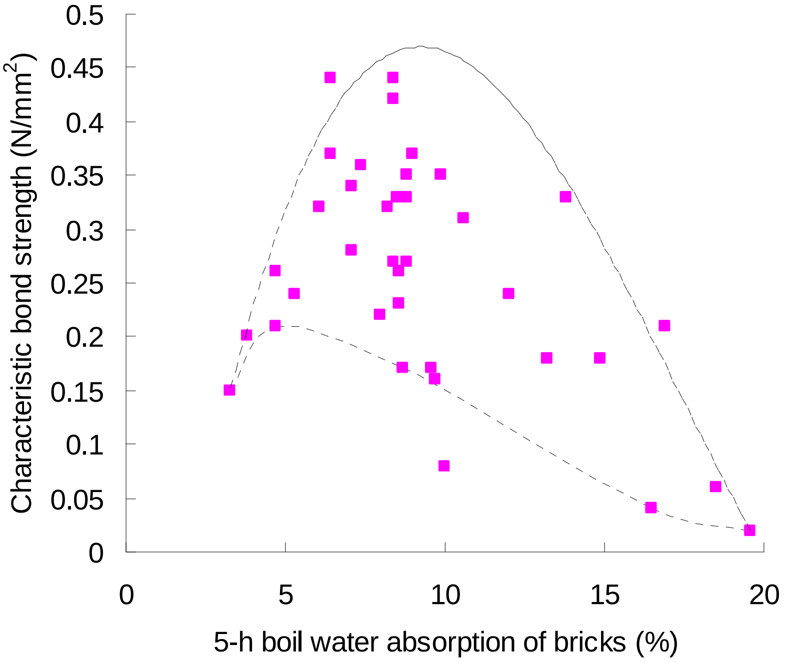


Figure 6.17 Relationship between bond strength and 5-h boil water absorption

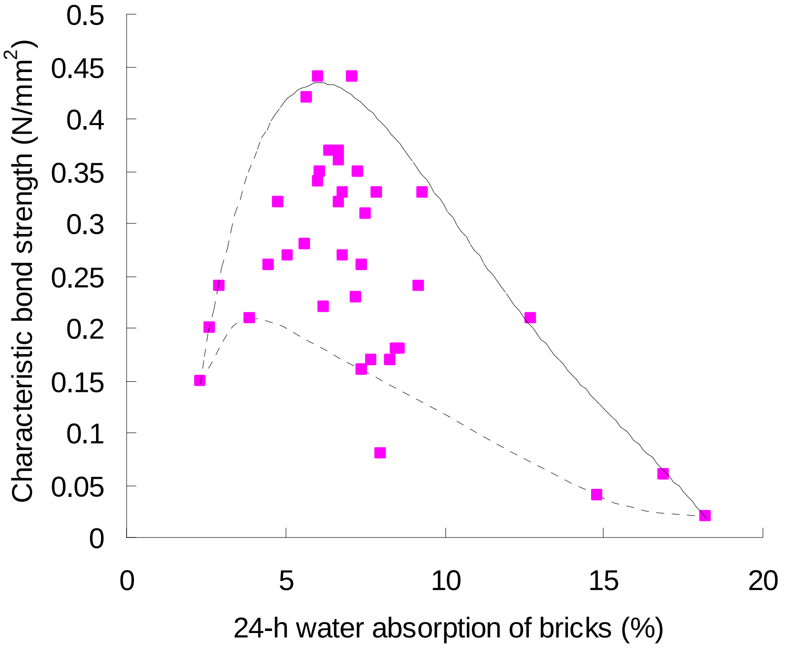


Figure 6.18 Relationship between bond strength and 24-h water absorption

There is considerable scatter in the data. For example for bricks with 24-hour water absorption in range 7-8% the characteristic bond strength ranged between 0.08 and 0.44N/mm^2. Despite its continued use in the UK NA to BS EN 1996-1, total brick water absorption does not provide a reliable indicator of bond strength for NHL mortars. The bond data at the extreme (low and high) water absorption values would seem better correlated with brick water absorption, however there are fewer data points in these regions.

In EC6 for cement: lime: sand mortar and clay unit, bond strength are the highest for bricks with total water absorption ‘less than 7%’, 12.5% lower (for M2 mortars) for bricks ranging in ‘between 7 and 12%’, and a further 25% lower when using bricks with total water absorption ‘over 12%’. The experimental data for NHL mortared brickwork does not support this trend, with highest bond strengths typically achieved for bricks with 5-h total water absorption in the range 5-10%.

The development of bond between brick and mortar is the result of a complex and dynamic process across the interface between the two materials. In recognition of its inherent complexity Groot, C.J.W.P. (1993) noted over 20 parameters influencing bond strength in cement mortared brickwork. The initial dewatering of the mortar by the brick suction has a significant effect as it governs water: binder ratio and transport of mortar products into the brick face pore structure. As noted earlier rapid dewatering also influences the process of carbonation, enabling earlier carbonation through drying of the mortar. Despite the earlier onset of carbonation in the mortars and the expected lower water: binder ratio, bond strengths in the highly absorbent bricks are very weak. Rapid dewatering on mortars is detrimental to development of brickwork bonding. The precise cause or causes for poor bonding remains unknown, but disturbance of the bond interface during the process of bricklaying, following initial contact and rapid dewatering, is suggested to play a significant role.

Unit total water absorption is a function of brick porosity and through this is related to the rate of water absorption (suction). Although total water absorption is preferred by National Annex to EC6, brick IRA and sorptivity would seem the more directly relevant parameters. The relationship between bond and IRA and sorptivity are discussed in the next two sections.

6.6.2 Influence of brick IRA on bond strength

The relationship between characteristic bond strength and brick IRA is presented in Figure 6.19. The experimental data has also been fitted with a fourth order polynomial, with a similar bell shaped plot to that presented earlier. The correlation coefficient is no better than with the total water absorption data, with a similar widespread scatter in data. The general trend is for bond strengths to initially increase with brick suction, reaching highest strengths at an optimum IRA of approximately 0.9kg/m^2/min. Thereafter bond strengths steadily reduce with increasing IRA, reaching minimum bond strength above 3kg/m^2/min IRA. As with total water absorption, however, there is significant scatter in performance: bond strengths for bricks with IRA close to the apparent optimum value of 0.9kg/m^2/min varied between 0.17 and 0.44N/mm^2. Although the range is still wide, it is less than that previously discussed for the total water absorption, with weakest brick series ('Red Multi (Nostell)') having unit IRA of 1.7 kg/m^2/min. Despite this, the overall correlation would suggest that IRA is a no more reliable material performance indicator for bond strength than total water absorption.

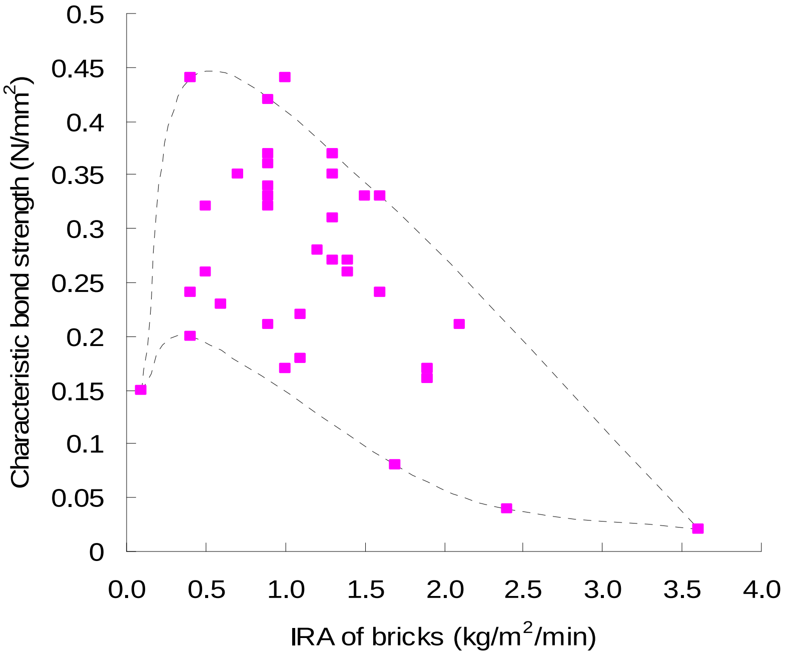


Figure 6.19 Relationship between bond strength and brick IRA

The IRA test measures brick suction in the first minute following contact with free water. IRA is therefore expected to be important due to dewatering effects on mortar as discussed earlier. However, the brick suction varies (reduces) with time after contact with water. The interaction between mortar dewatering and brick absorption is a longer term complex process. Setting times for hydraulic lime mortars are significantly longer than one minute (Ashurst in 1997, based on DSIR Special Report No 9 Lime and Lime Mortars (1927), stated 'the setting time in water' is 2-4 days for 'eminently hydraulic lime', 15-20 days for 'moderately hydraulic, and <20days for 'feebly hydraulic').

6.6.3 Influence of brick sorptivity on bond strength

The concept of sorptivity has been introduced into the research as an alternative expression for characterising brick dewatering effects. Sorptivity, including a test methodology, was adopted from Hall and Hoff (2002, 2005) who used it in the investigation of water movement in concrete and masonry. The test method used to determine sorptivity is outlined in Chapter 3.

The experimental correlation between bond strength and sorptivity is presented in Figure 6.20 below. The data are again fitted with a fourth order polynomial of similar shape to that reported for total water absorption and IRA. It is noticeable that sorptivity values are much less widely distributed than water absorption and IRA, concentrated around sorptivity values 0.3–0.6 mm $min^{1/2}$. However, there are still significant scatter in the data and the overall correlation is no better than that reported previously.

The three brick water absorption characteristics used in this study are inter-related as they are all determined by surface characteristics, porosity and pore structure of the brick units. As there is some correlation between these three characteristics it is perhaps not surprising that the correlation between them and bond strengths is apparently no better with any one of them. As, arguably, total 24-hour water immersion absorption is the easiest to measure this should remain the key determinant in design guides.

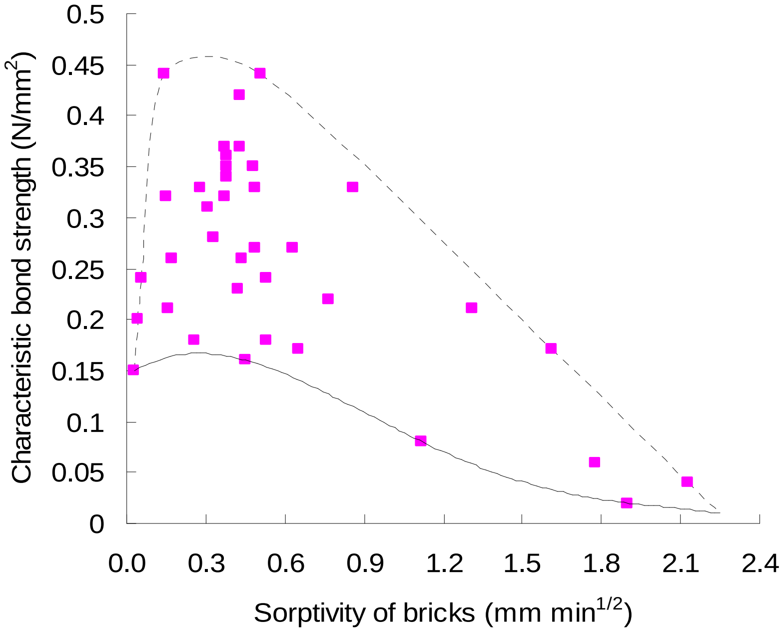


Figure 6.20 Relationship between bond strength and brick sorptivity

The correlations between brick water absorption properties and bond strength present the relationship between a data set of 12 bond tests and the statistical average water absorption characteristic derived from 10 identically representative bricks from the same sample batch delivered by Ibstock. The individual bond strengths have not been correlated directly with the dewatering properties of the two brick faces that form the joint. The water absorption properties in general exhibited very consistent performance, suggesting that the lack of direct correlation between individual bond and water absorption performance is unlikely to be a significant contribution to the data spread. More fundamentally it is clear that bond development is a complex process and that selecting one brick parameter over another as a means for determining design strengths is likely to remain an over simplification that will often result in conservative design material properties.

6.6.4 Influence of moisture content during construction on bond strength

It is common practice amongst bricklayers to submerge highly absorbent units in water before laying with mortar to control dewatering and maintain workability. Excessive docking (saturation) can lead to poor bond strengths and is generally considered poor practice. The addition of lime to mortars is considered to improve water retention and so reduce need for water docking. A limited study was undertaken as part of this study to study the effect of brick moisture on bond strength of NHL mortared brickwork. The high water absorption 'Hardwicke Welbeck Autumn Antique' brick was chosen to specifically for this study.

Samples of the high suction bricks were initially oven dried and then prepared to the following moisture contents before laying: 0% (oven dry), 3.7%, 7.8%, 11.8% and 15.6% (saturated). For each series 12 bond wrench joints were prepared and cured as normal practice for these tests. All brick specimens were tested at 91 days. The IRA values were also measured for different brick moisture contents to assess the effect of docking on suction.

The experimental relationship, for the 'Hardwicke Welbeck Autumn Antique' brick, between unit moisture content and IRA was very linear (Figure 6.21). The saturated brick had almost zero suction, confirming that saturation of bricks is not a good practice. However, it is clear by docking in water brick suction can be controlled. The results for bond strength are presented in Table 6.17 below.

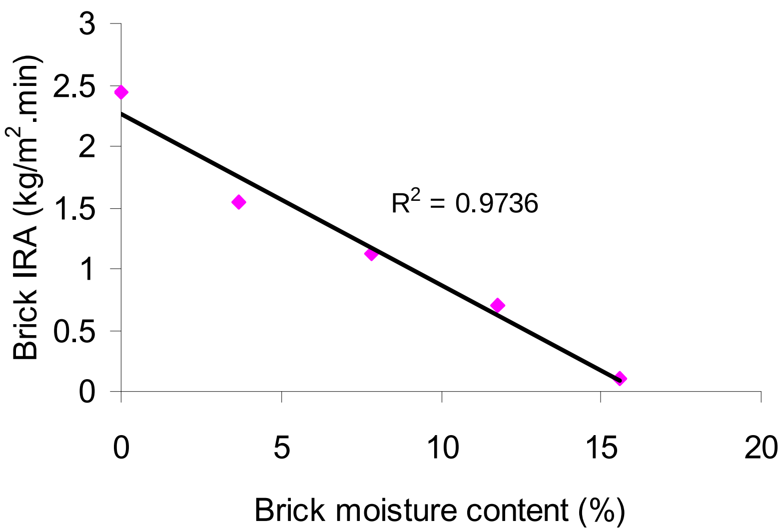


Figure 6.21 Relationship between brick moisture content and IRA

The variation in series performance was often significant, with coefficients of variation in three series exceeding 30%. This variation in performance has made interpretation of performance more difficult. The experimental bond strengths are presented in Figure 6.22. The lowest characteristic bond strength was achieved at oven dry moisture content where suction was highest; this was in accordance with expectations. Thereafter bond strengths improved at 3.7% and 7.8%. However, this trend as surprisingly not sustained at 11.8% moisture content. Trend lines for the variation in average and characteristic bond strengths have been fitted in Figure 6.22. However, given the variation at each moisture content a conclusion that bond strength is not influenced by brick moisture content is not unreasonable. Further tests, beyond the scope of this study, would hopefully clarify this.

Table 6.17 Influence of unit moisture content on bond strength

Brick moisture content	Brick IRA (kg/m^2/min)	Bond strength			
		Average (N/mm^2)	CV (%)	Characteristic (N/mm^2)	Range (N/mm^2)
0%	2.43	0.09	52.8	0.03	0.05-0.12
3.7%	1.54	0.17	36.3	0.07	0.07-0.26
7.8%	1.12	0.18	23.3	0.11	0.10-0.23
11.8%	0.70	0.09	44.6	0.03	0.04-0.15
15.6%	0.11	0.18	16.6	0.12	0.12-0.22

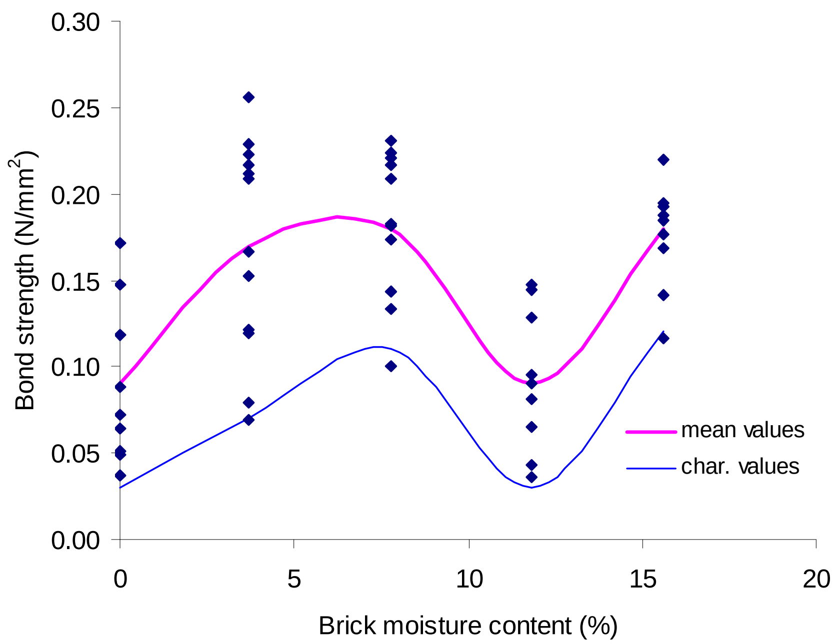


Figure 6.22 Influence of brick moisture content on bond strength

6.6.5 Development of bond with age

The bond wrench test method has made it much easier to examine the brickwork bond development with age. The study on hydraulic lime mortar properties presented in Chapter 4 showed that these mortars gain strength at a much slower rate than cement mortars. Long-term tests on bond wrench strength (up to 365 days) have been completed.

Development of bond strength in the baseline brickwork series (‘Berkeley Red Multi’ brick combined with 1:2.25 NHL3.5: Binnegar sand mortar) with age has been discussed in section 6.5.2. In this series the bond strength continued developing after 91 days; the 91-day characteristic bond strength was around 68% of the 1-year value. In test series IV, three more bricks (including ‘Holbrook Smooth’, ‘Chester Blend’ and ‘Cheshire Weathered’) were chosen to further investigate this behaviour. Bricks were built with the NHL3.5 baseline mortar and a 1:2.25 NHL 5 mortar (using ‘Berkeley Red Multi’ and ‘Holbrook Smooth’ bricks). The bond wrench strengths were tested at different ages (14, 28, 56, 91, 365 days). Test results are summarised in Table 6.18. The very high absorption brick (‘Hardwicke Welbeck Autumn Antique’) and the very low absorption brick (‘Staffordshire Slate Blue Smooth’) were tested at 14, 28, 56 and 91 days in series III.

