Assessment of Masonry Flexural Bond Strength

By

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Abstract

This thesis presents the results of an experimental assessment of masonry flexural bond strength. Since there is insufficient experimental data on key performance requirements for bond between units and mortar, investigations into the development of bond and flexural strength across a range of masonry units for both traditional and new mortar types, reflecting the recent changes in European standards, were conducted.

In order to demonstrate the performance of bond between unit and mortar, the latter ranging from weak to strong, a practical bond wrench testing rig was developed for use with couplets and stack bonded prisms. This involved carrying out investigations into existing designs and revaluations using up to date modelling techniques. The result is a new bond wrench applicable for use in laboratories and on site.

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Contents Page

List of Figures

List of Tables

List of Abbreviations

A_s	Gross area of the face of the specimen immersed in water - mm^2
AAC	Autoclaved Aerated Concrete
ASTM	American Standard Technical Measurement
BRE	British Research Establishment
BS	British Standard
$c_{w,s}$	Coefficient of water absorption due to capillary action - $g/(m^2xs0.5)$
$c_{wt,s}$	Initial rate of water absorption for clay masonry units - $kg/(m^2xmin)$
COV	Coefficient of Variation
CWA	Coefficient of Water Absorption
EC	Euro Code
EDU	Electronic Display Unit
EN	European Norm
HD	High Density
IRA	Initial Rate of Absorption
KUBW	Kingston University Bond Wrench
LD	Low Density
$m_{so,s}$	mass of the specimen in grams after soaking for time t - g
$m_{dry,s}$	mass of the specimen after drying - g
MC	Master Crete
M_W	Wet Mass
NHL	Natural Hydraulic Lime
NPL	National Physics Laboratory
OPC	Ordinary Portland Cement
PCL	Portland Cement Lime
prEN	Preliminary European Norm
STDEV	Standard Deviation
t_{so}	time of soaking – seconds
TLM	Thin Layer Mortar
Φ_{ULT}	Ultimate Creep Coefficient

1. Introduction

The flexural strength of masonry is defined as the strength of masonry in bending (EN1996-1); forming, the underlying criteria in the design of walls, to resist lateral loading such as wind, earth or explosives.

Historically, the flexural resistance of unreinforced masonry is determined in the UK by wallette testing in accordance with Appendix A.3 of BS 5628-1:1998. Currently in coexistence with, and eventually to be superseded by EN1052-2:1999 (part of Eurocode 6) by 2010, it employs a similar method with different predictive characteristic criteria.

The European Committee for Standardisation, since 1980, has been the driving force in the move towards the normalisation of standards and specifications between European states. Eurocode 6 deals with the design of masonry structures and part one (EN1996-1) provides general rules for reinforced and unreinforced masonry.

In the early days, the design criterion for walls resisting lateral loads was stability rather than the flexural strength of masonry. Since, old masonry structures do not necessarily conform to current standards of materials or construction; an understanding of how modern materials used for the repair of these structures is essential in preserving a sustainable heritage.

A simple test method for accurately determining the flexural strength of masonry at right angles to the bed joint has been formalised as of 2005. The Bond Wrench test described in EN 1052-5 has been incorporated into Eurocode 6.

The principal areas of investigation are concerned with the following:

- Bond Wrench Designs
  (Chapter 3),
- Comparison of Bond Wrench Couplets with B Wallettes and Mortar properties
  (Chapter 6),
- Observations for Natural Hydraulic Lime and Thin Layer Mortar masonry structures (Chapter 7)

1.1 Essential terms for the thesis

Throughout the thesis, technical terms are explained on first occurrence, either explicitly, or by context. However, a number of elementary terms merit definition, or explanation, at the outset.

Flexural strength of wallettes is tested using a flexural testing rig and calculated using the formulae given in BS5628-1:1992; taking into account the load at failure. This principle applies to tests for strength parallel to the bed joint (B wallette) and perpendicular to the bed joint (P wallette).

Flexural bond strength of a couplet is tested using a bond wrench and calculated using the formula given in EN1052-5:2005; taking into account the geometric configuration of the wrench and the load at failure.

For the purpose of this thesis the mortars will have the following abbreviations:

- Natural Hydraulic Lime = NHL
- Ordinary Portland Cement = OPC
- Thin Layer Mortar = TLM

The brick and block units were provided by "Hanson" and "HH Celcon" and will be referred to in the thesis as:

- "Hanson" – "Smooth Red" - Clay = Red
- "Hanson" – "Melford Yellow" - Clay = Yellow
- "Hanson" – Concrete = Concrete
- "HH Celcon" – Autoclaved Aerated Concrete = Aircrete

The work size of the units was 215 x 102.5 x 65 mm (l x w x h). This is the most common size for clay bricks, whilst, Aircrete blocks have most commonly a work face dimensions of 440 or 620 mm long by 215 mm; in a range of thickness from 60 mm to 355 mm.

The sand was purchased from "Jewson" and "Travis Perkins" and will be referred to in the thesis as:

- "Jewson" – Soft Building Sand = Soft Sand
- "Jewson" – Sharp Sand = Sharp Sand
- "Travis Perkins" – Leighton Buzzard (sharp) = Leighton Buzzard

1.2 Aspects for Investigation

The thesis in the following chapters has been organized as follows:

Chapter 2 sets the research results of this investigation in their proper historical context; that of the development of ideas about testing masonry flexural strength, with particular attention to wallette and bond wrench testing. A review of the bond wrench test technique appears redundant in the light of the thorough account by McGinley (1994) and the later accounts which bring the subject up to date, notably by Van Der Pluijm and Vermeltfoot (1995), and more recently Samarasinghe et al (1999).

Geometrically and physically the properties of the bond wrench test vary depending on the laboratory. Chapter 3 provides a critical analysis with reference to other published work of the different designs; which then informed the development of the new bond wrench.

Testing procedures have a bearing on the results that are obtained, and the test procedures used in this research, and used or recommended by other workers, are technically discussed in Chapter 4.

The first body of results is presented in Chapter 5. The constituent materials of masonry are both introduced and analysed, whilst, a brief overview is given of the age effects in mortar, wallettes and bond wrench couplets

Chapter 6 builds upon the results, analysing the mortar properties and the comparisons of the Reutt wrench to wallette tests. Variability and statistical significance in the correlation of the different test data is investigated.

Chapters 7 summarises the work as a whole, and points to resulting technical issues regarding the testing of masonry flexural bond strength that require further attention.

1.3 Objectives

The principle areas of investigation are concerned with the following:

1. To evaluate the bond and flexural strength between unit and mortar for natural hydraulic lime, Portland cement and thin layer mortars with a range of units including clay, concrete and Aircrete brick sized units; at various ages in accordance with relevant European standards.

2. To evaluate the compressive, flexural and direct tensile strength of natural hydraulic lime, Portland cement and thin layer mortars at a range of ages in accordance with relevant European standards.

3. To develop a practical bond wrench for testing couplets manufactured with a range of weak and strong mortars

4. To evaluate the variability of masonry tested to determine its bond and flexural strength and constructed using natural hydraulic lime, Portland cement and thin layer mortars in combination with clay bricks, concrete bricks and Aircrete bricks.

5. To evaluate the variability of the compressive, flexural and direct tensile strength of natural hydraulic lime, Portland cement and thin layer mortar.