In general, and in line with the expectations and previous work, bond strength increased with age (Chapter 2). With the NHL 3.5 mortar series, the four bricks used at 14 days achieved 32-41% of their corresponding bond strength at 365 days. By 28 days they had developed 40-83% and by 91 days they had reached 68-100% of the 365-day strengths. For the combination of brick ‘Holbrook Smooth’ and 1:2.25 NHL 5 mortar, bond strength developed faster at early age reaching over 50% of its 365-day bond at 14 days due to the higher early strength lime NHL 5.

Table 6.18 Influence of age on brickwork bond development

Lime grade	Brick type	Age (days)	Mortar		Bond strength				
			Compressive strength (N/mm^2)	Proportion of 365-day strength	Average (N/mm^2)	CV (%)	Characteristic (N/mm^2)	Proportion of 365-day strength	Range (N/mm^2)
NHL 3 .5	'Berkeley Red Multi' (Series I)	14	0.39	40%	0.21	10.6	0.17	32%	0.18-0.25
		28	0.60	61%	0.30	18.5	0.21	40%	0.21-0.42
		56	0.85	87%	0.40	19.5	0.25	47%	0.23-0.46
		91	0.95	97%	0.46	12.2	0.36	68%	0.36-0.52
		365	0.98	100%	0.63	8.6	0.53	100%	0.53-0.70
	'Staffordshire Slate Blue Smooth' (Series III)	14	0.53	-	0.08	23.4	0.05	-	0.04-0.10
		28	0.63	-	0.16	15.9	0.12	-	0.12-0.20
		56	1.08	-	0.18	15.7	0.13	-	0.13-0.23
		91	0.95	-	0.23	14.2	0.15	-	0.18-0.28
	'Hardwicke Welbeck Autumn Antique' (Series III)	14	0.53	-	0.11	58.4	0.03	-	0.05-0.26
		28	0.63	-	0.11	33.8	0.05	-	0.05-0.18
		56	1.08	-	0.17	67.1	0.03	-	0.04-0.38
		91	0.95	-	0.13	54.0	0.04	-	0.06-0.24
	'Holbrook Smooth' (Series IV)	14	0.39	48%	0.14	32.0	0.07	39%	0.09-0.21
		28	0.52	63%	0.26	29.4	0.15	83%	0.16-0.44
		91	0.93	113%	0.44	35.6	0.17	94%	0.13-0.68
		365	0.82	100%	0.46	50.0	0.18	100%	0.26-0.88

NHL 3 .5	‘Chester Blend’ **(Series IV)**	14	0.39		0.16	29.4	0.07	41%	0.06-0.21
		28	0.52		0.15	24.3	0.09	53%	0.09-0.20
		91	0.93		0.33	31.4	0.17	100%	0.15-0.54
		365	0.82		0.34	36.6	0.17	100%	0.21-0.56
	‘Cheshire Weathered’ **(Series IV)**	14	0.39		0.16	28.5	0.09	41%	0.09-0.23
		28	0.52		0.24	22.3	0.16	73%	0.16-0.32
		91	0.93		0.35	22.8	0.22	100%	0.21-0.49
		365	0.82		0.31	15.9	0.22	100%	0.21-0.39
NHL 5	‘Berkeley Red Multi’ **(Series II)**	14	0.67		0.28	7.0	0.24		0.26-0.31
		28	0.94		0.35	17.0	0.25		0.27-0.47
		56	1.19		0.45	10.2	0.37		0.40-0.52
		91	1.28		0.63	16.3	0.45		0.40-0.80
	‘Holbrook Smooth’ **(Series IV)**	14	0.66	86%	0.31	20.9	0.20	53%	0.19-0.40
		28	0.92	119%	0.26	15.4	0.19	50%	0.21-0.34
		91	0.97	126%	0.44	34.7	0.21	55%	0.23-0.73
		365	0.77	100%	0.68	30.8	0.38	100%	0.42-1.18

The long-term performances are plotted in Figure 6.23. Baseline brick 'Berkeley Red Multi' achieved the highest bond strength and high absorption brick 'Hardwicke Welbeck Autumn Antique' developed the lowest bond. As previously discussed, very high absorption bricks rapidly dewater the fresh mortar joint and disturbed the normal mortar hydration process, which prevented good bond formation at the interface between unit and mortar. Whereas the low absorption brick 'Staffordshire Slate Blue Smooth' absorbed relatively little water and so fewer mortar hydration products formed into its pores close to brick surface. 'Chester blend', having high IRA and sorptivity values, developed low bond strength. However, the reason why the 'Cheshire Weathered' and 'Holbrook Smooth' bricks, having similar 5-h and 24-h absorption, IRA and sorptivity values to the 'Berkeley Red Multi' brick, developed much lower bond is not clear, and may be attributable to higher proportions of perforation. As discussed before, brick bond development is a very complex process. Brick water absorption is only one of the influencing factors.

Although the baseline brickwork carried on improving bond strength after 91 days, the three other brick series ('Holbrook Smooth', 'Chester Blend' and 'Cheshire Weathered') did not significantly improve their bond strengths after 91 days. The precise reason for this performance inconsistency is not clear. However, the compressive strengths of mortar specimens cast in moulds increased little for baseline brickwork, but decreased for other three brickworks after 91days (Table 6.18), whereas the mortar property in brickwork mortar joints was very likely changed due to brick absorption.

Bond strengths with the 'Berkeley Red Multi' and 'Holbrook Smooth' bricks were also studied using 1:2.25 NHL 5 mortars. Their long-term bond developments are compared with NHL3.5 series in Figure 6.24. The 'Berkeley Red Multi' brick series achieved much higher bond strength than the 'Holbrook Smooth' series for both mortars. The study on brick 'Holbrook Smooth' combined with NHL 5 mortar confirmed the improved bond improvement after 91 days. Bond strength increased 81% from 91 days to 365 days for 'Holbrook

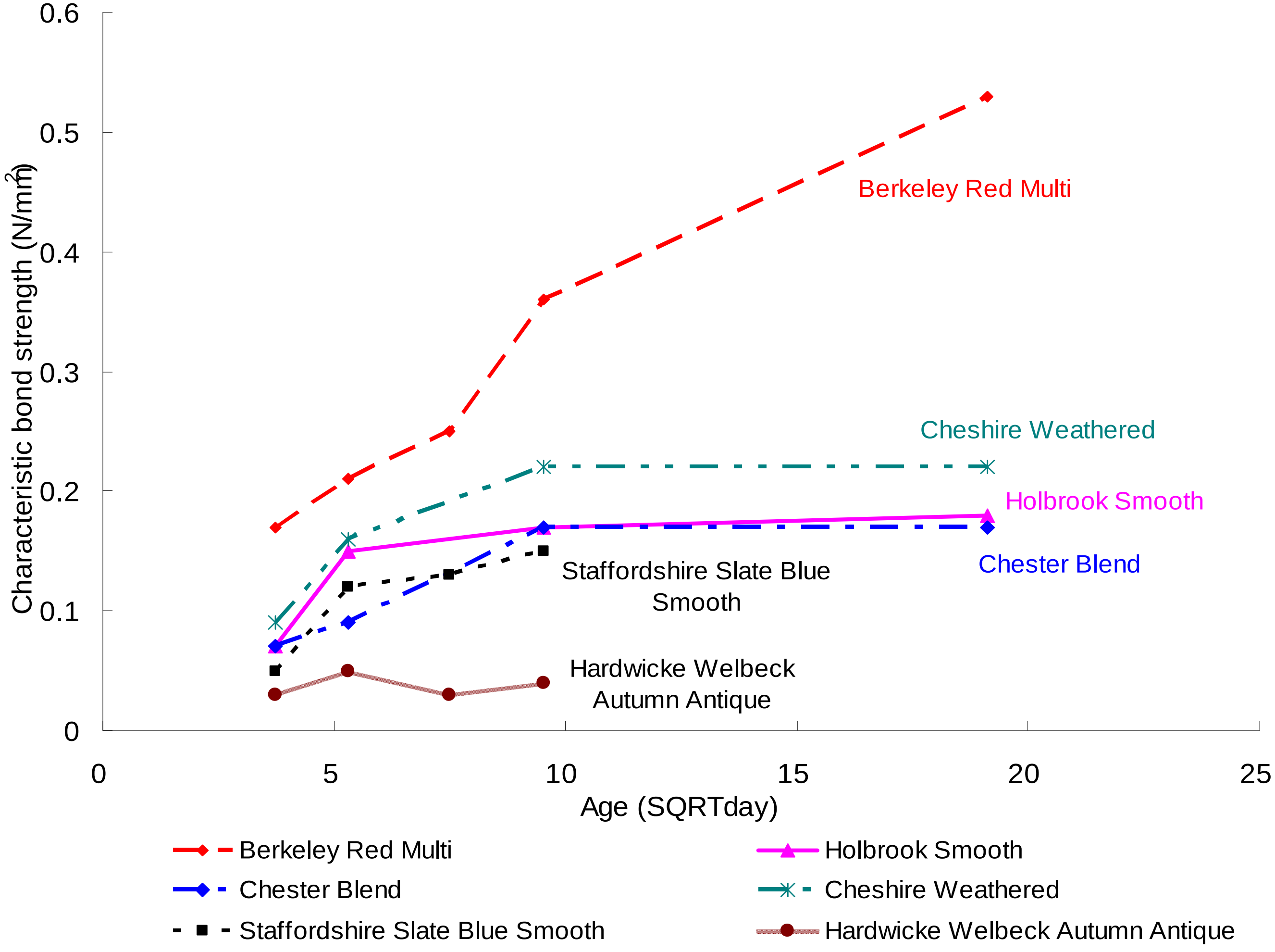


Figure 6.23 Development of brickwork bond for NHL 3.5 mortared brickwork with age

Smooth' combined with NHL 5, compared to a 47% increase for the 'Berkeley Red Multi' combined with NHL 3.5 (see Table 6.18). Further work is required to clarify longer term bond performance in NHL mortared brickwork. In this research the influence of brick type on bond is more significant than the influence of changing NHL grade.

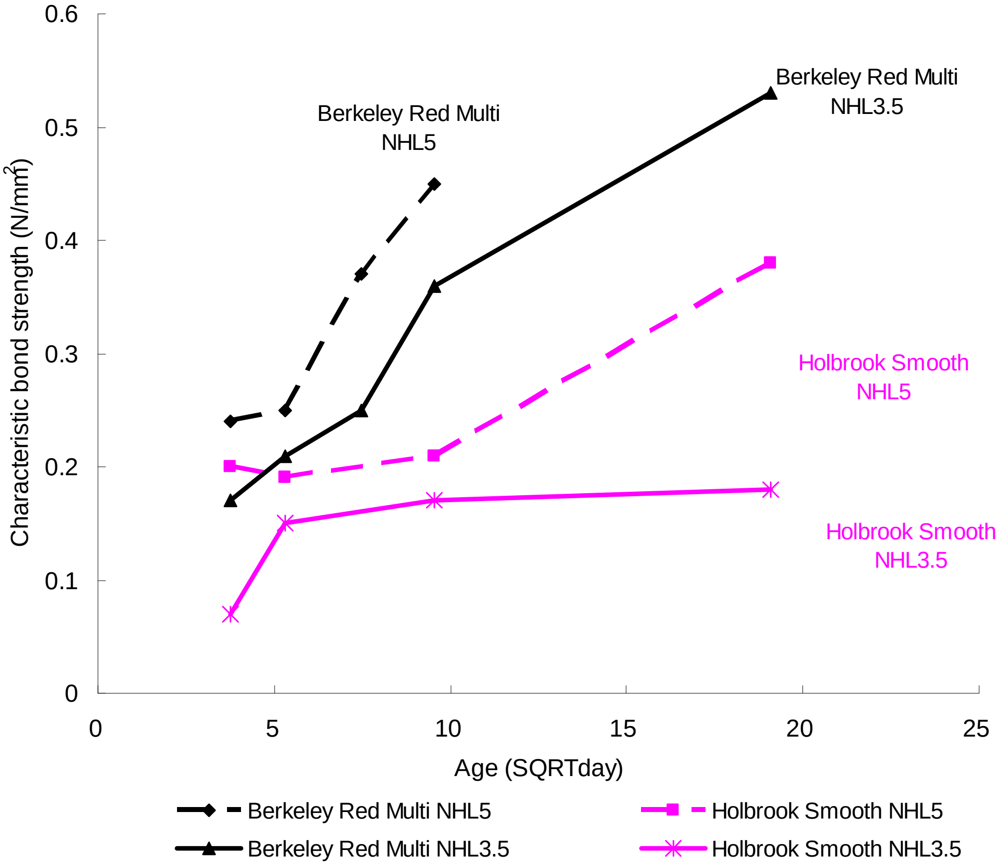


Figure 6.24 Brickwork bond performances with age

6.7 Characteristic flexural strength (f_{xk1}) for NHL mortared brickwork

Figure 6.25 represents the distribution of all the 91-day bond strength test results from the 37 brick series. The sample distribution for the frequency of the bond wrench strength values tends towards a Normal Distribution. It is likely that with a larger sample population this trend would be strengthened, and thus brick bond strength might be regarded as a normally distributed random variable.

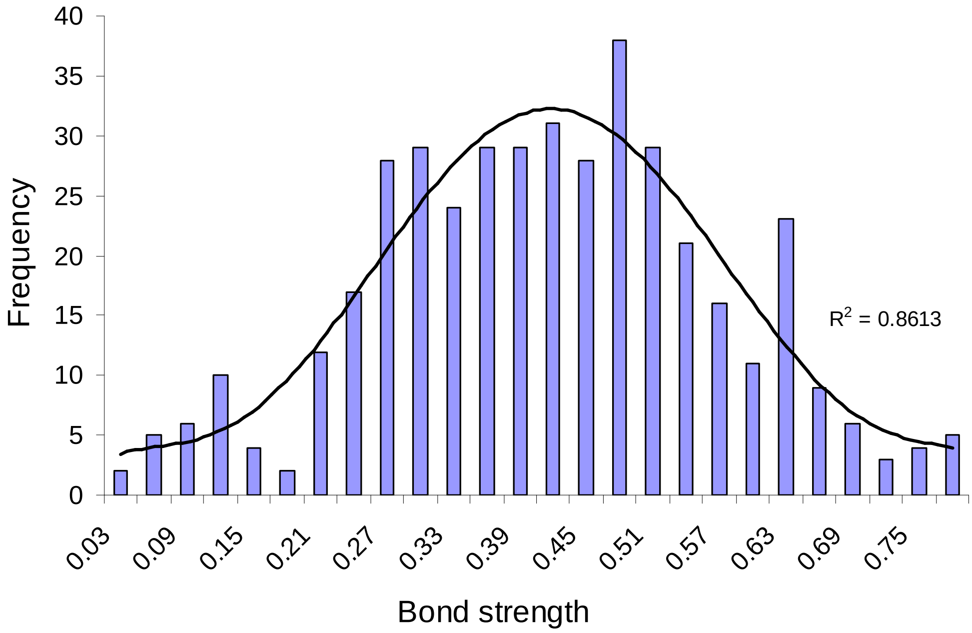


Figure 6.25 Distribution of bond strengths

In EC 6 (BS EN 1996-1-1:2005) the characteristic flexural strength value for f_{xk1} for plane of failure parallel to bed joint of clay brick combined with f_m < 5 N/mm^2 general purpose mortar is taken as 0.1 N/mm^2. The 91-day characteristic flexural bond strength for 427 tests (all 91-d 37 brick series tests except some prematurely failed joints during handling) was 0.19 N/mm^2. Although this simplifies bond performance, irrespective of brick type, it can be considered unnecessarily conservative for many bricks; the influence of brick water absorption properties should be considered in design recommendations.

In NA to BS EN 1996-1-1:2005, clay masonry units are divided into three water absorption classifications. At present NHL mortared brickwork is not included in these data. The values of f_{xk1} for plane of failure parallel to bed joints are given for different combinations of bricks and mortars, shown in Table 6.19. At present the NHBC Foundation guide recommendations (Draft for development standard: the structural use of unreinforced masonry made with natural hydraulic lime mortars-technical annex for use with BS 5628-1:2005) use two brick water absorption classifications: ‘up to and including 12%’ and ‘over 12%’.

Taking the same brick water absorption classifications as the NHBC guidance, this project recommends the characteristic bond strengths for M1 NHL mortars in Table 6.19. By taking separating bricks by water absorption, rather than simply taking overall characteristic values (0.19 N/mm^2 as stated above), improves characteristic bond strength by 37% for bricks with water absorption less than 12% (Figure 6.26). Given in previous discussions the correlation between bond strength and IRA or sorptivity was no better than for total water absorption, total water absorption is maintained here as the brick parameter.

Table 6.19 Characteristic flexural strength of masonry f_{xk1} in N/mm^2

<table>
<tr><td>Current guide</td><td colspan="2">NA to BS EN 1996-1-1</td><td>NHBC</td><td>NA to BS EN 1996-1-1</td><td>NHBC</td><td>Proposed</td></tr>
<tr><td>Mortar strength class</td><td>M12</td><td>M6, M4</td><td>M2.5</td><td>M2</td><td>M1</td><td>M1</td></tr>
<tr><td>Clay bricks having a water absorption of: less than 7%</td><td>0.7</td><td>0.5</td><td rowspan="2">0.2</td><td>0.4</td><td rowspan="2">0.2</td><td rowspan="2">0.26</td></tr>
<tr><td>between 7% and 12%</td><td>0.5</td><td>0.4</td><td>0.35</td></tr>
<tr><td>over 12%</td><td>0.4</td><td>0.3</td><td>0.1</td><td>0.25</td><td>0.1</td><td>0.07</td></tr>
</table>

Note: The total water absorption of clay bricks is 5-h boil test value.

The relationships between bond strength (for all test data) and brick IRA or sorptivity are given in Figures 6.27 and 6.28 respectively. The recommended characteristic bond strengths are also outlined in these figures. The three figures (Figure 6.26, 6.27 and 6.28) display similar trends between brickwork flexural strength and the water absorption characteristics, medium absorption bricks generally developing higher bond strength than very low and high absorption bricks. Contrary to the current NA to BS EN 1996-1-1:2005, bricks with low absorption generally achieved lower flexural bond strength than medium absorption bricks.

By separating by 5-h boil absorption, IRA or sorptivity values, the characteristic flexural strength values f_{xk1} are recommended and summarised in Table 6.20 for the brick water absorption parameters. With sorptivity test quite time-consuming, in practice total water absorption or IRA tests can be a good way to classify bricks into different groups for f_{xk1} in structural design.

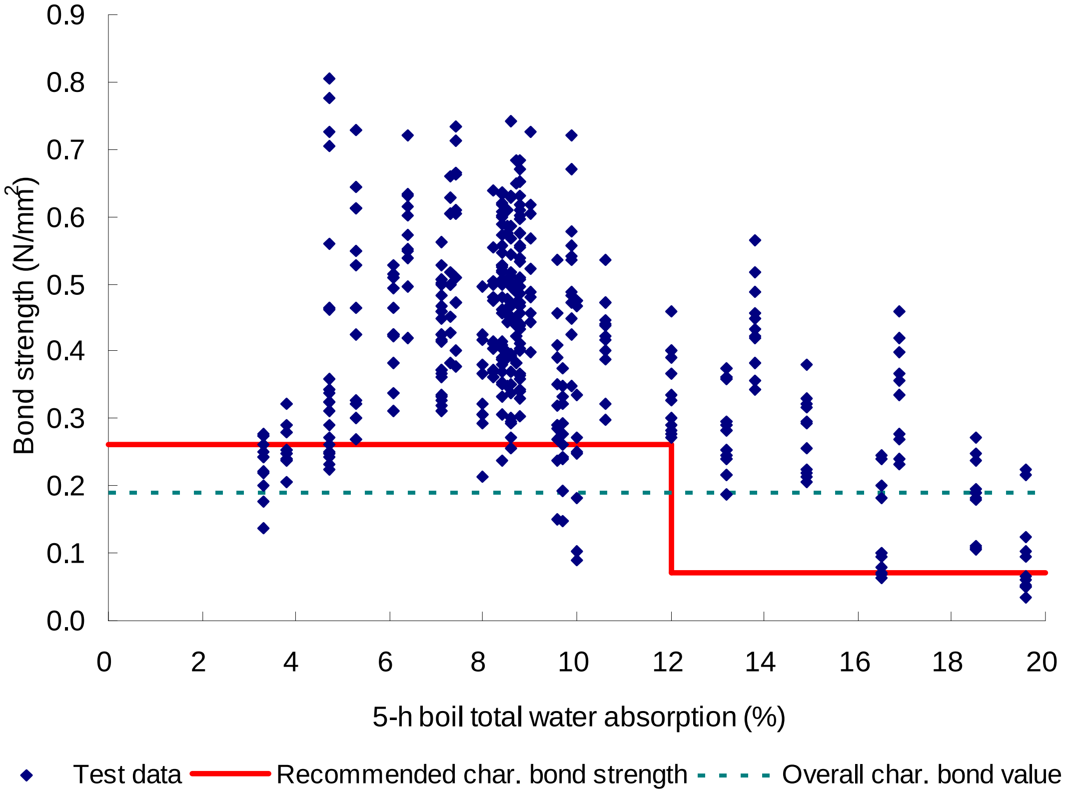


Figure 6.26 Test data and recommended characteristic flexural strengths f_{xk1} with separating bricks by 5-h boil water absorption

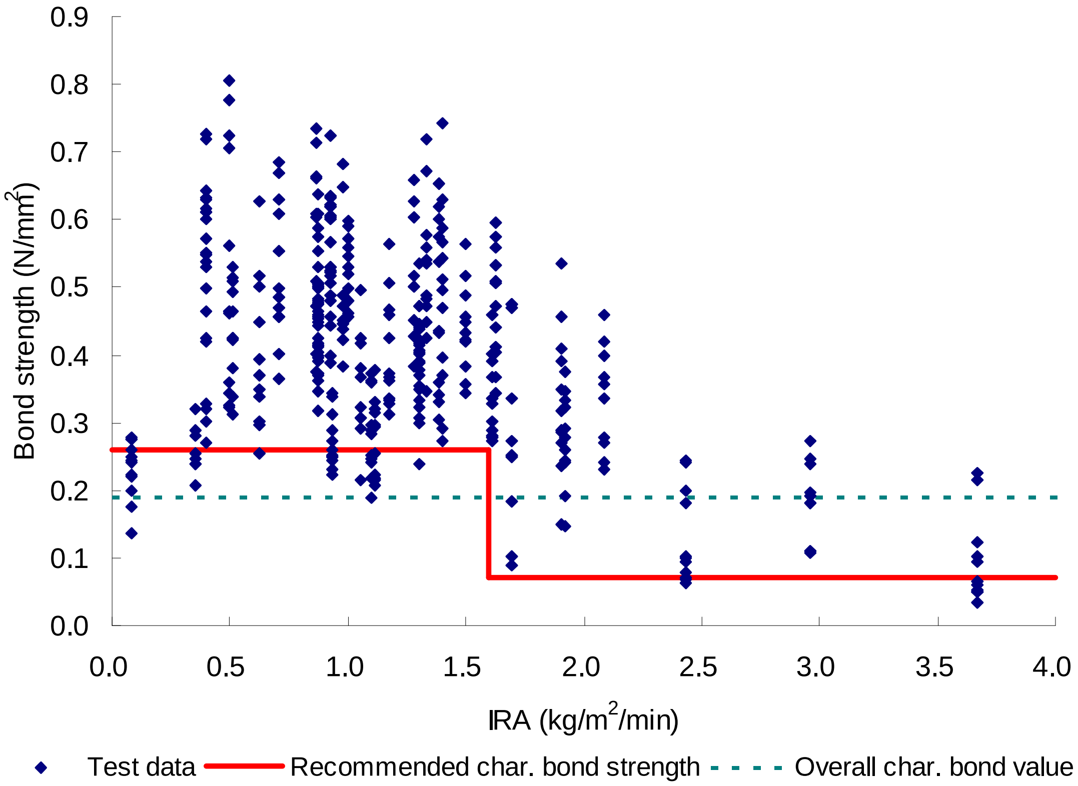


Figure 6.27 Test data and recommended characteristic flexural strength f_{xk1} with separating bricks by brick IRA

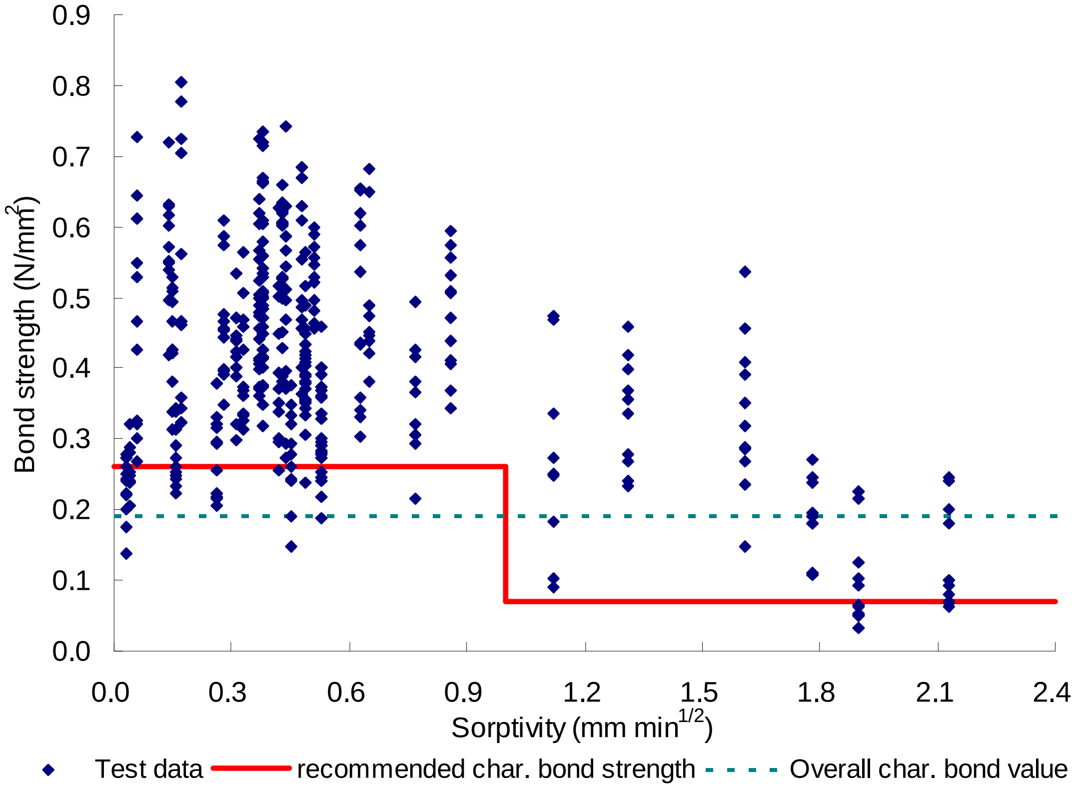


Figure 6.28 Test data and recommended characteristic flexural strength f_{xk1} with separating bricks by sorptivity

Table 6.20 Recommended characteristic flexural strength f_{xk1} in N/mm^2

Clay unit absorption				Mortar strength class
	5-h boil	IRA	Sorptivity	M1
less than	12%	1.6 kg/m^2/min	1.0 mm min$^{1/2}$	0.26
over				0.07

6.8 Summary and conclusions

Using bond wrench test, this chapter reported and discussed the influence of mortar property and brick absorption characteristics on brickwork bond strength. Many parameters were investigated, including NHL lime content and grade, sand grading, lime source, lime property consistency, brick 5-h boil water absorption, 24-h cold water immersion absorption, brick IRA, sorptivity and brick moisture content before laying. Using bond wrench test facilitated investigation of brickwork bond development.

The effects of the various influencing factors on brickwork flexural bond strength were analysed and discussed. The following conclusions have been drawn:

1. Failure modes, mortar joint carbonation and the progress rate of carbonation in bond wrench test are strongly related to brick absorption characteristics.
2. Bond wrench strength increased with NHL lime grade and lime content.
3. Sand grading influenced both mortar strength and brickwork bond strength development. In general, well-graded sand achieved higher bond strengths.
4. A variation in lime properties, and therefore in the resultant brickwork performance, was evident when sourcing binders from different lime suppliers.
5. Small variations in performance were detected between different batches of the same specification materials.
6. There is a correlation between mortar compressive strength and brickwork bond strength.
7. Bond wrench strength is greatly varied with different bricks. Unit absorption had greater influence on bond wrench strength than variation in lime mortar properties.
8. Brick moisture content at the time of laying did have a significant influence on brick bond strength.
9. NHL mortared brickwork increased bond strength with age. Same as NHL mortars developed strength at slow rates, NHL mortared brickwork achieved its maximum strength at 91 days or even much longer.
10. Characteristic flexural strength f_{xk1} of clay brick masonry for plane of failure parallel to bed joint was recommended as 0.26 N/mm^2 for bricks with 5-h boil water absorption less than 12% and 0.07 N/mm^2 for more than 12%.

BLANK PAGE

7. Shear and compressive strengths of NHL mortared brickwork

7.1 Introduction

Although the focus of this study has been on flexural bond strength, initial shear strength and compressive strength are important design parameters for which there are little reported data for NHL brickwork. The shear and compressive strength of NHL mortared brickwork tested as part of this study are reported and discussed in this chapter. The influences of various mortar mixes by varying hydraulic lime grade and content on characteristic initial shear strength were investigated. Cement: lime: sand mortared brickwork was also examined for comparison. In view of the effect of brick type on flexural bond strength, low and high absorption bricks were also studied in shear testing. Based on the experimental data, recommendation for calculating characteristic initial shear strength is proposed. Test of NHL mortared brickwork in compression, which is not the main focus of this research, was only on the baseline brickwork for introductory understanding.

7.2 Shear testing: failure mode and mortar carbonation

7.2.1 Overview

In the UK National Annex to Eurocode 6, the values of the characteristic initial shear strength of clay brickwork are determined by mortar strength class. In this research, the initial shear strength of NHL mortared brickwork was investigated, focusing mainly on the effects of mortar mix variation on performance. Using the baseline 'Berkeley Red Multi' brick, the influences of natural hydraulic lime content and grade on shear strength performance have been studied. As with the study of flexural bond strength, cement: lime: sand mortared brick specimens were also tested for comparison. In addition, a limited study of the influence of brick properties on shear behaviour was also completed using the high water absorption ‘Hardwicke Welbeck Autumn Antique’ and low water absorption ‘Staffordshire Slate Blue Smooth’ bricks.

In total eight brick/mortar combinations (80 brick triplets) were constructed and tested in accordance with BS EN 1052-4 (Chapter 3). Three levels of normal stress were applied in testing: nominally 0.2 N/mm^2, 0.6 N/mm^2 and 1.0 N/mm^2. The variables studied are summarised below:

- NHL content (tested at 91 days): 1:2, 1:2.25 (baseline) and 1:2.5 NHL 3.5: sand;
- NHL grade (tested at 91 days): NHL 2, NHL 3.5 (baseline) and NHL 5;
- Cement: lime: sand mortar (tested at 28 days): 1:3:12;
- Brick type (tested at 91 days):
  - medium absorption ‘Berkeley Red Multi’ (baseline)
  - high absorption ‘Hardwicke Welbeck Autumn Antique’
  - low absorption ‘Staffordshire Slate Blue Smooth’

Brickwork failure modes during shear testing and mortar joint carbonation of the fractured surface with different brick/mortar combinations are reported in this section. The analysis and discussion on shear strength test results are presented in section 7.3. Recommendations for characteristic initial shear strength of NHL mortared brickwork are also proposed.

7.2.2 Failure modes of shear test specimens

Failure of the triplet specimens under in-plane shear loading was generally sudden and brittle. Following peak shear load the middle brick in the triplet arrangement slid noticeably relative to the outer two bricks in the loading direction. In most cases both joints failed simultaneously in shear (Figure 7.1(a), though in some tests (around 10%) either the upper or lower joint only failed, such that the remaining two bricks remained bonded after peak loading (Figure

7.1(b)); this later case was not very common except for the specimens built with 1:2:9 C: L: S mortar (the strongest mortar used in shear testing). Shear fracture (cracking) in the mortar joints was either confined to one of the interfaces (Figure 7.1(b), or in a number of tests stepped diagonally from the inner interface to the outer interface (when viewed in direction of the load) as shown in Figure 7.2 (the top interface of the specimen on the right cracked horizontally).

(a) (b)

Figure 7.1 Shear test specimens after failure

Figure 7.2 Crack patterns in shear test mortar joints

As with the flexural bond wrench test discussed previously, there were three different mortar joint modes of failure observed along the mortar joint and brick interfaces during shear strength testing. Broadly these have been classified as interface failure (Figure 7.3 (a)), mortar joint failure (Figure 7.3 (b)) and combined failure (part interface failure and part within joint failure) (Figure 7.3 (c)). However, characteristics of these failures differ from the bond tests as directions and states of stress fundamentally differ between the two tests. In the shear test mortar along the broken interfaces often crumbled as a result of the sliding friction.

(a) Interface failure

(b) Mortar failure

(c) Combined failure

Figure 7.3 Failure modes in shear testing
('Berkeley Red Multi' brick specimens)

Failure along the interface (Figure 7.3(a)) occurred in approximately half of the tests. This failure generally occurred along both interfaces simultaneously, but less frequently was limited to just one of the brick/mortar interfaces. Mortar joint failure (Figure 7.3(b)) was observed in around 30% of cases, whilst the combined failure mode (Figure 7.3(c)) was seen in the remaining 20% of tests. As aforementioned, the normal stress was applied at three varying levels, the highest of which was comparable with the mortar cube strengths. However, there was no noticeable change in shear failure modes for specimens at the higher normal stress levels.

There was no evidently strong relationship between observed failure mode and mortar properties. The relatively high levels of normal stress, compared to the mortar prism compressive strengths, are expected to have diminished any effect that mortar mix variation may have had on failure mode. However, the effect of brick type was more evident. In both the low (‘Staffordshire Slate Blue Smooth’) and high (‘Hardwicke Welbeck Autumn Antique’) water absorption bricks interface failure occurred in all tests, as a result of their bond.

In the low absorption series triplet tests, the clean fracture surface occurred along one interface with little mortar remaining on the brick after testing (Figure 7.4). The mortar joints in the ‘Hardwicke Welbeck Autumn Antique’ brick triplets were also relatively weak and many had disintegrated at failure (Figure 7.5 (a) and (b)). The rapid dewatering of the mortar and its poor strength is attributed to this performance. Moreover, in half of the ‘Hardwicke Welbeck Autumn Antique’ specimens cracking appeared in the bricks. This was always observed in the middle bricks and sometimes cracking was also seen in the upper and/or lower bricks (Figure 7.5 (c), (d) and (e)). Some of the ‘Hardwicke Welbeck Autumn Antique’ bricks failed by splitting lengthwise in half, as result of their relative low strength further weakened by large perforations in the section (Figure 7.5 (e) and (f)). At the medium and highest normal stress levels it would seem that the shear strengths of the bricks were the governing factor.

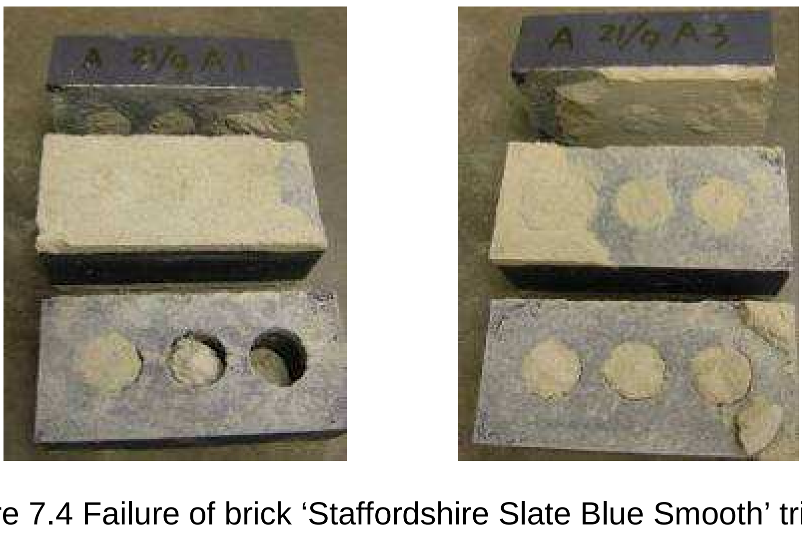
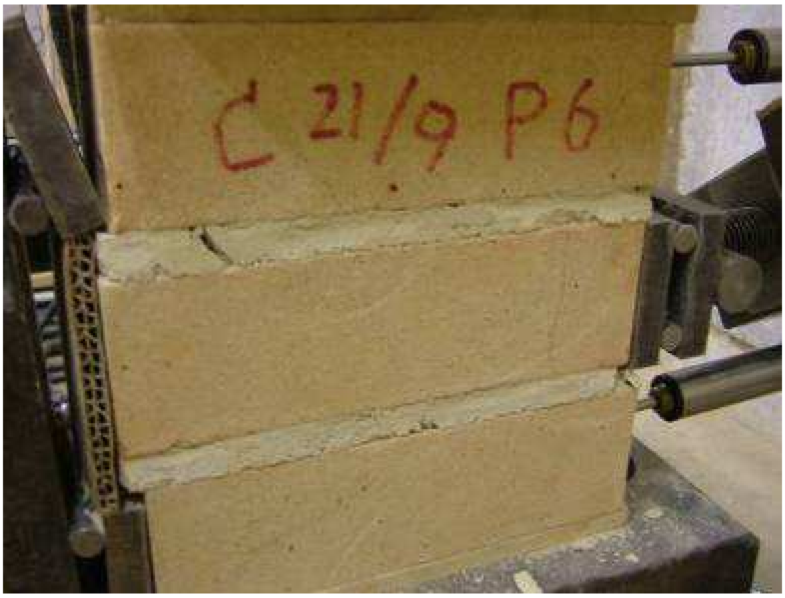


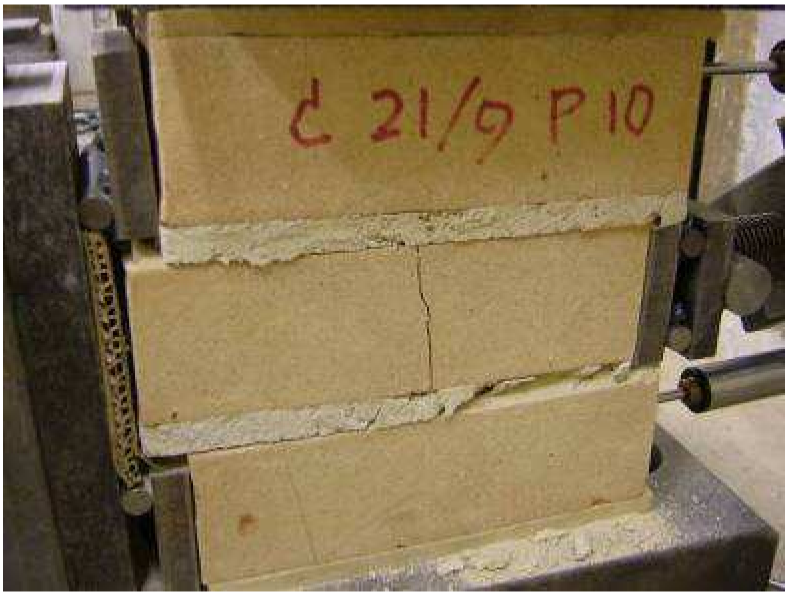
Figure 7.4 Failure of brick ‘Staffordshire Slate Blue Smooth’ triplets

(a)

(b)



(c) Crack in the middle brick



(d) Crack in the upper, middle and lower bricks

(e) (f)

Figure 7.5 Failure of brick 'Hardwicke Welbeck Autumn Antique' triplets

7.2.3 Mortar joint carbonation

Following testing for shear strength, mortar joints were sprayed with a solution of phenolphthalein indicator to assess extent of mortar carbonation. As expected these tests showed no significant variation in carbonation depths compared to those already discussed for the bond wrench series. In the shear specimens testing was only conducted after 91 days, so unlike bond wrench series it was not possible to map progress of carbonation with time. Rather these tests are presented to compare with the findings reported in Chapter 6.