This thesis sets out to investigate and resolve a number of technical issues relating to development of bond and flexural strength across a range of masonry units for both traditional and new mortar types reflecting the recent changes in standard. The testing programme used four different units and three mortar types which enabled experimental and theoretical comparisons between the above evaluations.

2. Overview of Masonry Construction

The need for the Construction Industry to be more environmentally friendly and sustainable is becoming increasingly evident and necessary to the ongoing prosperity of the sector.

The Earth Summit (1992) set worldwide targets for the reduction in use of fossil fuels and laid down objectives for more sustainable development. As a result the advantages of existing materials have been investigated to determine how to improve their use. Roberts (1998) stated that Government Standards and Planning as well as Industry self regulation would have to work together to develop policies to promote sustainable masonry construction, and these policies would need to reflect the outcomes of research. Masonry had been identified for its significant capability to retain the heat in buildings; this can partly be attributed to the development of cavity walls. The use of Portland cement in mortar facilitated this concept by minimising water penetration and dampness in buildings. Pettit and Robinson (2001) stated that the thermal performance of masonry can be significant in terms of contributing in degrees, varying from minor to major, to the insulation requirements of the building envelope.

The use of Silo's (Figure 2/a) for the transportation and site mixing of mortar to exact ratios has become the norm on larger building sites. Silos have two large internal chambers containing sand and cement. At the base there is a device seen in Figure 2/b, which, mixes the predetermined ratio of sand and cement, with the use of a cork screw mixer and automatic addition of water, the same consistency and properties of mortar are produced at the flick of a switch.

In the late 1990's Roberts (1998) enunciated the requirement that all the very positive aspects that masonry construction offers, be properly articulated and gaps in our knowledge filled and in doing so attempted to justify the requirement for continued investment in masonry research by explaining the necessity for informed decisions for sustainable masonry construction. Roberts (1998) explains that many aspects relevant to developing a comprehensive approach to sustainable masonry construction were at the time under investigation and would soon provide comparative data.

Figure 2.1 – Silos on a building site in Belgium

Figure 2.2 – Silos mixing unit

In addition Roberts (1998) concluded the approaches being adopted need to be informed by the extensive base of research, testing and experience relating to masonry which should be made readily available. In contrast to Roberts's optimism Sissons (1998) in the same year concluded that in light of present public perceptions "if someone was offered a brand new product that used commonly available materials and not scarce petrochemicals, a product that was sound-resistant, fire-proof, had permanent natural colours; a product which could be site adjusted to all of the tolerances of the preceding trades and idiosyncrasy of the design; no one would believe that such a product is possible". Clearly, masonry has all those qualities. Sissons concluded cynically that the success or failure of brickwork in the 21st century will depend on whether the marketing departments of the brick companies can convince a distracted and techno orientated public that the product that has lasted for over a thousand years is still the best product for the exterior of a building. Sisson sums up this rather premature pre-obituary to masonry as "The future of brick is at best flat, at worse declining".

Underlying all of these issues is the requirement to balance cost against environment concerns. Hendry (2001/2) identifies a number of ways in which current practice in masonry construction in the UK could improve economy, productivity and construction times. He uses case studies to illustrate the problems facing the masonry construction industry although unlike Sissons (1998) he does envisage improvements. Nevertheless he advises caution, noting that if the cost/environmental factors are not resolved, there will be a continued decline and replacement of masonry by newer, but probably not better, materials. In doing so Hendry reinforces Roberts (1998) justification for investment in research.

Research carried out by the British Geological Survey (2005), detailed in the Figure 2.3, shows the production of bricks by type in the UK from 1974 to 2005. The decline in the production of clay bricks is inline with the demand for 'brick clay' falling from over 16 million tonnes in 1974 to some 7.7 million tonnes in 2005. However this is mainly due to the demise of 'common' bricks frequently used for the internal walls. They have been replaced in the inner leaves of cavity walls in houses by concrete blocks and in internal walls by blocks and plasterboard. As shown in the figure below. The production by type shows the output of facing and engineering bricks to have remained fairly static in recent years.

The current market boasts 94% of all bricks to be clay-based and the remainder being principally concrete bricks. The current levels of production of clay bricks has been just less than 3000 million a year during the past decade.

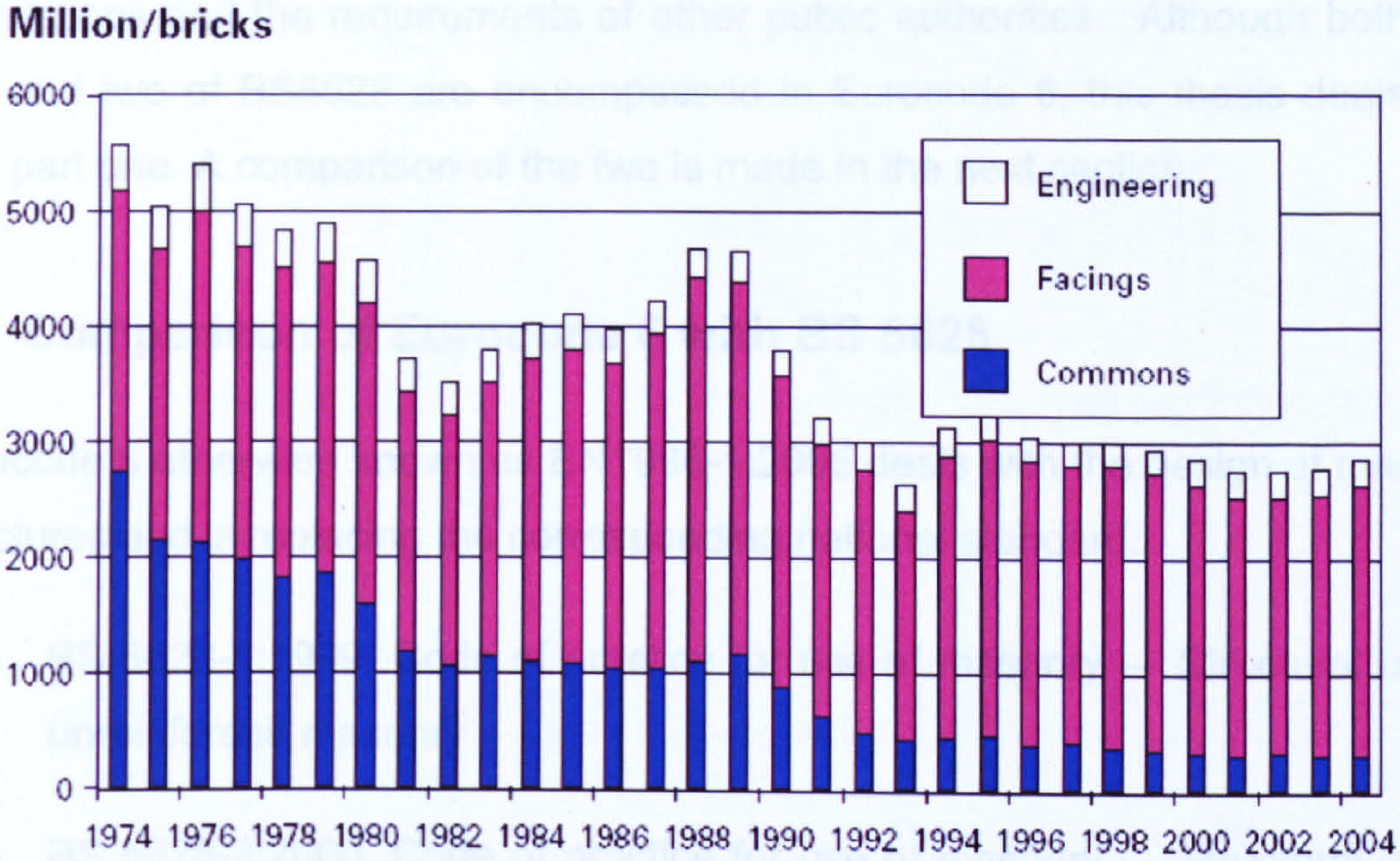


Figure 2.3 – Great Britain: Production of Bricks by type - 1974-2005
Source: DTI Monthly Statistics of Building Materials and Components

Figure 2.3 verifies Sissons' (1998) prediction of the downturn in brick sales seen in 2000/2001 and following improvements in research facilitating better building products and techniques mentioned by Roberts (1998) and Hendry (2001/2), the brick sector looks like it is making a comeback. Only time will tell the full story.

Hogg (2003) investigated the feasibility of prefabrication of brick walls using thin layer mortar. Vekemans and Ruben (2002) noted that Architects and Contractors usually instigated enquiries into using prefabricated elements. With the increasing interest, demand for such technologies was likely to increase in the near future. Therefore they concluded that more development into products integral to prefabrication was required. Analogous to Roberts (1998) although in a slightly different area, Vekemans and Ruben again imply the requirement for more research. Hogg (2003), further states that standards need to encompass the design of prefabricated brick panels, since the current BS 5628-1 code does not.

Eurocode 6 is part of the suite of European codes for structural design that have been developed over a period of more than twenty-five years. In 2005 it was published, as British Standards, initially as an alternative to the existing Standards. By 2010 it will replace the current BS5628 Part 1 & 2 as the primary basis for designing masonry buildings and structures in the UK. It is also likely to be used as an acceptable basis for meeting compliance with UK Building

Regulations and the requirements of other public authorities. Although both part one and two of BS5628 are encompassed in Eurocode 6, this thesis deals with only part one. A comparison of the two is made in the next section.

2.1 Comparison of Eurocode 6 with BS 5628

Eurocode 6 otherwise known as EN1996-1:2005 deals with the design of masonry structures and is replacing the corresponding national standard:

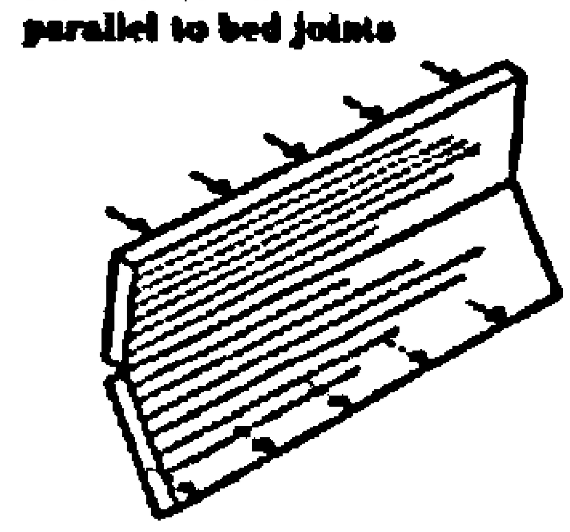
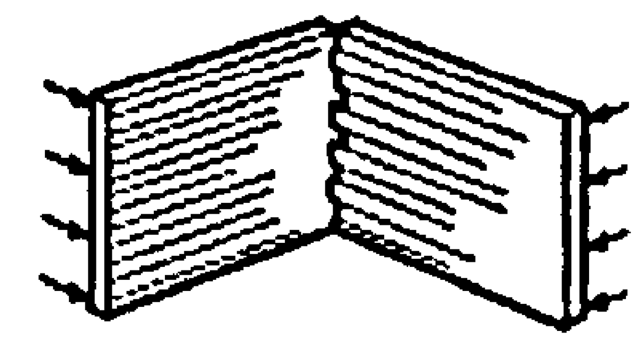
- BS 5628-1:1999, Code of practice for use of masonry — Structural use of unreinforced masonry
- BS 5628-2:2000, Code of practice for use of masonry — Structural use of reinforced and prestressed masonry

Following publication, a five year period exists for the national calibration and annexes to be issued, followed by a three year coexistence period. At the end of this coexistence period, the national standard is withdrawn.

Following comments by Arora (1991), it was concluded that previous draft Eurocode 6 (EC6) versions were not acceptable to the UK construction industry, primarily because masonry structures designed to EC6 are significantly less economical than similar structures designed to current UK practice.

Currently, Table 3 of BS 5628-1 gives values for characteristic flexural strength of failure parallel and perpendicular to the bed joint. Shown in Table 2.1/a, depending on the water absorption and mortar designation, the suggested characteristic flexural strength can be derived.

Table 3 — Characteristic flexural strength of masonry, f_{kx}, in N/mm²

	Plane of failure parallel to bed joints 			Plane of failure perpendicular to bed joints 		
Mortar designation	(i)	(ii) and (iii)	(iv)	(i)	(ii) and (iii)	(iv)
Clay bricks having a water absorption						
less than 7 %	0.7	0.5	0.4	2.0	1.5	1.2
between 7 % and 12 %	0.5	0.4	0.35	1.5	1.1	1.0
over 12 %	0.4	0.3	0.25	1.1	0.9	0.8
Calcium silicate bricks	0.3		0.2	0.9		0.6
Concrete bricks	0.3		0.2	0.9		0.6
Concrete blocks (solid or hollow) of compressive strength in N/mm²:						
2.8 } used in walls of thickness[a] up to 100 mm	0.25		0.2	0.40		0.4
3.5				0.45		0.4
7.0				0.60		0.5
2.8 } used in walls of thickness[a] 250 mm	0.15		0.1	0.25		0.2
3.5				0.25		0.2
7.0				0.35		0.3
10.5 } used in walls of any thickness[a]	0.25		0.2	0.75		0.6
14.0 and over				0.90[b]		0.7

[a] The thickness should be taken to be the thickness of the wall, for a single-leaf wall, or the thickness of the leaf, for a cavity wall.
[b] When used with flexural strength in parallel direction, assume the orthogonal ratio $\mu = 0.3$.

Table 2.1.1 – BS 5628 – "Table 3"

With reference to BS5628 and BS4721 the mortar designation classes has changed in relation to EN998-2. In comparison what would have been classed as a designation (iii) mix is referred to as an M4 mortar. Table 2.1.1 gives the mix ratio for the designation mortar in accordance with BS5628, whilst, Table 2.1.2 gives the conversion. An M12 mortar is the strongest whilst, M2 is the weakest.