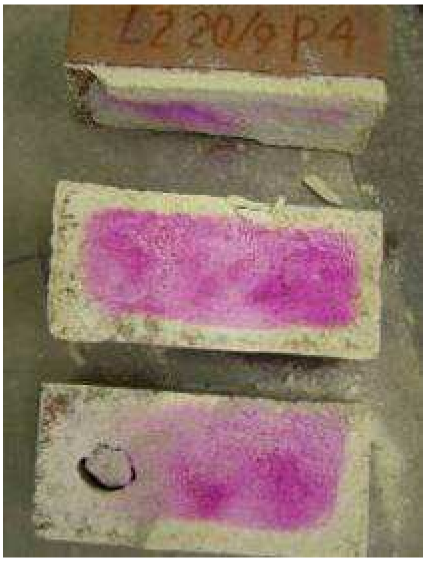
The carbonation depths measured ranged between 5 mm and 13 mm for all 'Berkeley Red multi' brick series (Figure 7.6), with an average carbonation depth reaching around 11 mm after 91 days. Carbonation depths were very similar to those measured as part of the bond wrench series.

The influence of different brick types on mortar joint carbonation in brickwork has been discussed in bond wrench test in Chapter 6. As in the shear strength test series only two other brick types (low and high absorption) were studied. The further examination of carbonation is limited to a comparison with previous test data. As with the bond wrench tests, the low absorption 'Staffordshire Slate Blue Smooth' brick series had very similar carbonation depths (average around

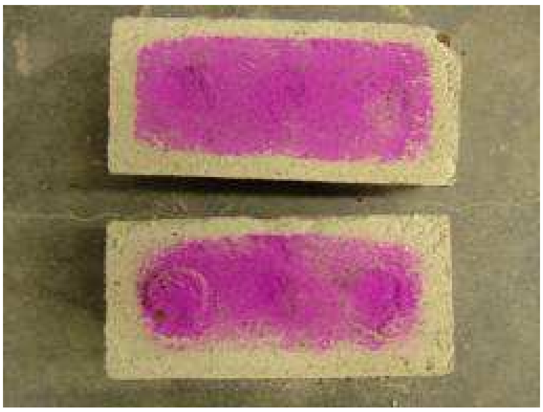
(a) 1:2.25 NHL 3.5:sand

(b) 1:2.5 NHL 3.5:sand

(c) 1:2 NHL 3.5:sand



(d) 1:2.25 NHL 2:sand

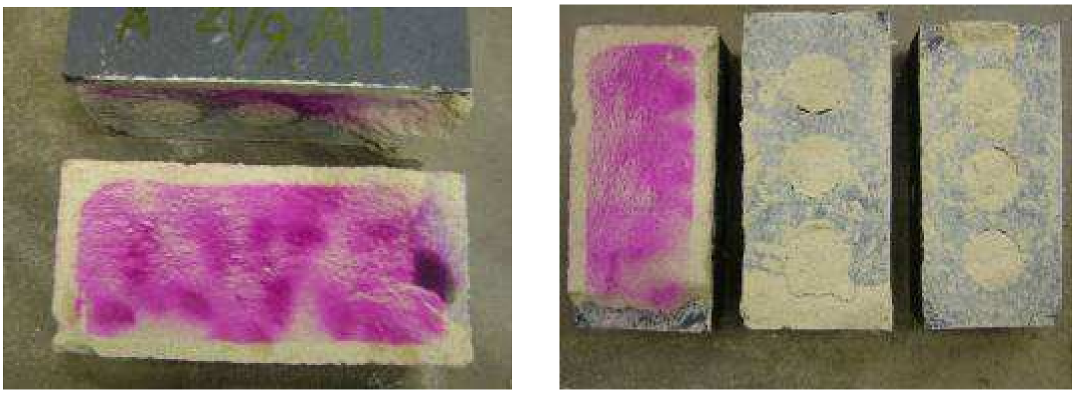


(e) 1:2.25 NHL 5:sand

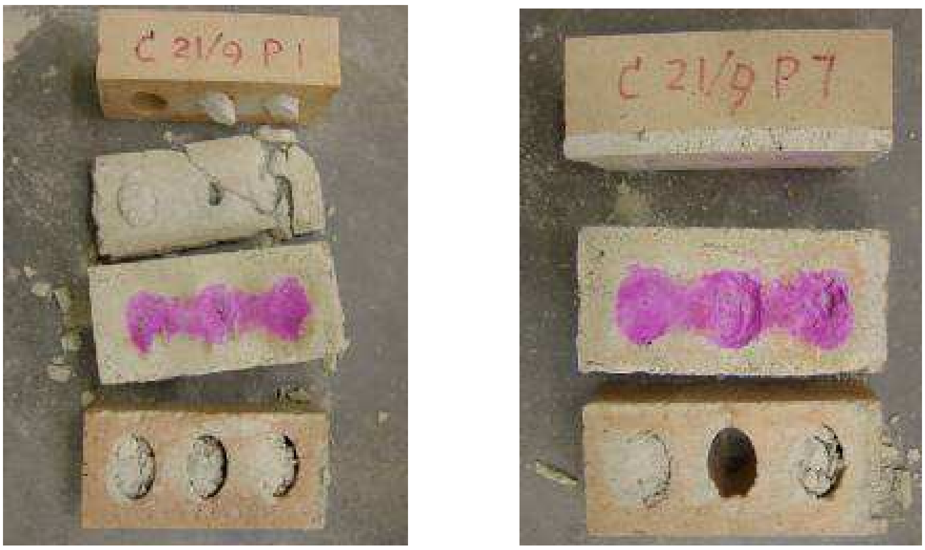
Figure 7.6 ‘Berkeley Red multi’ brick mortar carbonation patterns (various NHL mortars)

11 mm) at 91 days after curing (Figure 7.7 (a)) to that reported previously for the same mortar. Whilst the high absorption 'Hardwicke Welbeck Autumn Antique' brickwork carbonated much further (ranging from 15 mm to 35mm with average depth around 30 mm Figure 7.7 (b)).

In comparison the carbonation of the 40 x 40mm section mortar specimens cast in steel moulds had reached around 20 mm at 91 days (i.e. fully carbonated). The 'Berkeley Red multi' and 'Staffordshire Slate Blue Smooth' brick triplets had carbonated much less than mortar specimens, whilst the 'Hardwicke Welbeck Autumn Antique' brick had carbonated much more. It was confirmed again that brick water absorption had a significant effect on the microstructure property of mortar joint and therefore its carbonation.



(a) 'Staffordshire Slate Blue Smooth'



(b) 'Hardwicke Welbeck Autumn Antique'

Figure 7.7 Influence of brick type on mortar carbonation patterns

When the fresh mortar is laid on faces of the dry bricks, the bricks absorb water until a mutual water transport balance at the interface between unit and mortar is reached. The 'Staffordshire Slate Blue Smooth' brick and 'Berkeley Red multi' brick 24-hour cold water immersion absorptions are 2.3% and 5.1% respectively, and are likely to have reached this balance sooner. The mutual water transport hinders joint drying, delaying onset of carbonation. However, for the 'Hardwicke Welbeck Autumn Antique' brick (24-hour water absorption 14.8%), high absorption required much more water from mortar to reach the balance, rapidly drying out the mortar joint such that mortar porosity and thus the carbonation rate increased greatly.

7.3 Shear testing: initial shear strength results

7.3.1 Summary of tests

For each brick and mortar combination ten three-brick high prisms were built and tested after 91 days of curing. Individual experimental prism shear strengths were obtained by subjecting each prism to an in-plane three-point shear loading whilst under constant pre-compression loading. In each test series at least three repeat tests were completed at three different levels of pre-compression, as specified in BS EN 1052-3:2002. The initial shear strength, defined as the shear strength at zero pre-compression, and the coefficient of friction for each series was determined from the linear regression of the ten test results (section 3.5.4). The characteristic initial shear strength and the characteristic coefficient of friction values were obtained from multiplying by 0.8. As with the bond strength tests the combination of 'Berkeley Red Multi' brick and 1: 2.25 NHL 3.5: Binnegar sand mortar was set as the baseline series for comparison. All test results are summarized in Table 7.1 below.

The 91-day characteristic initial shear strengths (f_{vok}) of the NHL mortared brick triplets ranged between 0.11 and 0.24 N/mm^2. The corresponding characteristic coefficients of internal friction ($tan\ \alpha_k$) varied between 0.43 and 0.64. For the 'Berkeley Red Multi' brick series, the variations of f_{vok} and $tan\ \alpha_k$ were not significant, ranging 86-114% and 85-108% respectively, of the baseline

Table 7.1 Initial shear strength of NHL mortared brickwork

Brick type	Mortar mix	Age (days)	Mortar compressive strength (N/mm^2)	Initial shear strength f_{vo} (N/mm^2)	Characteristic initial shear strength f_{vko}		f_{vko} /f_{wk} (x100%)	Coefficient of internal friction *tan α*	Characteristic coefficient of internal friction $tan\ \alpha_k$		Characteristic bond wrench strength f_{wk}	
					(N/mm^2)	Relative to baseline				Relative to baseline	(N/mm^2)	Relative to baseline
Berkeley Red Multi	1:2.25 Baseline Series I	91	1.12	0.26	0.21	100%	58%	0.74	0.59	100%	0.36	100%
	1:2 Series I		1.20	0.24	0.19	90%	42%	0.80	0.64	108%	0.45	125%
	1:2.5 Series II		1.00	0.27	0.22	105%	71%	0.63	0.50	85%	0.31	86%
	NHL 5 Series II		1.28	0.30	0.24	114%	53%	0.78	0.62	105%	0.45	125%
	NHL 2 Series II		0.97	0.22	0.18	86%	86%	0.72	0.58	98%	0.21	58%
	1:3:12 Series I	28	1.22	0.29	0.23	110%	77%	0.73	0.58	98%	0.30	83%
Staffordshire Slate Blue Smooth	1:2.25 Series II	91	1.23	0.17	0.14	67%	93%	0.54	0.43	73%	0.15	42%
Hardwicke Welbeck Autumn Antique			1.28	0.14	0.11	52%	275%	0.60	0.48	81%	0.04	11%

brickwork. Shear strengths and friction coefficients are strongly correlated with mortar lime grade; either increasing or decreasing with mortar strength changes relative to the baseline series, though varying lime content only resulted in the corresponding variation of friction coefficients (discussed further below). The 1:3:12 cement: lime: sand mortared series performance was very similar to the baseline NHL mortared brickwork. Though the UK National Annex to EC6 does not currently consider clay brick type as an influencing factor for shear strength, the results from the 'Staffordshire Slate Blue Smooth' and 'Hardwicke Welbeck Autumn Antique' brick series indicated significant strength reductions, the characteristic initial shear strength f_{vok} achieving only 67% and 52% respectively, with the characteristic initial coefficient of friction 73% and 81% respectively, of the baseline 'Berkeley Red Multi' series.

In comparison with the characteristic flexural bond strengths, which varied between 11%-125% of the baseline series performance with material changes, the initial shear strength test values were much less sensitive, achieving between 52%-114% of the baseline series. The relatively high normal stresses (0.2–1.0 N/mm^2) applied during shear testing may have had a normalising effect on the performance. Although the highest level of normal stress was in fact higher than some of the measured mortar prism compressive strengths, the highest level of applied normal stress was only 7.5-15% of the estimated (in accordance with BS EN 1996-1) brickwork compressive strengths.

All of the bricks used in shear testing were perforated with three holes. Mortar from the bed joints had dropped into the holes, as in normal practice, during construction, though they were not purposefully filled. This physical shear key may have benefited the shear capacity of the masonry triplets. Previous research work (Marzahn, 1996) showed that greater percentage of perforations increases the shear strength due to the dowel action of the mortar inside the perforations. As only three repeat tests were completed for each level of normal stress it is difficult to establish consistency of performance for identical series. The dispersion of experimental data (Figures 7.9-7.14) was perhaps due to the intrinsic inhomogeneity of the masonry assemblage. As seen from the 'Hardwicke Welbeck Autumn Antique' brick series in Figure 7.8, condition of mortar in the perforations varied significantly; in some cases perforation were completely filled with well compacted mortar whilst in other cases poorly compacted mortar only partially filled the perforation. Shear failure of mortar that had dropped into the brick perforations could be seen in many of the series after testing (Figure 7.8).

‘Berkeley Red Multi’

‘Staffordshire Slate Blue Smooth’

‘Hardwicke Welbeck Autumn Antique’

Figure 7.8 Mortar inside brick perforations

7.3.2 Influence of lime grade and content on shear performance

The characteristic initial shear strength of brickwork with varying mortar lime grade and content are presented in Table 7.1. The 91-day initial shear strengths increased in line with lime grade changes, linked with improving mortar compressive strength performance. However, for increasing NHL3.5 content the link between mortar strength and initial shear strength was not as expected. The highest initial shear strength was developed by the weaker 1:2.5 mortar, whilst the weakest shear strength was developed by the strongest 1:2 mortar. However, it should be noted that variation in mortar compressive strength was only 1.00-1.20 N/mm^2 as a result of the increased lime content. And, as shear performance may also have been influenced by factors such as workmanship and mortar penetration into the brick perforations the inconsistency is perhaps less surprising.

The graphs of individual shear strength versus its corresponding normal compressive stress were plotted in Figure 7.9 and 7.10. The trend lines showed very strong correlations, R^2 values ranging 0.92-0.99. The coefficient of internal friction values, tan α, consistently increased with both lime grade and content (also see Table 7.1). The experimental shear strengths consistently increased with increasing levels of pre-compression stress. It can be argued that mortar dowelling action would play a more significant role at zero normal stress (initial shear strength values), the influence of improving mortar strength is more evident at higher stress levels. Based on the experimental trend lines (Figure 7.10), the 1:2.25 mortar achieved higher shear strength than the weaker 1:2.5 mix, once level of pre-compression stress was above 0.06 N/mm^2, whilst the 1:2 mortar achieved higher shear strength than 1:2.25 mortar once the pre-compression stress was over 0.44 N/mm^2.

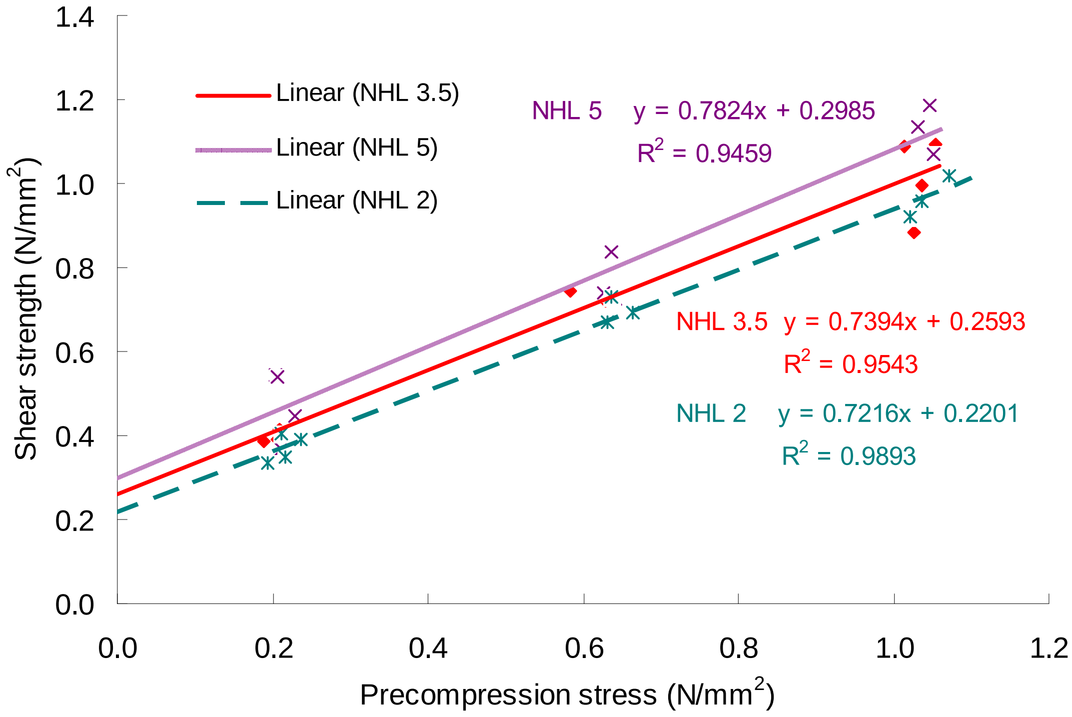


Figure 7.9 Influence of lime grade on brickwork shear strength

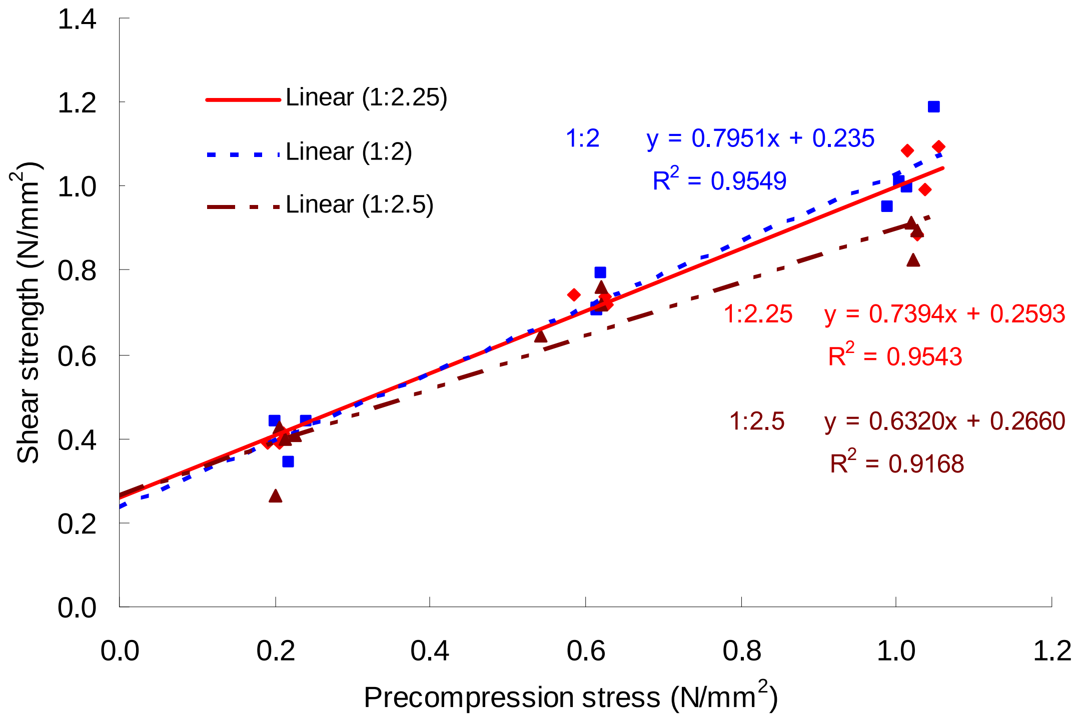


Figure 7.10 Influence of lime content on brickwork shear strength

7.3.3 Comparison with cement: lime: sand mortared brickwork

At 28-days the 1:3:12 cement: lime: sand mortared brick triplet series had developed slightly greater initial shear strength, in line with the slightly higher mortar strength, than the 91-day performance of the baseline 1:2.25 (NHL 3.5:Binnegar sand) series. The two coefficients of internal friction were comparable (Table 7.1 and Figure 7.11), thus the shear strengths of the NHL mortared and the weak cement mortared brickwork series increased at similar rates with increasing pre-compression.

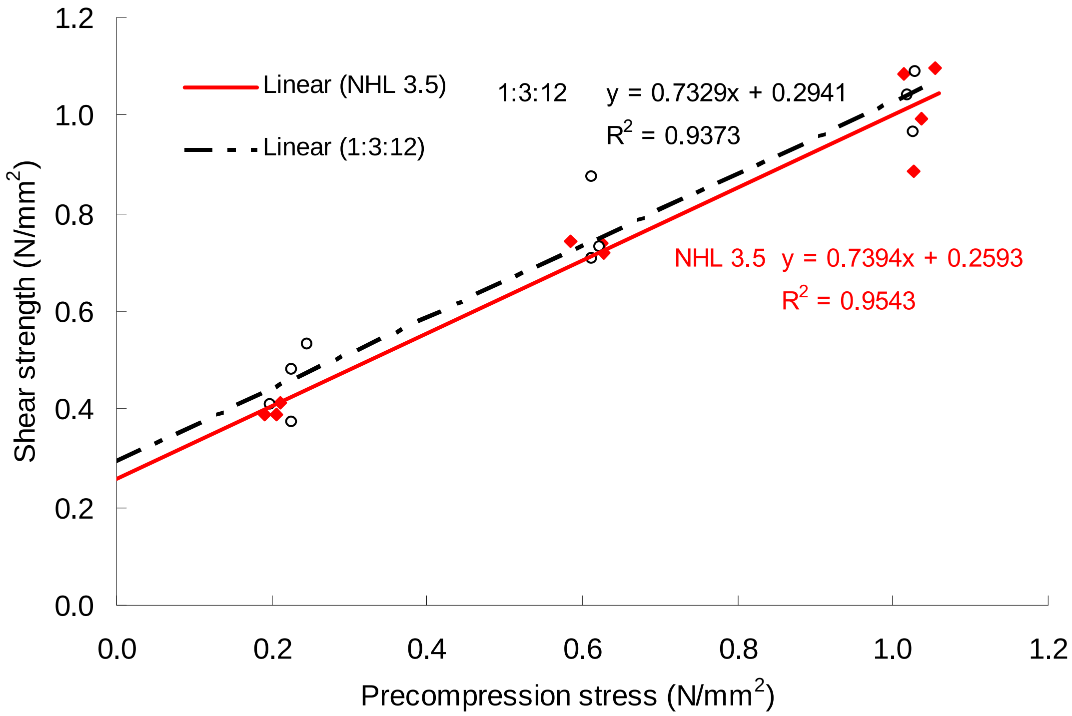


Figure 7.11 Shear strength comparisons between 1:3:12 mortared and baseline NHL mortared brickwork

7.3.4 Influence of brick properties on shear strength

In the current UK National Annex to EC6, the initial shear strength values f_{vko} of clay brick masonry are only categorised according to mortar type (general purpose mortar, thin layer mortar or lightweight mortar) and mortar strength class (M2, M4 and M6 or M12). However, we have already seen in this work that brick water absorption property has a significant effect on mortar performance and on resultant bond strength between the two materials.

Therefore, it would not be surprising if variation in bricks had an effect on shear strength. To investigate this, the shear performances of three different clay bricks (‘Berkeley Red Multi’, ‘Staffordshire Slate Blue Smooth’ (low absorption) and ‘Hardwicke Welbeck Autumn Antique’ (high absorption)), combined with same 1:2.25 NHL3.5: ‘Binnegar sand’ mortar, were tested after 91-days. As expected the three series presented very different initial shear strengths (Table 7.1 and Figure 7.12).

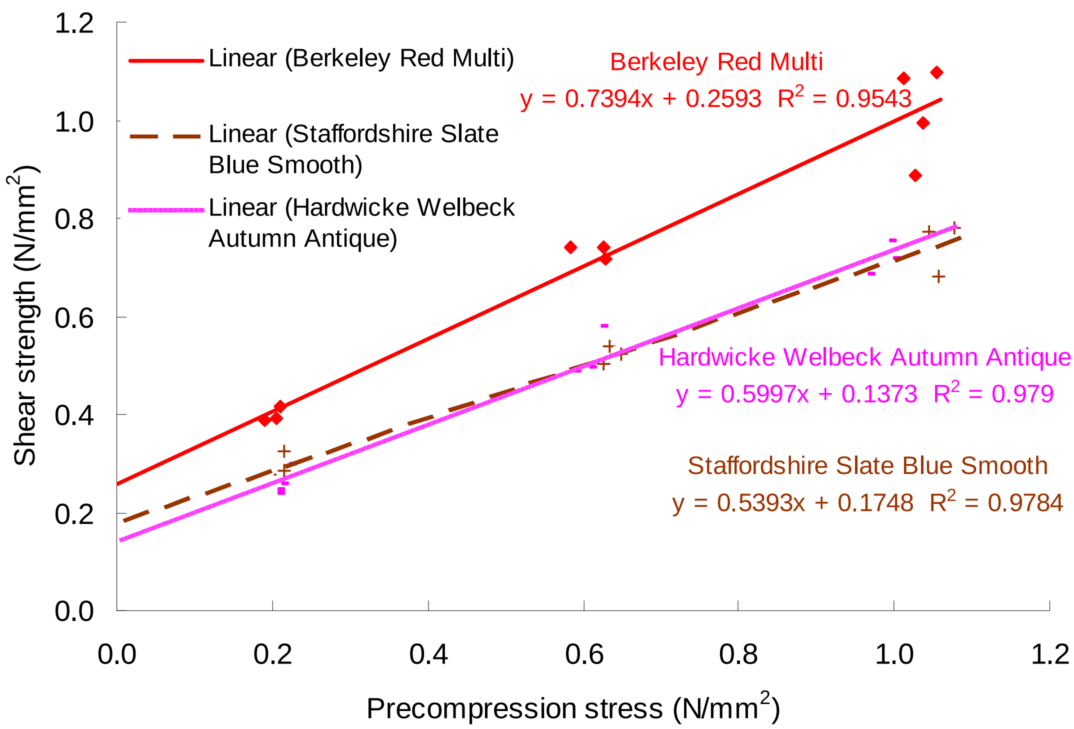


Figure 7.12 Influence of clay brick type on brickwork shear strength

The ‘Staffordshire Slate Blue Smooth’ series achieved only 67% of the initial shear strength of baseline brick series, whilst the ‘Hardwicke Welbeck Autumn Antique’ bricks reached only 52% of the baseline performance. All three bricks have very similar perforation patterns, so it is unlikely that effect of mortar shear key action could be solely attributed to this variation. As with flexural bond strength it is reasonable to expect that different brick dewatering properties have influenced both the shear bond between mortar and brick face as well the resultant strength between the bricks, and also possibly the mortar strength within the perforations.

The coefficients of internal friction were also influenced by change in bricks. Interestingly the coefficients of the low and high absorption brick series were very similar. Both brick series were lower than all other test series, significantly lower than other combinations of the baseline brick ‘Berkeley Red Multi’ and various mortar mixes. As with flexural bond brick type (water absorption characteristics) has had a significant influence on brickwork shear strength.

7.3.5 Design recommendations

The strength criterion f_{vk} of masonry can be characterised as a Coulomb type friction failure (De Buhan, 1997). Herein the cohesion causes initial shear strength, and thus is represented by it. Different coefficients of internal friction (generally 0.3-0.8) have been suggested by various studies (Chiostrini, 2000). In Eurocode 6 (BS EN 1996-1:2005), the characteristic shear strength of masonry f_{vk}, using general purpose mortar with all joints (bed and perpend joints) filled, is taken from equation below:

$$f_{vk} = f_{vko} + 0.4\,\sigma_d$$

where:

f_{vko} is the characteristic initial shear strength, under zero compressive stress;

σ_d is the design compressive stress perpendicular to the shear plane;

For grade M2 mortars the f_{vko} value is given as 0.1 N/mm^2 in National Annex to EC6 for general purpose mortar; whereas for the grade M1 NHL mortar, all test series attained characteristic initial shear bond strength more than 0.1 N/mm^2. Figure 7.13 shows the relationships between shear strength and normal compressive stress of all brick-mortar combinations tested herein. The trend line equations are summarized on the graph as well.

In accordance with BS EN 1052-3:2002, the characteristic initial shear strength (f_{vko}) is taken as 0.8 x f_{vo} and the characteristic coefficient of friction is taken as 0.8 x *tan* $\alpha_{k.}$ The experimental data presented in Figure 7.13 has been replotted in Figure 7.14 as characteristic trend lines. The high absorption 'Hardwicke Welbeck Autumn Antique' brick series, as with developing the lowest bond wrench flexural strength, it developed the lowest shear bond strength. Based on data presented in Figure 7.14, the following equation is recommended for NHL mortared brickwork:

$$f_{vk} = f_{vko} + 0.4\ \sigma_d$$

with f_{vko} taken as 0.1 N/mm^2, as shown in Figure 7.14.

Both the suggested equation and f_{vko} value for NHL mortared brickwork are in agreement with the cement mortared masonry for M1 class mortar in Eurocode 6.

7.3.6 Relationship between shear and flexural strength of brickwork

The experimental shear strength relationships presented above, assuming them to present a Mohr-Coulomb failure criterion (Figure 7.15), can be used to estimate the tensile strength of the brickwork. By extrapolating the linear relationships the principal stress at zero shear stress represents the corresponding estimated (theoretical) tensile resistance.

Tensile strengths and characteristic tensile strengths of various combinations of brick-mortar are obtained by extrapolating the linear relationships in Figure 7.13 and 7.14 respectively, presented here, for reasons of brevity, only as characteristic strength in Figure 7.16. The estimated values of average and characteristic tensile strengths for all series where shear tests exist are calculated with the trend line equations and compared with the corresponding flexural bond wrench strength data obtained in experiments in Table 7.2.

In general the average flexural strength was expected to exceed corresponding tensile strength by around 1.5 times. For the small average performance data set herein this relationship varies widely between 0.57 and 2.03 (Table 7.2), suggesting this method of indirectly estimating flexural performance is

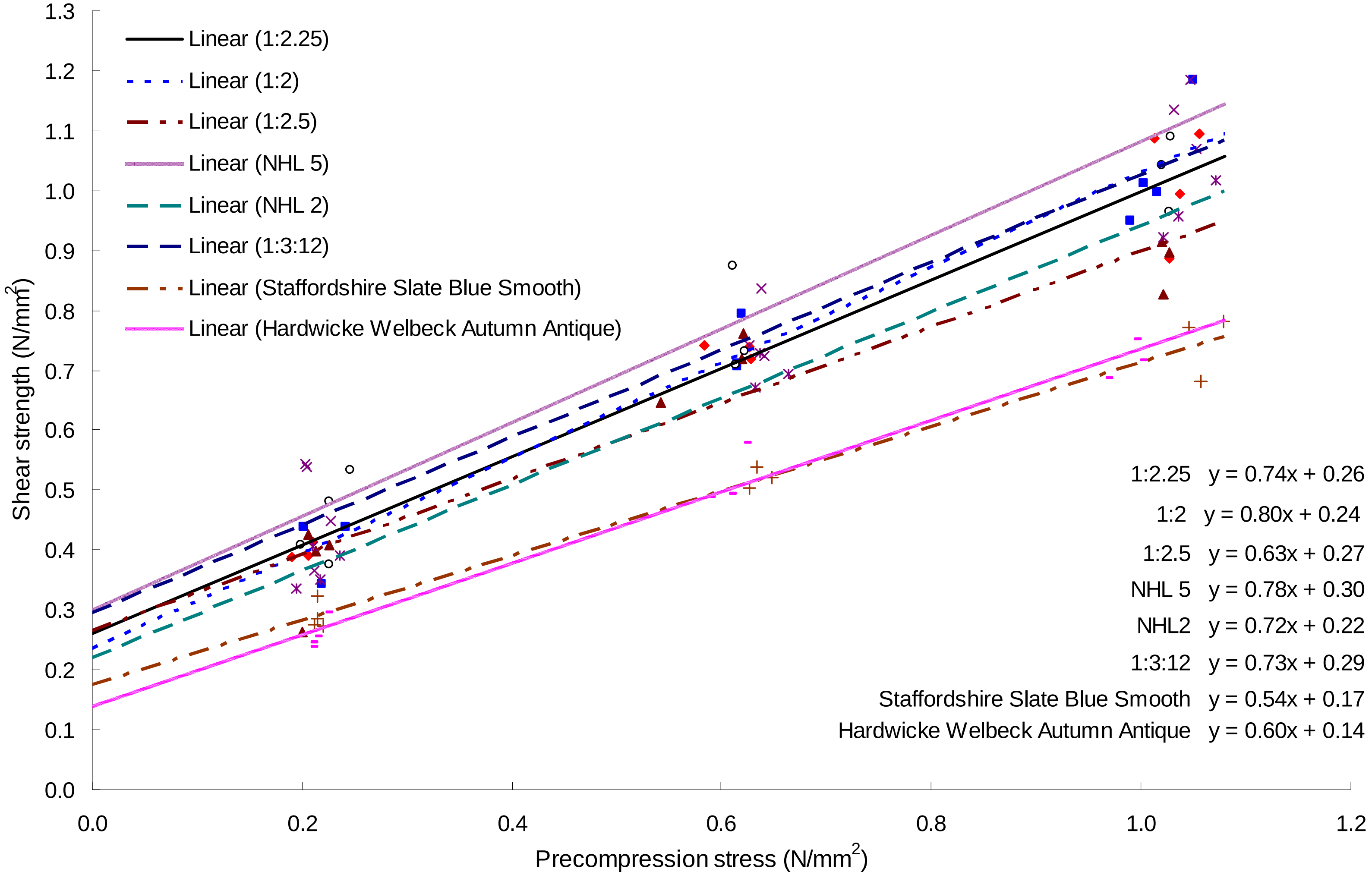


Figure 7.13 Shear strengths of various brick/mortar combinations

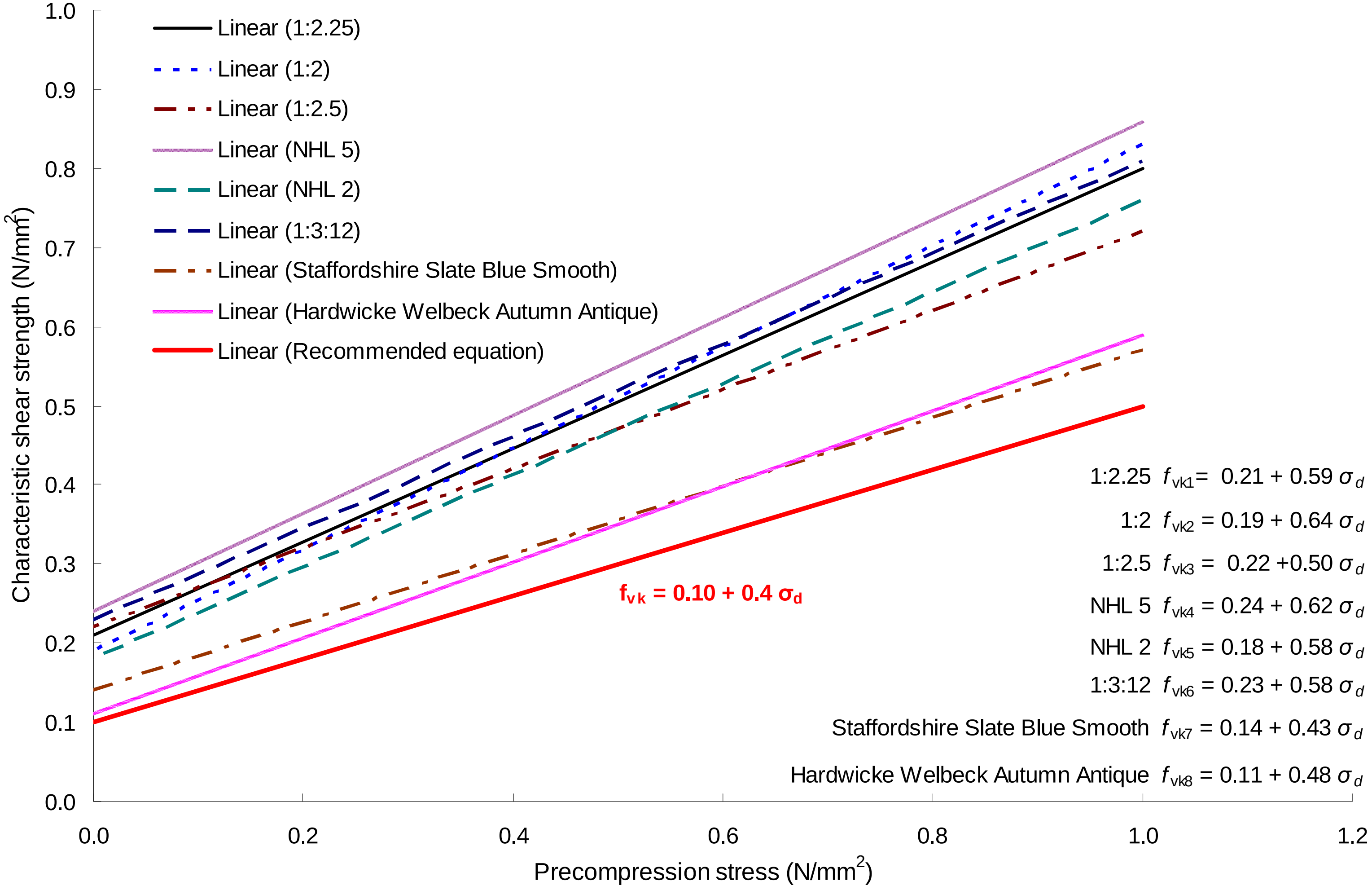


Figure 7.14 Recommended characteristic shear strength and characteristic coefficient of internal friction

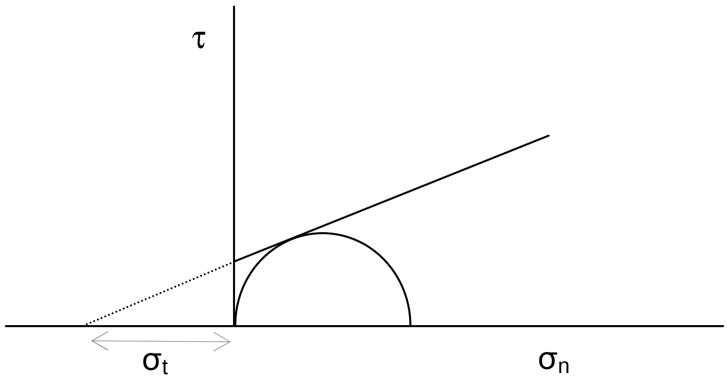


Figure 7.15 Mohr-Coulomb failure criterion

unreliable. Variation in relationship is also seen in characteristic material performance, although for the weakest series the estimated tensile strength is as much as 5.75 times of the measured performance. This in part may also be attributed to the methodology used to estimate characteristic shear strength performance, by applying a factor of 0.80, rather than through statistical derivation as with bond strength.