Table 1 — Requirements for mortar

	Mortar designation	Type of mortar (proportion by volume): Cement : lime : sand	Masonry cement : sand	Cement : sand with plasticizer	Mean compressive strength at 28 days: Preliminary (laboratory) tests N/mm²	Site tests N/mm²
↑ Increasing strength / Increasing ability to accommodate movement, e.g. due to settlement, temperature and moisture changes ↓	(i)	1 : 0 to ¼ : 3	—	—	16.0	11.0
	(ii)	1 : ½ : 4 to 4½	1 : 2½ to 3½	1 : 3 to 4	6.5	4.5
	(iii)	1 : 1 : 5 to 6	1 : 4 to 5	1 : 5 to 6	3.6	2.5
	(iv)	1 : 2 : 8 to 9	1 : 5½ to 6½	1 : 7 to 8	1.5	1.0
Direction of change in properties is shown by the arrows		Increasing resistance to frost attack during construction → ; ← Improvement in bond and consequent resistance to rain penetration				

Table 2.1.2 – BS5628 – Mortar designations

Table NA.1 — Mortar mix designation

BS 4721:1981 – Mix designation[a]	EN 998-2:2003 – Mortar class
(i)	12
(ii)	6
(iii)	4
(iv)	2
[a] This designation is also used in BS 5628.	

Table 2.1.3 – EN998-2 – Equivalent Mortar designations for new Mortar Class

2.2 Properties of mortar

Until about 1840 when ordinary Portland cement (OPC) was developed, lime was exclusively used in mortars for all masonry buildings.

Some of the benefits of lime mortars are that they allow walls to breathe, are relatively flexible (accommodating some movement), give some protection to surrounding brick and stone against salt and frost damage, 'self-heal' when exposed to air, and allow brick and stone to be reclaimed after demolition.

It is now enjoying a revival and is being promoted by conservation organisations for restoration work and by environmentalists as an environmentally friendly material. Lime mortar can be used for new build as well as for restoration and conservation work. De Vekey (2005)

For each situation, mortar is required to attain certain properties. These can be obtained by changing the constituents and mix ratios. Within the testing program the properties of three mortar types; and their interaction with building units were examined.

From a sustainable, environmentally conscientious point of view Lime is a better option when compared to Portland cement. Pritchett (2003) explains that during the manufacturing process more energy is required to produce a tonne of cement than a tonne of hydraulic lime, thereby increasing CO_2 emissions. The bulk density of lime is half that of cement, thus, there is an overall energy saving of between 30-50% when using lime. In addition, as lime carbonates whilst Portland cement hydrates, further reductions in CO_2 levels will result. Pritchett points out that, decisions need to be made now; because millions of homes will need to be built over the coming decades. The physical properties of lime and its ability to bond to units will also have an impact on decisions.

Binda et al (1988) established the complexity of ductile masonry behaviour indicating how difficult it is to analyse mathematically and hence the importance of test results. Using experimental findings Galimberti et al (2002) evaluated the performance of a mortar based on a new masonry cement; (Adasonrv) conforming to prEN 413-1 type MC12.5. This was then compared with mortars formed using a Portland cement and a cement/hydraulic lime compound. They found that it had a longer period of workability than its older counterparts. It was also less absorbent; therefore having the advantage of being more rain resilient. These comparative tests were on wall samples made with perforated bricks. They used three types of mortar compressive strengths and rheological properties. This was achieved by using the same sand but different binder contents. The work, according to Jackson (1995), supported the recommendations given in BRE Digest 362. This was especially true in regarding the requirement for the production of a mortar;

- with a good level of durability
- Able to withstand severe freezing and thawing conditions.

2.2.1 Portland cement mortar

The suggestion made by Jackson (1995) that the durability can be improved under conditions of combined freeze-thaw and sulphate attack. By maintaining the tricalcium aluminate (C_3A) component in the Portland cement below 9%. Flexural bond strength of masonry built using traditional Portland cement-lime mortars was found by Schuller and Thomson (1998) to be greater than the bond strength when lime-replacement mortars were used. The mortar / unit interface investigations by Schuller and Thomson found concrete brick specimens had greater bond strengths than clay brick specimens although interestingly bond strengths measured for concrete brick specimens had less within-test variability than bond strengths measured for clay brick specimens.

Investigations by Bingel et al (2002) into the creep and moisture movement behaviour of clay brickwork panels built with a 1:3 (by volume) natural hydraulic lime: sand mortar and a 1:2:9 (by volume) cement (OPC): hydrated lime: sand mortar revealed that the 28 day site requirements according to BS5628-1:1992 for compressive strength was not achieved by the 1:3 hydraulic lime mortar although the 1:2:9 cement mortar did comply when mortar cubes were tested.

Analogously, Canziani et al (1998) found that, a mortar obtained by replacing cement with 30% of hydrated lime shows a satisfactory level of workability and acceptable mechanical performance; moreover, since hydrated lime reacts with carbon dioxide in the air and hardens as time goes by, this type of mortar increases in strength in the long run even if strength reductions occur in the short term.

Goodwin and Saunders (1988) observed that the method of lime preparation during wall manufacture is critical to the flexural strength. Matthys (1988) concluded that the flexural bond strength of Portland Cement Lime (PCL) mortars is greater than that of Masonry Cement (MC) mortars. Based upon the conditions of materials, construction, testing, and evaluation in this study the data appears to support the conclusion that the flexural bond strength of similarly proportioned MC and PCL mortars are not equivalent. Potential inaccuracies were noted by Goodwin and Saunders (1988) to be associated with lime batching, treatment of bricks, strength increase with age, the number of courses above the joint tested and problems with replication of tests. Some correlation between binder amount and mortar strength was observed: increased binder content increases flexural strength but within limits. Binder amounts in excess of 2:1 (by volume) have shown a strength reduction according to Lanas, and Alvarez-Galindo (2003) who observed the maximum strength to be related to the presence of a certain amount of uncarbonated portlandite. The use of angular limestone as a binder, the lack of discontinuity between the binder matrix and aggregate of the same nature which improves strength, as well as good packing of aggregate with angular edges. They also noted that limestone aggregates show medium and large radius pores that allow carbonation, avoiding stress during drying and the crystallization process and consequently enhancing bond.

Bingel et al (2002) do question the suitability of the mortar cube testing procedure as the exposed surfaces of the brickwork joints appeared stiffer than the equivalent mortar of the test cubes. In terms of creep Bingel et al discovered that after 600 days under load, creep of the hydraulic lime mortar brickwork in the header face direction was similar to that of the brickwork built with the cement mortar, although after 150 days loading, creep of the cement mortar brickwork in the bed face direction was approximately twice that found in the header face direction whereas the hydraulic lime mortar brickwork creep in the bed face direction was less than in the header direction, and only 46% of that in the brickwork with cement mortar. Overall Bingel et al concluded that the predicted values of ultimate creep coefficient Φ_{ult} for the two types of brickwork tested varied between 0.57 and 1.20 and, as such, were within BS5628 guidelines.

2.2.2 Thin layer mortar

Fudge (2000) commented that the thin joint technology has been slow to take off in the UK although it is anticipated that more future use will occur if construction speed is seen to be the driver and experience outside the UK indicates using thin joints to be advantageous. In the Netherlands and Belgium, masonry built using thin layer mortar is used more frequently. Martens (2002) studied veneer walls constructed with thin layer mortar and describes using thin layer mortar to form lintels in these walls. Indeed, he proposes a design method for such lintels, and presents the results of limited tests on clay brickwork to verify it. His paper includes investigations into the long term behaviour and shear capacity of thin layer mortar masonry. This will undoubtedly be watched by the UK as Fudge (2000) predicts the use of solid wall, rather than cavity wall construction for the shell of the building finished with sprayed thin coat plasters and renders.

Thin Layer Mortar (TLM) is factory made and usually comprises of a 1:2 mix of cement and sand, together with water retaining agents and other ingredients. Stupart (1996) reports that the compressive strength of blockwork masonry built using TLM with a different construction process and large blocks is higher than equivalent traditional masonry. Flexural strength is at least comparable although it is likely that there will be greater shrinkage than with traditional mortar but this is not expected to cause problems of blockwork cracking.

2.2.3 Lime mortar

Lime mortars are broken down into the following designation types by EN 459-1:2001:

Designation	Notation
Calcium lime 90	CL 90
Calcium lime 80	CL 80
Calcium lime 70	CL 70
Dolomitic limes 85	DL 85
Dolomitic limes 80	DL 80
Hydraulic lime 2	HL 2
Hydraulic lime 3,5	HL 3,5
Hydraulic lime 5	HL 5
Natural hydraulic lime 2	NHL 2
Natural hydraulic lime 3,5	NHL 3,5
Natural hydraulic lime 5	NHL 5
• In addition, air limes are classified according to their conditions of delivery, quicklime (Q) or hydrated lime (S). In the particular case of hydrated dolomitic limes, the degree of hydration is identified S1: semi hydrated; S2: completely hydrated.	

Table 2.2 – Types of building limes – Table 1 in EN 459-1

Many of these types can be blended to produce 'hybrid' mortars with intermediate properties. Following a consultation session

Procter (2001) highlighted the major disadvantage of hydraulic mortar due to the cost at up to five times that of hydrated lime mortars; although differences in labour costs are insignificant. The cheaper lime mortar option has problems, these being the complexity of lime mortar and the fact that lime mortar is less forgiving of poor construction practices so requiring good quality control and site supervision. Failure to correctly apply and cure lime mortar can result shrinkage and cracking and finally many of the techniques for producing and applying traditional lime mortars have been lost and need to be relearned.

Australian Site Advice as reported by Guirguis (2003) recommends the simplest way to batch mortar accurately is to use a mixer of known volume. After placing the required volume of cement and lime into the mixer it can then be filled with sand plus a suitable quantity of water with the latter volume dictating the workability requirements which will in turn affect bond strength. Guirguis also advises caution at placement of bricks as this can result in a lower bond strength.

2.3 Types and properties of units

A major advantage of brick units is that with their many hues and patterns they can be used to create aesthetically pleasing patterns and designs not offered by other construction materials such as concrete and steel.

Brick clays are essentially sedimentary mudstones of different geological ages and compositions. These range from relatively soft, plastic clays to hard mudstones. Concrete aggregates as the name implies is made up from crushed aggregates formed into brick sized units.

The constituents and process of manufacturing a building unit designates its type and character. With regard to the nature of the brick surface, Ribar and Dubovoy (1989) using a surface profilometer concluded that the fineness of the surface does indeed affect bond strength.

2.3.1 Clay units - BS EN 771-1: 2003

Clay units are the most common type currently in use within the construction industry. They are made of fired clay; the method of forming

- Moulding – these are frogged
- Extruding – these are perforated

The frog in a brick arose from the moulding techniques that were used in the manufacture of bricks. The following pictures show a man in the process of throwing unfired brick clay into a mould. This mould is shown in the following two pictures. The rectangular pyramid type shape on the bottom of the mould is what forms the frog. It serves as a purpose to push the clay into the furthest corners in the bottom. This gives a defined square edge to the bricks. If the frog were not present the clay would not be forced into the corners of the mould and the brick would have one square edge and one rounded.

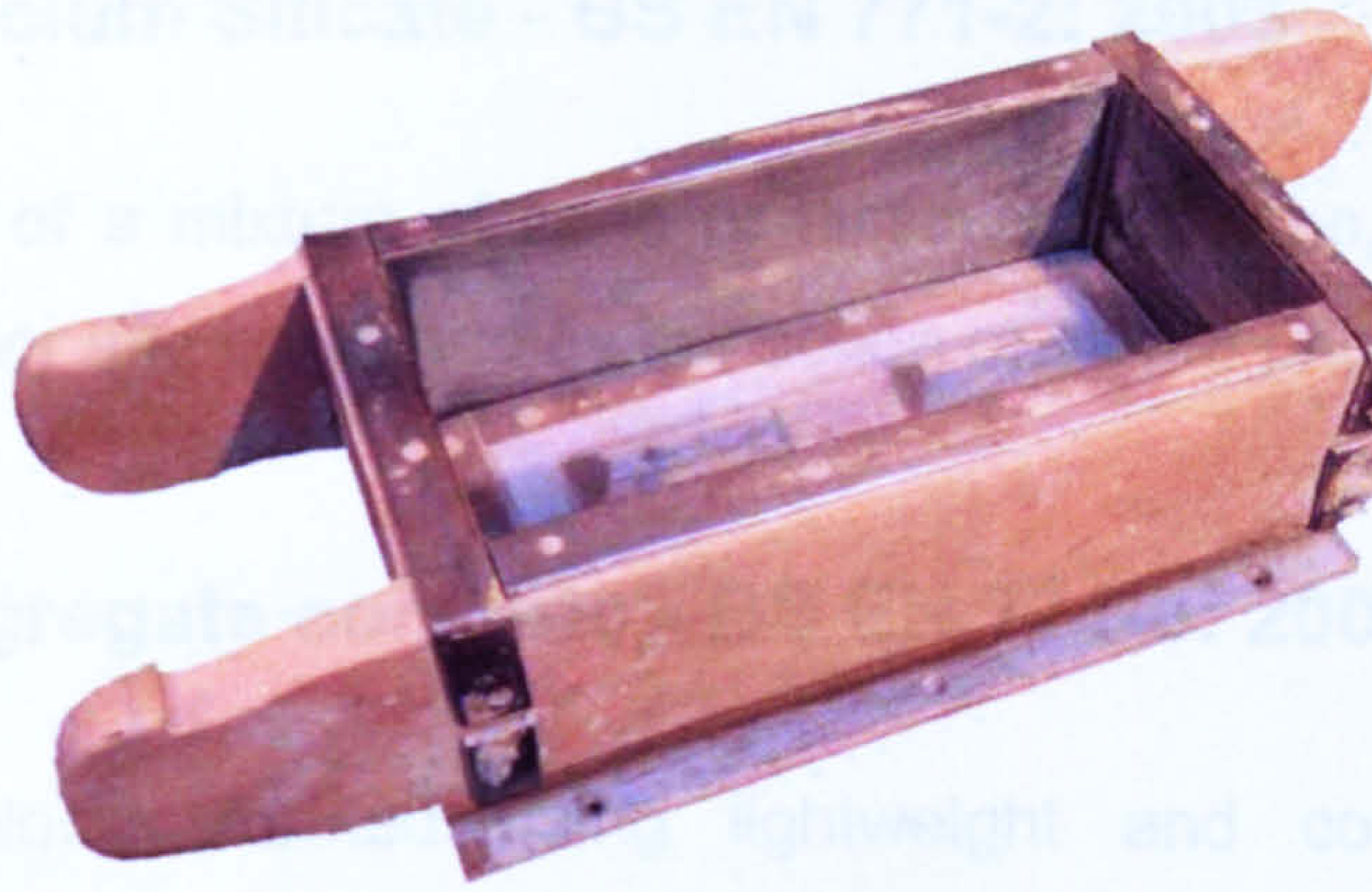


Figure 2.3.1.1 – Brick mould used by brick maker

Figure 2.3.1.2 – Brick mould disassembled and showing the frog

Most bricks are made to a standard size (65×102.5×215mm) although non-standard sizes can be made. The appearance and strength of clay masonry are considerably influenced by the properties of the original clay which used.