Table 7.2 Comparison between the estimated tensile strengths and experimental flexural strength values

Test series	Average strength (N/mm^2)			Characteristic strength (N/mm^2)		
	Experimental flexural	Estimated tensile	Expt./ Estimated	Experimental flexural	Estimated tensile	Expt./ Estimated
1:2.25	0.46	0.35	1.31	0.36	0.36	1.00
1:2	0.61	0.30	2.03	0.45	0.30	1.50
1:2.5	0.38	0.42	0.90	0.31	0.44	0.70
NHL 5	0.63	0.38	1.66	0.45	0.39	1.15
NHL 2	0.29	0.31	0.94	0.21	0.31	0.68
1:3:12	0.35	0.40	0.88	0.30	0.40	0.75
Staffordshire Slate Blue Smooth	0.23	0.32	0.72	0.15	0.33	0.45
Hardwicke Welbeck Autumn	0.13	0.23	0.57	0.04	0.23	0.17

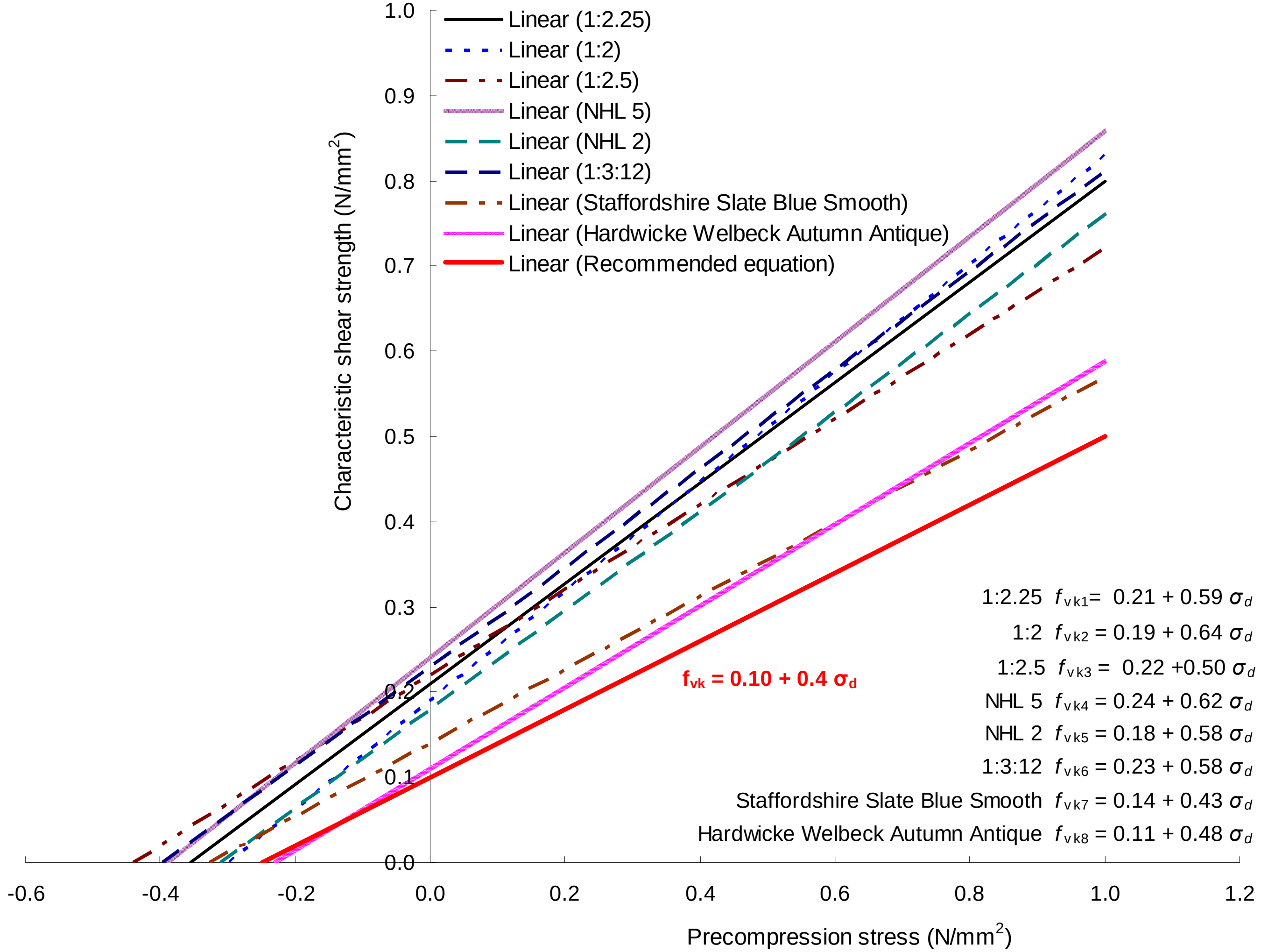


Figure 7.16 Tensile strength estimation based on Mohr's failure theory

7.4 *Compressive strength of NHL mortared brickwork*

Although the focus of this study has been to investigate bond strength (flexure and shear), given that the characteristic compressive strength of masonry is a fundamental parameter for load-bearing design, this aspect could not be entirely ignored in this study. As shown in the literature review, there have been very little other data reported on this aspect. Consequently, the compressive strength performance of one series, the baseline bricks and NHL3.5 mortar mix, was investigated experimentally. Results and findings from this series are presented below. Tests were undertaken in accordance with BS EN 1052-2; six identical specimens were prepared and tested in uni-axial compression to failure.

7.4.1 Failure mode

Under increasing compression loading the first signs of distress to the brickwork was crushing of the mortar and vertical cracking of the bricks. The mortar joints started to crumble when the load was around over 70% of the maximum load. Small cracks started to appear in some brick units when the load was over 80 percent of the maximum load. Vertical splitting cracks developing on four faces of the walls gradually led to the failure of brickwork (Figure 7.17). This well-known effect is due to the difference in movement properties of the two materials. Under stress the softer mortar tends to spread more than the stiffer and stronger bricks. Confined by the bricks the mortar is induced into a state of triaxial compression, placing the bricks into biaxial lateral tension in planes perpendicular to the line of principal stress (loading). When the stresses are sufficient the bricks crack.

7.4.2 Test results

The stress versus strain graphs for the compressive testing of the baseline NHL mortared wall panels are shown in Figure 7.18. Modulus of elasticity or Young's modulus E_i was calculated by measuring the slope of secant between ordinates corresponding to $^{1}/_{20}$th to $^{1}/_{3}$rd of the ultimate strength of the brickwork specimens. The relationships can be approximately taken as linear and then parabolic. The experimental results, together with the mean and characteristic strength values, are shown in Table 7.3. The modulus of elasticity and compressive strength are both very consistent.

Figure 7.17 Failure mode of masonry in compression

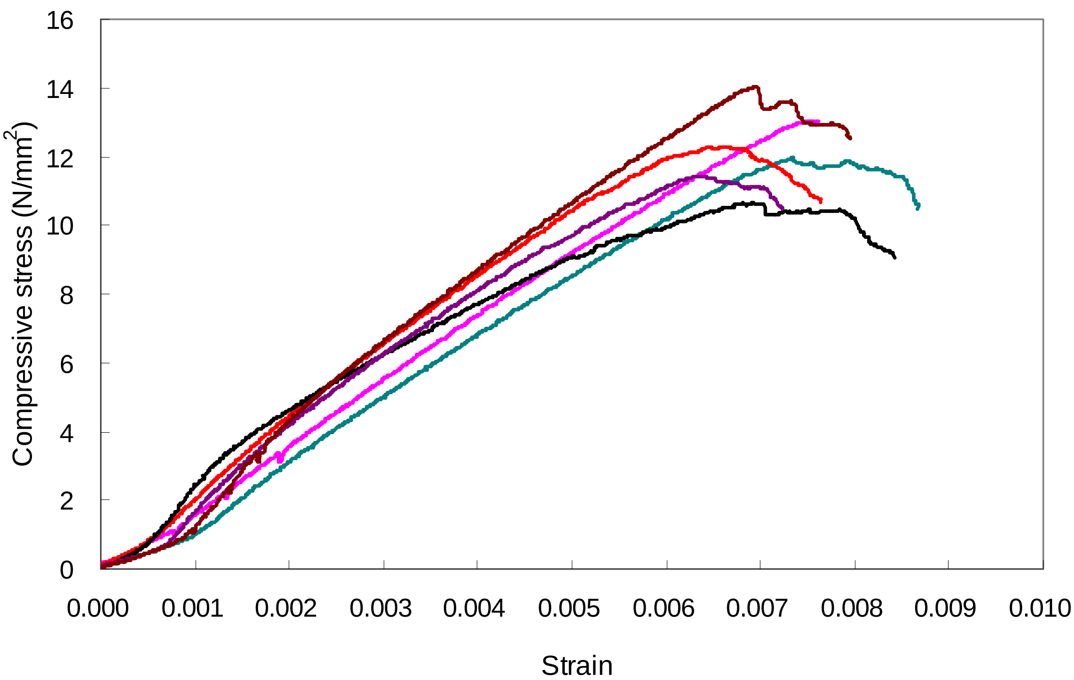


Figure 7.18 Compressive stress-strain curve for NHL mortared masonry

Table 7.3 Compressive strength of the baseline NHL mortared brickwork

Specimen	Modulus of elasticity			Compressive strength			
	E_i (N/mm^2)	Mean (N/mm^2)	CV (%)	f_i (N/mm^2)	Mean f (N/mm^2)	CV (%)	Characteristic f_k (N/mm^2)
1	1907	1900	12.2	13.1	12.2	9.8	10.1
2	1844			12.0			
3	2043			12.3			
4	1491			10.6			
5	1937			11.4			
6	2178			14.1			

It is generally accepted that masonry strength is primarily dependent upon characteristics of masonry unit, mortar and the bond between them. In the UK National Annex to EC6 the characteristic compressive strength of masonry f_k is determined from equation:

$$f_k = K\, f_b^{\alpha}\, f_m^{\beta}$$

where

- K — is a constant according to Table NA.4 (taken as 0.5 for group 1 clay bricks combined with general purpose mortar)
- f_b — is normalised mean compressive strength of the units, in N/mm^2 (= 55 N/mm^2 for the 'Berkeley Red Multi' brick)
- f_m — is the compressive strength of the mortar, in N/mm^2 (taken as 1 N/mm^2 for NHL3.5 mortar)
- α, β — are constants (for general purpose mortar, α = 0.7, β= 0.3)

On this basis the characteristic compressive strength of the brickwork f_k = 7.4 N/mm^2; the experimental value f_k =10.1 N/mm^2 is 136% of the predicted strength.

Previous research on the compressive strength characteristics of lime mortared brickwork were conducted by Hughes (2005). Their characteristic compressive strengths tested at 56 days, 2.38 N/ mm^2 and 5.11 N/ mm^2 for Blue Lias (BL) and Charlestown (CH) lime mortars respectively, were much lower than reported here. Hughes used quicklime whilst hydraulic limes were used in this research. Although the strengths of the mortars used in Hughes's study were much higher, 2.43 and 3.52 N/ mm^2 for BL and CH mortars respectively, than the NHL baseline mortar herein, the relatively low strength 25-35 N/mm^2 Hanson London brick, with very high water absorption (20-24%), obviously had a more significant influence. The mean reported values (BL mortar only obtained three valid values in the study) of the compressive strengths of the masonry specimens only achieved 38% and 73% for BL and CH mortars respectively, of their predicted characteristic values in the UK National Annex to EC6.

Allen (2007) reported results of 13.9 N/mm^2 for characteristic compressive strength of brickwork, using 35 N/mm^2 brick with a M2 mortar, which can generate characteristic compressive strength of the brickwork f_k = 5.6 N/mm^2 according to British Standards. Based on work presented here and previous studies EC6 can be used to safely estimate the characteristic compressive of lime mortared brickwork.

7.5 Conclusions

This chapter presented the results from initial shear and compressive strength tests of NHL mortared brickwork. Failure mode, mortar joint carbonation and shear strength were reported and discussed. The influences of lime grade and lime content on shear strength of brick triplets were also investigated. Compression test on baseline brickwork also gave some basic understanding. The conclusions below can be drawn from previous discussions.

1. Brick type, mainly brick absorption characteristics, had the most significant influence on shear failure mode and mortar carbonation rates.
2. Initial shear strength is less sensitive than bond wrench strength to variations in mortar strength.
3. Initial shear strength of NHL mortared brickwork improved by both increasing lime grade and content.
4. A weak 1:3:12 cement lime mortar showed comparable initial shear strength and angle of internal friction to the NHL mortared specimens.
5. Brick absorption had significant effect on shear strength.
6. Relationship between shear strength and pre-compression stress is proposed for NHL mortared brickwork design guide.
7. The experimental characteristic compressive strength of the baseline brickwork test specimens was higher than the calculated value given by EC6.

8. Conclusions and recommendations for further work

This thesis has presented work on structural performance of hydraulic lime mortared brickwork and constituent materials, focusing on bond strength development. Materials, including binders, sands and bricks, were carefully selected to represent those in common usage in the UK. Mortar and brickwork specimens were prepared, cured for various ages and tested using a variety of methods. Experimental results have been supported by analytical techniques to develop greater understanding of performance. A wide variety of material and other parameters have been studied. The work has provided basis for developing design guidance on hydraulic lime based brickwork for new build supported by a wide range of experimental data. In this project the following tests have been completed:

- 750 mortar flexural strength tests.
- 1500 mortar compressive strength tests.
- 80 masonry flexural ‘parallel to bed joint’ wall panel tests.
- 60 masonry flexural ‘perpendicular to bed joint’ wall panel tests.
- 1968 masonry bond wrench tests.
- 90 masonry initial shear strength tests.
- 6 masonry compressive strength wall tests.

In addition a variety of other experiments have also been conducted, including mortar flow table tests and mortar carbonation indicator tests.

Main conclusions from this work are summarised below together with recommendations for further work.

8.1 Main conclusions

Chapter 2 Literature review

To begin with previous work on the properties of lime-based mortars is reviewed. Previous research has considered the effect of many variables on both fresh and hardened mortar properties, including lime grade, mix proportion, sand grading and curing time. The studies have mainly focussed on properties of mortars rather than masonry. Previous research in the literature has mostly focussed on cement mortared masonry. Significant parameters from previous work, for consideration in this work, included mortar properties, masonry unit water absorption, brick moisture content, curing time and curing conditions. A variety of testing methods for examining masonry flexural, shear and compressive strengths have been reviewed. A number of previous studies on hydraulic lime mortar based masonry properties are reviewed in detail.

The main findings from the literature review concerning development of bond strength in masonry can be summarised as follows:

1. The interface between unit and mortar is important for bond development; bond is primarily a mechanical interlocking force dependent on mortar hydration and water movement at the interface which transports chemical hydration products into the masonry unit surface.
2. Bond in masonry is established through the interaction between brick suction and mortar water retention. There should be good compatibility between the two materials to develop a good bond. Brick dewatering should ensure that the fresh mortar has sufficient moisture for hydration.
3. Many parameters contribute to the achievement of a good bond in masonry, including mortar composition, unit absorption and surface texture, curing condition and time, and quality of workmanship.
4. A variety of test methods have been used by researchers to investigate masonry properties, making it difficult to compare test results. Standardisation of test methods will ease comparison in future work.

Throughout the literature it is acknowledged that masonry strength development is a very complex process, which needs a great deal of work to understand.

Chapter 3 Experimental materials and test methodology

In previous work, brick water absorption has been identified as an important factor for the development of bond at the unit-mortar interface. Initial experiments in the early stages of this research confirmed that brick water absorption also has a significant influence on performance of NHL mortared brickwork.

Two different brick total water absorption tests (24-h cold water immersion and 5-h boil water) have been used in previous work, together with the initial rate of absorption test. In this work these tests have also been used to characterise the experimental bricks. In addition the sorptivity testing has been performed for the first time in this regard. Correlative relationships between the differing parameters have been explored. As expected the 5-h boil water absorption consistently attained higher values than the 24-h immersion test. Stronger correlations were established between brick IRA or sorptivity and 24-h water absorption rather than the 5-h boil water.

Properties of mortar constituent materials, binders and aggregates, used in this project have been characterised and a series of mortar mixes are proposed. The experimental programme has been formulated, and methodologies were chosen to investigate NHL mortar properties as well as the strength characteristics of NHL mortared brickwork including: flexural strength ‘parallel to bed joint’ and ‘perpendicular to bed joint’ by wall panel tests; bond wrench strength testing of brickwork quadruplets; shear bond strength testing of brick triplets; and, limited compressive strength wall testing. For comparison a baseline mortar (1:2.25 NHL 3.5: Binnegar sand by volume) and brick combination (‘Berkeley Red Multi’) was selected for the research project.