The following varieties of clay bricks are available:

1) Facing bricks: Specially made to give attractive appearance when used without rendering or other surface treatment of the wall.
2) Stock bricks. These have similar properties to facing bricks but do not have a special face.
3) Engineering bricks: May not look too good, but have a minimum guaranteed compressive strength.

2.3.2 Calcium Silicate - BS EN 771-2: 2003

These consist of a mixture of sand or flint mix with lime, which is mechanically pressed together and combined by the action of steam under pressure.

2.3.3 Aggregate concrete - BS EN 771-3: 2003

Bricks and blocks formed using lightweight and concrete aggregate are manufactured from pressed, cast or extruded aggregate concrete. They are available in solid or hollow rectangular prisms. Special lightweight aggregates are often used to improve insulation properties.

2.3.4 Aircrete (AAC) - BS EN 771-4: 2003

Aircrete is a low density material made principally from a formed, fine-grained siliceous material bonded together with calcium silicate. Aircrete masonry units are generally manufactured as solid rectangular prisms usually in the form of blocks 215mm high, between 50 and 350mm thick and between 440 and 630mm long. Their principal advantage is excellent insulating properties.

2.3.5 Dimensions - BS EN 772-16: 2000

A sign of the close link between society and masonry is that the brick has traditionally been small enough to be carried in one hand. However it has been necessary in modern times to provide a firmer definition for the dimensions of bricks. British standards have set precise guidelines for brick dimensions. It has also been divided into two categories – Work Size and Coordinating Size. Work size is the size of the actual brick itself; Length 215mm, Height 65mm, and width is 102.5mm. Coordinating size has 10mm added to help estimate for a standard mortar joint.

Depending on which country even within the European Union the bricks are manufactured, regional sizes are also available. The European brick is longer and shallower in comparison to availability in the UK.

According to BS 3921 the following dimension tolerances are permissible:

Over 24 bricks laid out the maximum allowed deviations are:

24 stretchers touching (24 x 215 mm)	=	5160 ± 75 mm
24 headers touching (24 x 102.5 mm)	=	2460 ± 45 mm
24 bricks on edge (24 x 65 mm)	=	1560 ± 45 mm

2.3.6 Density – BS EN 772-13:2000

The thermal properties of a masonry wall are significantly affected by the density of the brick rather than the type. Purkiss (1996) writes that most significant material property characterising the fire performance of masonry is the density. Brick units having the capability of withstanding high temperatures is yet another parameter where the density plays a major part.

2.3.7 Initial rate of absorption – EN 772-11:2000

The absorption of fluid by a rigid porous material may be characterized by the sorptivity. In masonry term this is known as the initial rate of absorption or also known as brick suction.

The laboratory measured initial rate of absorption (IRA) of brick indicates the brick's suction and whether it should be wetted prior to use. However, it is the actual suction at the time of laying which influences bond strength. Therefore it is true that in practically all cases; mortar bonds best attach to brick whose suctions are less than 30 g/min/30in^2 (1.55 kg/m^2/min) when they are originally laid. If the brick's suction is greater than the above stated figure; then the brick should be wetted three to twenty-four hours prior to laying. However the wetted brick should be surface dry before they are laid in mortar.

As the above is written it would be easy to assume it was straight forward. However; several researchers have shown that IRA appears to have little actual influence on bond strength. They have shown that the bond between brick and mortar is largely influenced by the contest of attraction between the capacity of the brick to absorb water and the ability of the mortar to retain the water. This water within the mortar is needed for the proper hydration of cement where the mortar contacts the brick; and is part of the bond structure.

If the brick wins this contest, then the mortar strung out for the bed joint stiffens so rapidly that the bricks in the next course cannot be properly bedded. If however the mortar retains too much water, then bricks tend to float on the mortar bed. This then makes it difficult to lay plumb walls at a reasonable rate. In either case there will be poor bond and therefore structural inconsistencies.

The power of a brick to absorb water is measured by the initial rate of absorption. Low suction bricks need a leaner mortar to give good bond. Usually this is done by increasing the proportion of washed sand in the mix. The reverse is true for high suction bricks; they require a mortar with very high water retention, making it necessary to shorten the length of the bed joint or wet the bricks to reduce their suction. It should be noted however that wetting the bricks can lead to efflorescence in the brickwork.

Experiments show that an increase of IRA from 2 $kg/m^2/min$ to 4 $kg/m^2/min$ reduces the strength of brickwork by 50%. Generally, bricks with IRA exceeding 2 $kg/m^2/min$ will give rise to difficulties in laying using common cement mortars. Th modern brick extruder with de-airing action produces denser brick with lower IRA.

2.3.8 Absorption – BS EN 771-1:2003

Fried and Songbo (1994) found that in general a reduction in the water absorption capability of units resulted in an increase in flexural strength. This of course is under the proviso that altering the water/cement ratio of the mortar, will affect this trend. They continue from this point and state that in all cases tested an increase in water absorption lead to firstly an increase and then a decrease in tensile bond strength. From this they drew the conclusion that it is within a band of 2-9% absorption that the maximum tensile bond strength occurs.

2.3.9 Aesthetical properties

Since the chemical properties of different brick clays differ due to their mineralogical composition and grain size. Their chemical properties, which are related to their mineralogical composition, and physical properties, particularly grain size, are critical to determining their suitability for the manufacture of structural clay products.

The chemical properties of brick clays differ due to their mineralogical composition and grain size which bare relevance to the forming behaviour of the clay, (the process prior to firing in which the ware is shaped), also behaviour during drying and firing, as well as the final properties of the fired product. These properties include compressive strength, water absorption, density and thus durability and performance in service. Importantly, they also affect aesthetic appearance, such as specific colours and textures.

Red bricks have their colour due to iron oxide and are produced in most parts of the UK. They are the typical colour for the Home Counties (around London). Yellow bricks include London stock bricks and are predominantly made from the brick earth and chalk found in Kent and Essex.

Different ranges of properties are achieved through the blending of different clays which as time moves on provides an ever evolving scope for research and development. The varieties of clay give rise to distinctive regional variations and appearance enabling aesthetically pleasing hues.

2.4 Factors affecting bond in masonry

According to Appa Rao (2001) the single largest factor affecting the strength of mortar is the water:cement ratio. This factor influences all mortar properties as well as the interaction between mortar and unit. Melander & Conway (1995) noted that varying the curing conditions, the unit moisture content and how the unit is bedded all altered bond strength. Masonry specimens subjected to low humidity air curing yielded relatively low bond strengths compared to those matured by moist curing or wetting specimens after fabrication. They noted, however, that bond can be enhanced even in a low humidity environment by wetting the specimens several days after fabrication. Investigations conducted by De Vitis et al (1998) indicate that mortar type, brick type, and age are all factors which significantly affect the development of bond strength in masonry which tended to increase with age for all masonry types. De Vitis et al concluded that the major influences on bond strength are the interaction of the suction of the masonry unit and the water retention characteristics of the mortar. Any available water allows the complete hydration of cement products at the mortar/unit interface and in the mortar joint itself.