Chapter 4 Mortar properties

The properties of NHL mortar specimens were presented and analysed in Chapter 4. Fresh mortar workability was assessed by the flow table test. Mortar desorptivity testing was performed at the University of Manchester. Hardened mortar property testing focussed on investigating the influences of variables on mortar flexural and compressive strengths, including: lime grade; mortar mix proportion; sand grading; lime source; consistency of production batches; and, water: lime ratio. Mechanical testing was performed at various ages up to 1 year. Mortar carbonation was tracked with the increasing age by indicator tests. The main conclusions from this investigation included:

1. The water content required to maintain mortar workability increased with sand content and sand fineness but decreased with lime hydraulicity.
2. The desorptivity test provided an indication of the water retention performance of the experimental mortars. Although there was some inconsistency, mortar desorptivity values generally increased with the degree of hydraulicity, lime content decreasing and sand particle coarseness and poor grading.
3. Mortar strength increased with lime hydraulicity and content, but varied significantly with same lime grade sourced from different suppliers.
4. Mortar mixes using coarser well-graded sands developed noticeably higher strengths.
5. As expected the flexural and compressive strengths of mortar increased with age, however, the initial rates of strength development of NHL mortars were lower than comparative cement mortars. The NHL mortars continued significantly gaining strength after 28 days.
6. The 91-day NHL mortar strengths were taken as approximate final strengths. Most of the NHL 3.5 and NHL 5 mortars tested met the requirement for M1 strength class mortar.

Chapter 5 Flexural strength of NHL mortared brickwork: comparison of wall panel and bond wrench tests

In one of the main aspects of this research, two different wall panel tests were carried out to establish brickwork flexural strengths f_{xk1} and f_{xk2}. Identical brick and mortar combinations were also studied by bond wrench test to compare with the wall panel f_{xk1} strength. The influences of mortar and brick properties such as lime grade, mix proportion and brick absorption, on NHL mortared brickwork were studied. Observations on the specimen failure modes after testing and the mortar joint carbonations at fracture surface were also presented in this chapter. The main conclusions from this work are summarised below:

1. The flexural bond strength of NHL mortared brickwork improved with increasing mortar strength.
2. Brick water absorption has the controlling influence on brickwork bond development. In general, the bricks with mid-range absorption developed the highest flexural bond strengths, whilst the highest absorption bricks developed the lowest flexural strength.
3. There is a strong correlation between flexural bond strengths determined by the wall panel test and by the bond wrench test. The ease of the bond wrench makes it more suited to a wider study of material influences on bond performance.
4. The NHL mortars developed bond of comparable strength to those developed by the weak cement: lime: sand (1:2:9 and 1:3:12) mortars.
5. Compared to mortar properties, brick water absorption characteristics have a more significant influence on failure mode, mortar joint carbonation and bond strength.

Chapter 6 Influence of material properties on bond strength of NHL mortared brickwork

In this chapter, using the bond wrench test, a comprehensive study of the material influences on brickwork bond strength was presented. Parameters studied included: lime grade and content; sand grading; lime supplier; lime production batch; brick 5-h boil water absorption; brick 24-h cold water absorption; brick IRA; brick sorptivity; and, brick moisture content at laying. Bricks covering a wide range of water absorption values were selected to explore the effects of water absorption properties on bond wrench strength. Specimen curing time was also studied in several combinations of brick and mortar. Characteristic flexural strength f_{xk1} values have been recommended for NHL mortared brickwork design. The main conclusions were as follows:

1. Compared to mortar mix variations, brick absorption properties had a more significant influence on the failure modes and mortar joint carbonation rates of NHL mortared brick prisms.
2. Flexural bond strength in brickwork increased with NHL lime grade and content. Well-graded coarse sands also improved bond development.
3. Lime sources showed a considerable effect on NHL mortars and the resultant brickwork performance. Some variation was also noted in different batches of lime production from the same source.
4. Brick water absorption characteristics, compared to mortar mixes variation, had a more significant influence on bond wrench strength. Brick moisture content at laying, varied by dipping, which correlates with water absorption ability, also influenced bond development in brickwork.
5. As with NHL mortar, NHL mortared brick prisms developed initial bond strength at slower rates than cement based mortars. The 91-d bond strength may be taken as approximate peak strength, though some brickwork continued to develop significant strength increase beyond this time period.
6. The recommended characteristic flexural strength f_{xk1} of clay brick NHL mortared masonry is 0.26 N/mm^2 for bricks with 5-h total water absorption less than 12%, and 0.07 N/mm^2 for bricks with 5-h absorption more than 12%.

Chapter 7 Shear and compressive strengths of NHL mortared brickwork

Shear and compressive strength tests of NHL mortared brickwork, essential for masonry design, were also investigated, although they were not the main focus of this project. As with flexural strength tests, failure modes and mortar carbonation (in the shear test specimens) were recorded. In shear strength testing mortar variables examined included lime grade and mortar mix proportion; a high and a low absorption bricks were also studied. Compressive performance test of wall panels was also completed on the baseline NHL mortared brickwork. The main conclusions from Chapter 7 were:

1. Initial shear strength and coefficient of friction of NHL mortared brickwork generally increased with higher lime grade and content.
2. Brick water absorption influenced shear specimen failure mode, mortar carbonation and shear bond strength more than changes in the mortar mix.
3. The higher levels of normal stress applied during shear testing had an apparent normalising effect on brickwork specimen performance, reducing the influence of variations in mortar mixes and brick types.
4. A design equation has been proposed for the relationship between characteristic initial shear strength and the applied pre-compressive stress.
5. Both shear and compressive strengths test results showed NHL mortared brickwork achieved higher strengths than the values given in BS EN 1996-1 for weak cement mortared brickwork.

8.2 Recommendations for further research

Although a great deal of novel work has been conducted in this project, the research on lime mortared masonry performance is still limited. Therefore, further work on a great many aspects of NHL mortared masonry can be found. Some of the most significant research work suggested is listed below.

1. The results presented in this project showed that brick water absorption plays a very important role in developing good bond in brickwork. However, there were considerable scatter in data resulting in conservative design recommendations for many brick and mortar combinations. Further study of different brick types, especially those with a range of low and high absorption, can provide more test data, and form basis for less conservative design guidance.
2. Whilst this research only focused on clay brickwork, tests on other types of masonry units, such as calcium silicate bricks; normal, lightweight and aerated concrete blocks; natural stones and manufactured stones, are required to develop characterisation of NHL mortared masonry.
3. The commonly used lime grade, sand type, mix proportion and lime suppliers in the UK have almost all been involved in this research. However, the use of admixtures and additions, such as air entraining plasticisers, pozzolans and frost inhibitors, often used in cement mortar, have not been considered to use in lime mortar in this project. Further work is warranted in this area.
4. Further work is required to characterise compressive strength and shear strength performance of lime mortared masonry.
5. In this research standard testing procedures were followed, however, new experimental methods can be explored in future research to measure masonry strength characteristics.
6. Based on the results of the experimental study, theoretical analysis can be carried out for further investigation on the mechanism of the bond development in masonry.
7. This whole project only involved a variety of tests in laboratory. Performing field testing of NHL mortar and masonry is important and required to verify their structural performance.
8. Except the strength characteristics in NHL mortared brickwork, other properties such as masonry deformation including creep, moisture expansion, shrinkage and thermal expansion, need to be considered in masonry design as well. Movement accommodation, as one of the benefits

of NHL mortared masonry, should be examined and compared with the corresponding properties of cement mortar masonry. Furthermore, in design guidance masonry durability including unit, mortar and masonry durability, is an important part to be considered to resist the relevant exposure environmental conditions and requires related research.

BLANK PAGE

References

ALMEIDA, J.C., LOURENCO, P.B., BARROS, J.A., 2002. Characterization of brick and brick-mortar interface under uniaxial tension. *Proceedings of the VII International Seminar on Structural Masonry for Developing Countries*, 2002 Belo Horizonte, Brazil, pp. 67-76.

AL-MUKHTAR, M., BECK, K., 2006. Physical-mechanical characterization of hydraulic and non-hydraulic lime based mortars for a French porous limestone. *Journal of Heritage, Weathering and Conservation*, HWC 2006, pp. 37-42.

ALLEN, G., ALLEN, J., ELTON, N., FAREY, M., HOLMES, S., LIVESEY, P., RADONJIC, M., 2003. *Hydraulic Lime Mortar for Stone, Brick and Block Masonry.* Shaftesbury, Donhead Publishing Ltd.

ALLEN, G.C. AND BALL, R.J., 2010. Mechanical properties of hydraulic lime mortars. *In*: *APFAC, 3rd Congresso Portugues de Argamassas de Construção*, 18-19 March, 2010, Auditório LNEC, Lisbon.

ASHURST, J., 1997. The technology and use of hydraulic lime. *The Building Conservation Directory*.

ASTM C1072 – 11, 2011. *Standard Test Method for Measurement of Masonry Flexural Bond Strength*. ASTM International.

BALL, R.J., EL-TURKI, A., ALLEN, W.J., NICHOLSON, J.A., ALLEN, G.C., 2009. Deformation of NHL3.5 and CL90/PC hybrid mortars, *Proceedings of the Institution of Civil Engineers, Construction Materials,* Vol. 162, Issue CM1, pp. 29–35.

BALL, R.J., EL-TURKI, A., ALLEN, G.C., 2009. Influence of carbonation on the load dependent deformation of hydraulic lime mortars. *Proceedings of the 11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009)*, 6-9 September, Bath, UK.

BARTOS, P., GROOT, C., HUGHES, J.J., 1999. *Proceedings of the International RILEM Workshop on Historic Mortars: Characteristics and Tests*, Paisley, Scotland.

BECK, K., AL-MUKHTAR, M., ROZENBAUM, O. AND RAUTUREAU, M., 2003. Characterisation, water transfer properties and deterioration in tuffeau: building material in the Loire valley-France. *International Journal of Building and Environment*, Vol. 38, No. 9, pp. 1151-1162.

BOKAN BOSILJKOV, V., 2001a. The use of industrial and traditional limes for lime mortars, *In*: LOURENCO, P.B. AND ROCA, P., eds. *Proceedings of the 3rd International Seminar Historical Constructions*. University of Minho, Guimaraes, 2001, pp. 343-352.

BOKAN BOSILJKOV, V., 2001b. The use of lime mortars for sustainable restoration of ancient buildings, *Proceedings of the 9th Canadian Masonry Symposium*. University of New Brunswick. Canada.

BORCHELT, J.G. AND TANN, J.A., 1996. Bond strength and water penetration of low IRA brick and mortar, *Proceedings of the Seventh North American Masonry Conference,* The Masonry Society, Boulder, CO. June 1996, pp. 206-216.

BORCHELT, J.G., MELANDER, J.M., NELSON, R.L., 1999. Bond Strength and water penetration of high IRA brick and mortar, *Proceedings of 8th North American Masonry Conference*, The Masonry Society, Boulder, CO, June 1999, pp. 304-315.

BOYNTON, R.S. AND GUTSCHICK, K.A., 1964 (reprinted in 1975). *Bond of Mortar to Masonry Units, Masonry Mortar,* Technical Notes #3, National Lime Association, Washington, D.C.

BOYNTON, R.S., 1980. *Chemistry and Technology of Lime and Limestone,* 2nd ed. New York: John Wiley & Sons, Inc.

BRICK DEVELOPMENT ASSOCIATION (BDA), 2001. *Use of Traditional Lime Mortars in Modern Brickwork, Properties of Bricks & Mortar Generally*, No 1.3.

BRICK DEVELOPMENT ASSOCIATION (BDA), 2011. *Brick: Building a Sustainable Resource for the Future.*

BRITISH GEOLOGICAL SURVEY, 2005. *Mineral Planning Factsheets: Natural Hydraulic Limes*, Natural Environment Research Council.

BS EN 1015-2:1999. *Methods of test for mortar for masonry, Part 2: Bulk sampling of mortars and preparation of test mortars*. BSI.

BS EN 1015-3:1999. *Methods of test for mortar for masonry, Part 3: Determination of consistence of fresh mortar (by flow table)*. BSI.

BS EN 1015-11:1999. *Methods of test for mortar for masonry, Part 11: Determination of flexural and compressive strength of hardened mortar*. BSI.

BS EN 1052-1:1999. *Methods of test for masonry, Part 1: Determination of compressive strength*. BSI.

BS EN 1052-2:1999. *Methods of test for masonry, Part 2: Determination of flexural strength*. BSI.

BS EN 1052-3:2002. *Methods of test for masonry, Part 3: Determination of initial shear strength*. BSI.

BS EN 1052-5:2005. *Methods of test for masonry, Part 5: Determination of bond strength by the bond wrench method*. BSI.

BS EN 1097-3:1998. *Tests for mechanical and physical properties of aggregates, Determination of loose bulk density and voids*. BSI.

BS 1199 and 1200: 1976. *Specifications for building sands from natural sources*. BSI.

BS EN 1996-1-1:2005. *Eurocode 6. Design of masonry structures, Part 1-1: General rules for reinforced and unreinforced masonry structures*. BSI.

NA to BS EN 1996-1-1:2005. *UK National Annex to Eurocode 6. Design of masonry structures, Part 1-1: General rules for reinforced and unreinforced masonry structures*. BSI.

BS EN 459-1:2010. *Building lime, Part 1: Definitions, specifications and conformity criteria*. BSI.

BS EN 459-2:2010. *Building lime, Part 2: Test methods*. BSI.

BS EN 771-1:2003. *Specification for masonry units, Part 1: Clay masonry units*. BSI.

BS EN 772-7:1998. *Methods of test for masonry units, Part 7: Determination of water absorption of clay masonry damp proof course units by boiling in water*. BSI.

BS EN 772-11:2011. *Methods of test for masonry units, Part 11: Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units*. BSI.

BS EN 772-16:2011. *Methods of test for masonry units, Part 16: Determination of dimensions*. BSI.

BS EN 772-21:2011. *Methods of test for masonry units, Part 21: Determination of water absorption of clay and calcium silicate masonry units by cold water absorption*. BSI.

BS EN 933-1:1997. *Tests for geometrical properties of aggregates, Part 1: Determination of particle size distribution — Sieving method*. BSI.

BS EN 998-2:2010. *Specification for mortar for masonry, Part 2: Masonry mortar*. BSI.

CALLEBAUT, K., ELSEN, J., VNA BALEN, K., VIAENE, W., 2001. Nineteenth century hydraulic restoration mortars in the Saint Michael's Church (Leuven, Belgium), natural hydraulic lime or cement? *Cement and Concrete Research*, Vol. 31, pp. 397-403.

CHAROLA, A. ELENA AND HENRIQUES, F.M.A., 1998. Lime mortars: some considerations on testing standardization, use of and need for preservation standards in architectural conservation, *ASTM STP 1355*, *American Society for Testing and Materials*, pp. 142-151.

CHIOSTRINI, S., GALANO, L. AND VIGNOLI, A., 2000. On the determination of strength of ancient masonry walls via experimental tests, *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

CHOUBEY, U.B., GUPTA, U., AND MAIDASANI, A., 1999. An experimental study of flexural tensile strength of calcium silicate brick masonry, *Journal of Structural Engineering*, Vol. 26 No.2, pp. 143-148.

CIZER, Ö., VAN BALEN, K., VAN GEMERT, D., 2010. Competition between hydration and carbonation in hydraulic lime and lime-pozzolana mortars, *Advanced Materials Research*, Vol. 133-134, pp. 241-246.

COSTIGAN, A., PAVÍA, S., 2009. Compressive, flexural and bond strength of brick/lime mortar masonry, protection of historical buildings, *Proceedings of PROHITEC 09* – Mazzolani editor, 2009, Taylor and Francis Group, London, pp. 1609-1615.

COWPER, A.D., 1927 (republished in 1998). *Lime and Lime Mortars*, Building Research Special Report, No. 9, Donhead Publishing.

DAVEY, N., 1971. *A History of Building Materials*, New York: Drake Publishers.

DE BUHAN, P., DE FELICE, G., 1997. A homogenization approach to the ultimate strength of brick masonry. *Journal of the Mechanics and Physics of Solids*, Vol. 45, Issue 7, pp. 1085-1104.

DE VEKEY, R., 2005. Building masonry with lime-based bedding mortars. *BRE, Good Building Guide 66*. Watford,IHS BRE Press.

DE VITIS, N., PAGE, A.W., LAWANCE, S.J., 1995. Influence of age on the development of bond strength, *Proceedings of the 4th Australasian Masonry Conference*, Sydney, pp. 299-307.

ELERT, K., RODRIGUEZ-NAVARRO, C., PARDO, E.S., HANSEN, E., CAZALLA, O., 2002. Lime mortars for the conservation of historic buildings, *Studies in Conservation*, Vol. 47, No. 1, pp. 62-75.

ELLIS, P., 2001. Gauging lime mortars. *The Building Conservation Directory*.

EL-TURKI, A., BALL, R.J., ALLEN, G.C., 2007. The influence of relative humidity on structural and chemical changes during carbonation of hydraulic lime, *Cement and Concrete Research*, Vol. 37, pp. 1233-1240.

EL-TURKI, A., CARTER, M.A., WILSON, M.A., BALL, R.J., ALLEN, G.C., 2009. A microbalance study of the effects of hydraulicity and sand grain size on carbonation of lime and cement. *Construction and Building Materials*, Vol. 23, pp. 1423-1428.

EL-TURKI, A., BALL, R.J., CARTER, M.A., WILSON, M.A., INCE, C., ALLEN, G.C., 2010. Effect of dewatering on the strength of lime and cement mortars. *Journal of the American Ceramic Society*, Vol. 93, pp. 2074-2081.

EL-TURKI, A., BALL, R.J., HOLMES, S., ALLEN, W.J., ALLEN, G.C., 2010. Environmental cycling and laboratory testing to evaluate the significance of moisture control for lime mortars. *Construction and Building Materials*, Vol. 24, pp. 1392-1397.

ENGLISH HERITAGE, 1997. *Hybrid mortar mixes containing both non-hydraulic and hydraulic lime binders*. Technical Policy Statement. English Heritage.

FASSINA, V., BORSELLA, S., 1993. The effects of past treatments on the acceleration of weathering processes in the statues of Prato Delle Valle. *Proceedings RILEM/UNESCO Congress on the Conservation of Stone and Other Materials*, Paris. pp. 129- 136.

FASSINA, V., FAVARO, M., NACCARI, A. AND PIGO, M., 2002. Evaluation of the compatibility and durability of hydraulic lime-based plasters applied on brick wall masonry of historical buildings affected by rising damp phenomena. *Journal of Cultural Heritage*, Vol.3, pp. 45-51.

GABBY, B.A., 1989. A compilation of flexural bond stresses for solid and hollow Non-reinforced clay masonry and portland-Lime mortars. *Masonry: Components to Assemblages, ASTM STP 1063*, *American Society for Testing and Materials*, pp. 235-247.

GABOR, A., FERRIER, E., JACQUELIN, E., HAMELIN, P., 2006. Analysis and modelling of the in-plane shear behaviour of hollow brick masonry panels. *Construction and Building Materials*, Vol. 20, pp. 308-321.

GAZZOLA, E., BAGNARIOL, D., TONEFF, J., DRYSDALE, R.G., 1985. Influence of mortar materials on the flexural tensile bond strength of block and brick masonry, *ASTM STP 871, American Society for Testing and Materials*, pp. 15-25.