Schubert (1988/2) describes the main influences on experimental mortar strength and suggested a suitable new procedure for compressive strength testing. Kasten & Eden (1995) found a link between conditioning procedures and moisture contents of calcium silicate units and the resultant compressive strength although they recommended the oven-dry test be the reference method; to calculate the apparent air-dried strength, the compressive strength is multiplied by the conversion factor of 0.8.

Sugo et al (2000) determined that the mean bond strength developed by 1:0:4 (MC) masonry cement was approximately one third of that developed by the Portland cement lime (PCL) mortar confirming the trends observed by previous investigators, although the lower bond strength of the MC mortar appears to be primarily related to the high level of entrained air and lower mix water requirements resulting from the air entrainment. The moisture content of the masonry unit, (at the time of casting), has a significant influence on the flexural bond strength. Venu Madhava Rao et al (1996) discovered there is an optimum moisture content that leads to maximum bond strength, the values for burnt brick masonry and stabilized mud block masonry being 13% and 11% respectively, for both 1:4 cement mortar and 1:1:6 (soil:cement:mortar). Unfortunately, bond strength falls very rapidly as moisture content increases beyond the optimum level.

Movement in masonry is primarily a result of serviceability problems, generally consisting of cracks which may be unsightly. Although it remains disturbing to occupiers and at worst allow damp to penetrate, these are very seldom dangerous according to Sutherland (1996). Masonry, however, is more resilient to movement than is often appreciated, although verifying this is difficult. Sutherland notes the well appreciated fact that weaker mortars produce masonry more tolerant to movement and suggests that codes of practice should recognise weaker mortars, including pure lime, for structural use.

De Vekey and Edgell (1998) discovered that any masonry which suffers from frost or sulphate damage to the mortar beds due to the use of inappropriate materials or bad detailing in relation to its exposure state; is likely to result in a decline in bond strength and eventually could become unsafe.

Long term absorption of the masonry unit was demonstrated by De Vitis et al (1998) to be a better indicator of its suction characteristics and hence it's potential interaction with the mortar and by implication, bond strength. The findings indicate improvements will result to the flexural strength. De Vitis et al (1998) found the investigations had implications for design provisions, because the 7 or 28 day flexural strength is usually used in the calculation of member capacity, being assumed equal to the final strength. They remarked that the apparent in-built conservatism, may partly explain the common perception in Australia that its Code provisions underestimate the lateral load capacity of walls. Again De Vitis et al (1988) subjected further testing on a wider range of materials to clarify this aspect. Bowler and Sharp (1998) determined that mortar durability was predominantly controlled by the mix composition including sand grading, although fine sands containing clay minerals were observed to produce less durable mortars.

Dubovoy and Ribar (1990) demonstrated that a good bond between masonry units both in test prisms and masonry wall assemblies is not dependant on type or composition, being in agreement with Bowler and Sharp (1998). This research demonstrates that regardless of type or composition, masonry cement mortars are capable of producing good bond to masonry units both in test prisms and masonry wall assemblies. Masonry cements also produce reasonably watertight, single-wythe masonry walls when proper workmanship and placing techniques are used. The findings also demonstrate that the properties of masonry units affect bond at least to the same extent as do the properties of masonry cements.

During studies by Fyfe et al (2000) on defective panels there was a good agreement between theory and experimental results when investigating increase in bed joint thickness. The influence of the variability of the thickness of bed and of panels being out of plumb or of both these defects acting simultaneously resulted in a predicted overall value of the specific partial factor of safety of 2.08.

Although many methods have been proposed over the years for measuring the tensile bond strength of masonry, the review by Jukes and Riddington (1998) demonstrated that none of them can be considered to be ideal.

As a result to the review it was found that the most favoured method internationally was the bond wrench test. The bond wrench test is a form of flexural testing and for the purpose of these tests it seems to be the easiest to perform. Since flexural tests measure the bond strength at the edge of the joint; the strength at that point may not be representative of the strength over the main area of the joint. Further to their investigations Jukes and Riddington suggest that a flexural test method should only be used when out-of-plane failure is being considered and that for in-plane failure; a direct tension test is more appropriate.

A test method to determine the flexural bond strength by bending was introduced by Khalaf (2005) where specimens are constructed from 2 bricks in a Z-shaped configuration and three-point loading induces bond failure parallel to the bed joint.