GOODWIN, J.F. AND WEST, H.W.H., 1982. A review of the literature on brick/mortar bond. *British Ceramic Research Association*, Vol. 30, Issue 23, pp. 23-37.

GRIMM, C.T., AND TUCKER, R.L., 1985. Flexural strength of masonry prisms versus wall panels. *Journal of Structural Engineering*, Vol. 111, No. 9, pp. 2021-2032.

GROOT, C.J.W.P., 1993. *Effects of water on mortar-brick bond*. PhD-thesis. Delft University of Technology, Delft.

GROOT, C.J.W.P., 1997. The characterisation of brick and mortar considering mortar/brick bond, *Proceedings of the 11th International Brick/Block Masonry Conference*, 14-16 October, Shanghai, China. Tongji University, pp. 50-58.

HALL, C. AND HOFF, W.D., 2002. *Water Transport in Brick, Stone and Concrete*. Spon Press, London and New York.

HALL, C. AND HOFF, W.D., 2005. *Testing in Construction Vol. 2, The Testing of Ceramics in Construction*. Whittles Publishing, Caithness, UK.

HAMMETT, M., 1988. A basic guide to brickwork mortars, Part 1 Materials, mixes and selection. *Brick Development Association. Building Technical File* No. 22.

HAMMOND, G. AND JONES, C., 2011. Inventory of Carbon and Energy (ICE, V 2.0), 'Carbon Vision Buildings' programme, Sustainable Energy Research Team (SERT). Department of Mechanical Engineering, University of Bath, UK.

HANLEY, R., PAVÍA, S., 2008. A study of the workability of natural hydraulic lime mortars and its influence on strength. *Materials and Structures*, 41, pp. 373–381.

HENTIQUES, F.M.A., RAO, V.M., CHAROLA, E., 2004. The influence of the grain size distribution on the performance of mortars. *Proceedings of 10th International Congress on Deterioration and Conservation of Stone*, Vol. II, ICOMOS, Sweden, Elanders Gotab, Stockholm, pp. 1001-1008.

HOLMES, S. AND WINGATE, M., 1997 (2nd ed. 2002). *Building with Lime: A Practical Introduction*. London: Intermediate Technology Publications.

HOLMSTRÖM, I., 1981. Mortars, cements and grouts for conservation and repair. Some urgent needs for research. *Symposium of Mortars, Cements and Grouts used in the Conservation of Historic Buildings,* ICCROM, Rome, pp. 19-24.

HUGHES, D. AND SWANN, S., 1998. Hydraulic Limes: A Preliminary Investigation. *Lime News,* Vol. 6, pp. 41-52.

HUGHES, D.C., ILLINGWORTH, J.M., 2009. Dry-silo mortars based on a novel lime-drying process, *Proceedings of the 11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009),* 6-9

September, Bath, UK.

HUGHES, J.J., BARTOS, P.M., CUTHBERT, S.J., STEWART, R.N., VALEK, J., 1998. Micro-structures in historic Scottish lime mortars. In M.S. JONES AND R.D. WAKEFIELD, eds. *Stone Weathering and Atmospheric Pollution Network 97: Aspects of Stone Weathering, Decay and Conservation,* Imperial College Press, London, pp. 125-137.

HUGHES, J.J. AND TAYLOR, A.K., 2005. Compressive and flexural strength testing of brick masonry panels constructed with two contrasting traditionally produced lime mortars (unpublished paper).

INCE, C., CARTER, M.A., WILSON, M.A., COLLIER, N.C., EL-TURKI, A., BALL, R.J., ALLEN, G.C., 2011. Factors affecting the water retaining characteristics of lime and cement mortars in the freshly-mixed state, *Materials and Structures*, Vol. 44, pp. 509-516.

IS277, 1993. *Flexural Bond Strength Testing of Masonry.* Portland Cement Association.

JUKES, P., RIDDINGTON, J.R., 1998. A Review of Masonry Tensile Bond Strength Test Methods. *Masonry International*, Vol. 12, No. 2, pp. 51-57.

KAUSHIK, H.B., RAI, D.C., JAIN, S.K., 2007. Uniaxial compressive stress–strain model for clay brick masonry. *CURRENT SCIENCE*, Vol. 92, No. 4, pp. 497-501.

KAUSHIK, H. B., RAI, D.C. AND JAIN, S.K., 2007. Stress-strain characteristics of clay brick masonry under uniaxial compression. *JOURNAL OF MATERIALS IN CIVIL ENGINEERING, ASCE,* Vol. 19, Issue 9, pp. 728-729.

KENT, D., *Rain Penetration, 2005*. The Building Conservation Directory.

KHALAF, F.M., 2005. New test for determination of masonry tensile bond strength. *Journal of Materials in Civil Engineering, ASCE*, Vol. 17, Issue 6, pp. 725-732.

LANAS J., ALVAREZ, J.I., 2003. Masonry repair lime-based mortars: factors affecting the mechanical behaviour. *Cement and Concrete Research,* Vol. 33, Issue 11, pp. 1867–1876.

LANAS, J., PEREZ BERNAL, J.L., BELLO, M.A., ALVAREZ GALINDO, J.I., 2004. Mechanical properties of natural hydraulic lime-based mortars, *Cement and Concrete Research,* Vol. 34, Issue 12, pp. 2191-2201.

LAWRENCE, R.M.H., 2006. *A study of carbonation in non-hydraulic lime mortars.* PhD thesis, University of Bath, Bath, UK.

LAWRENCE, S.J. AND PAGE, A.W., 1994. Bond studies in masonry.

Proceedings of the 10th International Brick/Block Masonry Conference, Calgary, pp. 909-917.

LAWRENCE, S.J. AND SO, L., 1994. The influence of some factors on the tensile bond strength of masonry. *Proceedings of the 10th International Brick/Block Masonry Conference,* Calgary, 1994, pp. 929-938.

LAWRENCE, S., PAGE, A.W., 1995. Mortar bond - A major research program. *Proceedings of the 4th Australian Masonry Conference*, Sydney, pp. 31-37.

LECHTMAN, H. AND HOBBS, L., 1986. Roman Concrete and the Roman Architectural Revolution. *Ceramics and Civilization, Volume 3: High Technology Ceramics: Past, Present, Future*, American Ceramics Society, pp. 81-128.

LOURENCO, P.B., ALMEIDA, J.C., BARROS, J.A.O., 2002. Characterization of brick and brick-mortar interface under uniaxial tension. *Proceedings of the VII International Seminar on Structural Masonry for Developing Countries*, Belo Horizonte, Brazil, pp. 67-76.

LOURENCO, P.B., BARROS, J.O., OLIVEIRA, J.T., 2004. Shear testing of stack bonded masonry. *Construction and Building Materials,* Vol. 18, Issue 2, pp. 125–132.

LYNCH, G.C.J., 1994. *Brickwork: History, Technology and Practice.* Shaftsbury: Donhead Publishing.

MARAVELAKI-KALAITZAKI, P., KARATASIOS, I., BAKOLAS, A., KILIKOGLOU, V., 2005. Hydraulic lime mortars for the restoration of the historic masonry in Crete. *Cement and Concrete Research*, Vol. 35, Issue 8, pp. 1577-1586.

MARAVELAKI-KALAITZAKI, P., 2007. Hydraulic lime mortars with siloxane for waterproofing historic masonry. *Cement and Concrete Research*, Vol. 37, Issue 2, pp. 283-290.

MARZAHN, G., 1996. Improving the shear bond behaviour of masonry, *Masonry Structures*, Leipzig Annual Civil Engineering Report, LACER, Leipzig, Germany, No. 1, pp. 245-268.

MCGINLEY, W.M., 1990. IRA and the Flexural Bond Strength of Clay Brick Masonry. *Masonry: Components to assemblages, American Society for Testing and Materials,* ASTM STP 1063, pp. 217-234.

MOROPOULOU, A., MARAVELAKI-KALAITZAKI, P., BORBOUDAKIS, M., BAKOLAS, A., MICHAILIDIS, P., CHRONOPOULOS, M., 1998. Historic mortars technologies in Crete and guidelines for compatible restoration mortars. *Compatible Materials for the Protection of European, Cultural Heritage,* Technical Chamber of Greece, Athens, Vol. 55, pp. 55– 72.

MOROPOULOU, A., BAKOLAS, A., MOUNDOULAS, P., AGGELAKOPOULOU, E., ANAGNOSTOPOULOU, S., 2005. Strength development and lime reaction in mortars for repairing historic masonries. *Cement and Concrete Composites*, Vol. 27, pp. 289-294.

BRITISH GEOLOGICAL SURVEY, 2005. *Natural Hydraulic Limes.* Natural Environment Research Council.

NATIONAL LIME ASSOCIATION, 2000. *Lime-based Mortars Create Wall Tight Walls*. Building Lime Group.

NHBC FOUNDATION, 2008. Draft for Development Standard, *The structural use of unreinforced masonry made with natural hydraulic lime mortars – technical annex for use with BS 5628-1:2005 (The use of lime-based mortars in new build).*

NIEA, 2009. *The conservation of scheduled masonry monuments.* Technical guidance booklet for owners & builders, Northern Ireland Environment Agency.

OATES, J.A.H., 1998. *Lime and limestone: chemistry and technology production and uses*. John Wiley & Sons.

PAGE, C.L., TREDAWAY, K.W.J., 1982. Aspects of the electrochemistry of steel in concrete. *Nature*, Vol. 297, Issue 5862, pp. 109-115.

PAGE, A.W., 1992. The design, detailing and construction of masonry: the lessons from the Newcastle earthquake. *Civil Engineering Transactions*, Vol. 34, No. 4, pp. 343-353.

PASLEY, C.W., 1997. *Observations on Limes*. Donhead Publishing.

PAVÍA, S. AND TREACY, E., 2006. A comparative study of the durability and behaviour of fat lime and feebly-hydraulic lime mortars. *Materials and Structures*, Vol. 39, pp. 391–398.

PAVÍA, S., FITZGERALD, B., AND TREACY, E., 2006. An assessment of lime mortars for masonry repair. In: CIARAN MCNALLY, ed. *Concrete Research in Ireland Colloquium*, Dublin University College, Dublin, pp. 101-108.

PAVÍA, S. AND TOOMEY, B., 2008. Influence of the aggregate quality on the physical properties of natural feebly-hydraulic lime mortars. *Materials and Structures*, Vol. 41, pp. 559–569.

PAVÍA, S., HANLEY, R., 2010. Flexural bond strength of natural hydraulic lime mortar and clay brick. *Materials and Structures*, Vol. 43, pp. 913–922.

PERONI, S., TERSIGNI, G., TORRACA, G., CEREA, S., FORTI, M., GUIDOBALDI, F., ROSSI-DORIA, P., DE REGE, A., PICCHI, D., PIETRAFITTA, F.J., AND BENEDETTI, G., 1981. Lime based mortars for the repair of ancient masonry and possible substitutes. *Mortars, Cements and Grouts Used in the Conservation of Historic Buildings*, Rome, 3-6 Nov. 1981. pp. 63-99.

PLATZMANN, C.R., 1924. Hydraulic Limes, Natural and Artificial. *Rock Products.* Vol. 27, No. 23, pp. 49-51.

PLATZMANN, C.R., 1938. Continental Natural and Artificial Hydraulic limes. *Cement and Lime Manufacture,* Vol. 11, No. 4, pp. 67-72.

REDA TAHA, M.M., EL-DIEB, A.S. AND SHRIVE, N. G., 2001. Sorptivity: A Surface Absorption Criteria for Brick Units: A Proposal for the Canadian Masonry Standards. *Proceedings of the 9th Canadian Masonry Symposium*, Fredericton, NB, Canada.

REDA TAHA, M.M., EL-DIEB, A.S. AND SHRIVE, N. G., 2001. Sorptivity: a reliable measurement for surface absorption of masonry brick units. *Materials and Structures*, Vol. 34, No. 7, pp. 438-445.

RITCHIE, T. AND DAVISON, J.I., 1962. Factors affecting bond strength and resistance to moisture penetration of brick masonry. *ASTM Special Technical Publication,* No. 320, pp. 16-30.

SARANGAPANI, G., VENKATARAMA REDDY, B.V. AND GROOT, C.J.W.P., 2002. Water loss from fresh mortars and bond strength development in low strength masonry. *Masonry international*, Vol. 15, No. 2, pp. 42-47.

SARANGAPANI, G., VENKATARAMA REDDY, B.V. AND JAGADISH, K.S., 2005. Brick-mortar bond and masonry compressive strength. *Journal of Materials in Civil Engineering*, Vol. 17, Issue 2, pp. 229-237.

SCHOFIELD, J., 1997 (3rd ed. 2005). *Lime in Building: A Practical Guide.* Black Dog Press.

SCRIVENER, J., 1992. *Old Masonry Buildings: Earthquake Performance and Material Testing*. Internal Report No. 624, National Research Council (NRC), Canada.

SEABRA, M.P., LABRINCHA, J.A., FERREIRA, V.M., 2007. Rheological behaviour of hydraulic lime-based mortar, Journal of European Ceramic Society, Vol. 27, pp. 1735-1741.

SEARLE, A.B., 1935. *Limestone and its Products, their Nature, Production and Uses.* Ernest and Benn Ltd, London.

SICKELS-TAVES, L.B., ALLSOPP, P.D., 2005. Lime and its place in the 21st century: combining tradition, innovation, and science in building preservation. *International Building Lime Symposium*, Orlando, Florida.

SINHA, B.P., 1983. Factors affecting the brick/mortar interface bond strength, *International Journal of Masonry Construction*, Vol. 3, Issue 1, pp. 14-18.

SINHA, B.P., NG, C.L., PEDRESCHI, R.F., 1997. Failure Criterion and Behaviour of Brickwork in Biaxial Bending. *Journal of Materials in Civil Enginee*ring, Vol. 9, Issue 2, pp. 70-75.

SMEATON, J., 1791. *A Narrative of the Building and a Description of the Building of the Eddystone Lighthouse with stone of the Building of the Eddystone Lighthouse with stone*. London, England.

SPAB, 2002. *Repointing Stone and Brick Walling.* Technical Pamphlet 5, London, England.

ST. ASTIER, 2006. *Pure & Natural Hydraulic Limes* [online]. Available from: www.stastier.co.uk/ [Accessed 1 Jan. 2012].

STEFANIDOU, M., PAPAYIANNI, I., 2005. The role of aggregates on the structure and properties of lime mortars. *Cement and Concrete Composites*, Vol. 27, Issues 9-10, pp. 914-919.

SUGO, H. O., PAGE, A.W., LAWRENCE, S.J., 2001. The development of mortar/unit bond. *Proceedings of the 9th Canadian Masonry Symposium*, University of New Brunswick. Canada.

SUGO, H., PAGE, A.W., LAWRENCE, S., 2007. The influence of age on masonry bond strength and mortar microstructure, *Canadian Journal of Civil Engineering*, Vol. 34, No. 11, pp. 1433-1442.

SUMANOV, L., STANISEVA, T., TRAJKOSKA, V., DANILOVSKI, D., AND SENSOVA, V., 1995. Lime mortar and lime based mixtures for conservation, restoration, repair and strengthening of Byzantine churches (9th-14th century) in Republic of Macedonia. *Methods of Evaluating Products for the Conservation of Porous Building Materials in Monuments*, ICCROM, Rome, pp. 49-66.

TATE, M., 2005. The Most Important Property of Cement-lime Mortar in Masonry Construction is…, *Internationals Building Lime Symposium*, Orlando, Florida.

VABLE, M., 2010. *Mechanics of Materials* [online], 2nd edition, PDF book: http://www.me.mtu.edu/~mavable/Book/Chap10.pdf [Accessed 1 Jan. 2012].

VAN BALEN, K., 2003. Understanding the lime cycle and its influence on historical construction practice. *Proceedings of the First International Congress on Construction History,* Madrid, 20-24th January, pp. 2041-2054.

VAN BALEN, K., PAPAYIANNI, I., VAN HEES, R., BINDA, L. AND WALDUM, A., 2005. Introduction to requirements for and functions and properties of repair mortars. RILEM Technical Committees, *Materials and Structures*, Vol. 38, No. 8, pp. 781-785.

VENKATARAMA REDDY, B.V. AND GUPTA, A., 2006. Tensile bond strength of soil-cement block masonry couplets using cement-soil mortars, *Journal of Materials in Civil Engineering*. Vol. 18, Issue 1, pp. 36–45.

VENKATARAMA REDDY, B.V., RICHARDSON LAL, NANJUNDA RAO, K. S., 2007. Enhancing bond strength and characteristics of soil-cement block masonry. *Journal of Materials in Civil Engineering*, Vol. 19, No. 2, pp. 164-172.

VENU MADHAVA RAO, K., Venkatarama Reddy, B.V., Jagadish, K. S., 1995. Influence of flexural bond strength on the compressive strength of masonry. *Proceedings of the National Conference on Civil Engineering Materials and Structures*, Osmania University, Hyderabad, India, 103–108.

VENU MADHAVA RAO, K., VENKATARAMA REDDY, B.V., JAGADISH, K.S., 1996. Flexural bond strength of masonry using various blocks and mortars. *Materials and Structures*, Vol. 29, pp. 119-124.

VICAT, L.J., 1837 (re-printed in 1997). *Mortars and Cements*. Shaftesbury, Donhead Publishing Ltd.

VITRUVIUS, P., 1914 (new ed. 2001). *The ten books of Architecture (25 BC)*. Cambridge University Press.

WALKER, P., 1999. Bond characteristics of earth block masonry. *Journal of Materials in Civil Engineering*, Vol. 11, Issue 3, pp. 249–256.

WILSON M.A., CARTER, M.A., HOFF, W.D., 1999. British Standard and RILEM water absorption tests: A critical evaluation. *Materials and Structures*, Vol. 32, No. 8, pp. 571-578.

WINGATE, M., 2003. An Introduction to Building Limes, Information Sheet 9, *Society for the Protection of Ancient Buildings (SPAB)*, London, England.

YUEN, C. AND LISSEL, S., 2009. Clay brick properties and their effects on flexural bond strength in masonry – A summary. *Masonry Research, The Masonry Society*. Jan. 2009, Vol. 1, Issue 1, pp. 1.

Appendix 1 Dissemination

Some of this study has been published, as listed below:

Zhou, Z., Walker, P., D'Ayala, D., 2008, Flexural bond strength development of brickwork using natural hydraulic lime (NHL) mortar, *In*: *14th International Brick & Block Masonry Conference*, 17-20 February 2008, Sydney, Australia

Zhou, Z., Walker, P., D'Ayala, D., Strength characteristics of hydraulic lime mortared brickwork (2008), *Proceedings of Institution of Civil Engineers, Construction Materials*, 161 (4), pp. 139-146

Zhou, Z., Walker, P., D'Ayala, D., Influence of materials on mortar and bond strength of hydraulic lime mortared brickwork (2008), *In*: *Proceedings of the 8th International Seminar on Structural Masonry (ISSM08)*, 5-8 November 2008, Istanbul, Turkey. Istanbul Technical University, pp. 89-95

The journal paper is reprinted below.