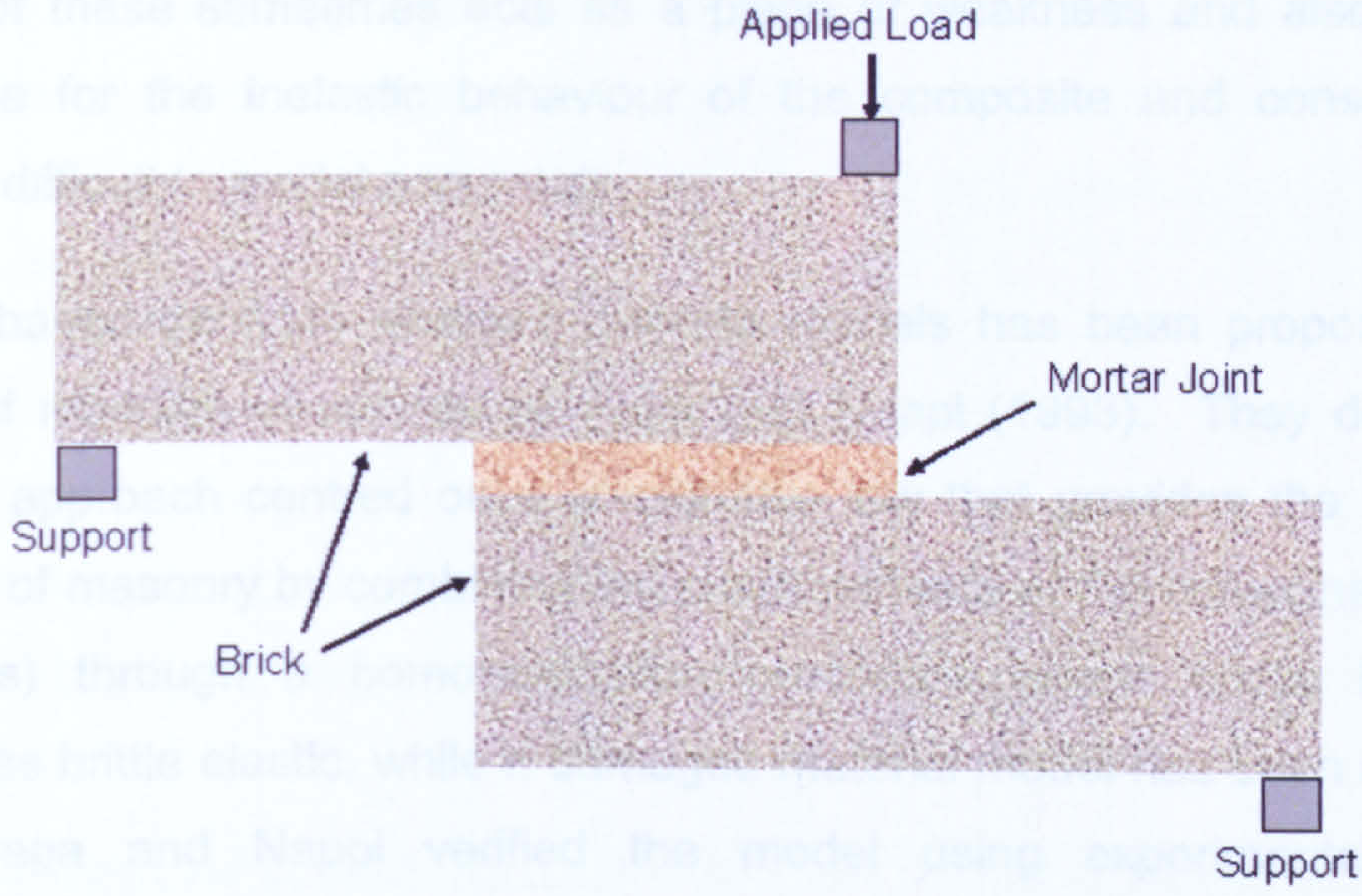


Figure 2.4 – Z shaped specimen showing point of loading

Krauklis (1992) discovered that certain procedures resulted in an increase in bond strength, namely:

- presoaking of the brick prior to laying,
- reducing lime to the minimum allowable,
- reducing the sand content,
- maximizing the fluidity of the mortar mix,
- laying the brick in running bond wallettes and then saw-cutting them into test prisms.

Lourence et al (1995) note that; developing a suitable mathematical model to enable accurate predictions of the lateral strength of masonry is difficult, especially with larger structures. Because masonry is a composite material that consists of

- units
- mortar
- interface between units and mortar

The last of these sometimes acts as a plane of weakness and also is largely, responsible for the inelastic behaviour of the composite and consequently is extremely difficult to model accurately.

A theory based on finite element discrete models has been proposed for the analysis of masonry structures by Papa and Nappi (1993). They developed a numerical approach centred on a constitutive law that provides the mechanical properties of masonry by combining the characteristics of the components (mortar and bricks) through a homogenization procedure where bricks have been assumed as brittle elastic, while a damaged material model has been adopted for mortar. Papa and Nappi verified the model using experimental tests on miniaturized panels, subjected to different plane stress states which appear to quite satisfactory correlate.

Mortars made from high strength cement perfectly obey the generalised strength water/cement ratio law as observed by Rao (2000). In essence as the water/cement ratio increases, the compressive strength development in mortars decreases. Consequently as the compressive strength increases so does the tensile strength. This was noted for specimens made at 3 and 7 days.

Schubert (1988/1) conducted investigations into methods of increasing the tensile strength of masonry and observed there were different properties which governed this property. These included increasing the tensile strength of the unit; increasing the adhesive shear strength and keeping the unit bond as large as possible.

Sise (1988) observed that many factors can affect the bond strength of masonry. His studies were undertaken on both bi and multivariate basis.. Sise concluded that joint thickness was the single most important parameter affecting bond strength; followed by three unit properties:

- modulus of rupture,
- moisture content before laying and
- absorption.

Sise (1998) did however mention that the dependency on the modulus of rupture and the other unit properties may reflect some other more fundamental parameter such as porosity and/or pore size distribution of the unit and foresaw the necessity for further research in this area.

Structural reliabilities were most affected by wall width, workmanship and discretising of masonry unit thickness. Stewart and Lawrence (2002) using a structural reliability model observed that the reliability indices for masonry walls are comparable to, although somewhat higher than, for other structural materials.

2.5 Effect of bricks and mortars on flexural bond strength

Ghosh, S.K. (1991), in reviewing previous works carried out with regards to the observed bond strengths in masonry, noted that in one report carried out by Construction Technology Laboratories based in Illinois USA noted that the bond strengths were lower with masonry cement mortars than for masonry with Portland lime-cement mortars only when certain types (Type M or S) of mortar were used but that this trend did not hold true when type N mortar was used.

Further reports were carried out by CTL and, in reviewing the first of these, Ghosh noted that in many cases the bond strengths were greatest when Type N Mortar was used when compared to Type S and, whilst an attempt was made to correlate this to various factors (including mortar water content, mortar air content, masonry cement fineness etc), low correlation coefficients indicated that none of the factors could be considered to be the principal factor in the strength of the bond. These investigations did not give a satisfactory explanation as to why the bond strength varied.

However, in reviewing the second of the reports, Ghosh noted that there were differences in the manufacturing procedure, and it was this difference that explained the differing results. In one test the bricks were wetted and in the other they were not and it was this that led to differences in the measured bond strength of the masonry cement mortars. This confirms previous findings that docking can affect bond. The tensile flexural strength of masonry is also affected by the water absorption of the units and good curing will tend to improve bond. Ghosh noted that different types of lime were used in one of the tests (one coarse, one fine and one air-entrained) and that this did not significantly affect the bond strength.

Ghosh concluded that different bricks, mortars, and the level of saturation do have an effect on bond strength and this was analysed in more detail by Rao et al (1996) who examined different types of masonry units, mortar and differing levels of unit saturation. Flexural strength was determined using a bond wrench. Masonry units included stabilized mud blocks, stabilized soil-sand blocks and burnt bricks and the masonry included a variety of different frogs. Five mortars including three cement mortars, a soil-cement mortar and a cement-lime mortar were used. In addition to noting what effect the differing types of brick and mortar had on flexural bond strength, the effect of the moisture content of the masonry unit was also noted to discern if this affected those mortars which hydrate.

Ghosh (1991) conducted research into the effects of brick and mortar, through a method of conditioning the brick units through air drying and then soaking in water for an exact time, enabling to keep the moisture content measurable. Through this meticulous method, the moisture content was assessed for its effects and the units were soaked in water for differing times. Mortar thickness in all cases was kept constant at 10mm. Further to his research Ghosh (1991) conclusively demonstrated that for all masonry, bond is actually a property of unit-mortar combination, and not of the mortar itself.

Christiansen (1996) identified one of the most important parameters for the design of masonry using the yield-line theory as the flexural strength. Ordinarily codes do not take account of the actual bricks and mortar, Christiansen proposed a theoretical approach for determining the flexural strength of masonry which does take into consideration basic parameters of the brick and mortar. As a basis of the theory Christiansen, used several assumptions;

- failure in the brick depends on the normalized compression strength of the masonry unit;
- failure in the mortar depends on the properties of the brick in particular the suction rate &

- failure in the mortar includes bond failure which occurs when the strength distribution over the mortar cross section is concave.

Adams and Hobbs (1994) investigated both the wallette and the crossed couplet tests. They found that the wallettes gave bond strength values and high variability similar to those observed by other investigators. Whilst, the crossed couplet test produced bond strength values similar to other investigations; but with significantly lower variability. Adams and Hobbs attributed the lack of variability with the crossed couplet test to the meticulous way the procedure was followed; as a result of these limited results, it was considered that the use of the cross couplet test as a method of determining bond strength was more accurate than the flexural wallette test. Schubert & Hetzemacher (1992) discovered that there was only poor correlation between masonry flexural strength perpendicular to the bed joints and unit-mortar bond tensile strength, even though failure always occurred in the mortar joint apart from when using AAC masonry.

Investigations into the development of procedure surrounding flexural bond strength are often complex with conflicting theories. As an alternative to the Bond Wrench Khalaf (1998) introduced a new small size Z-shaped specimen which provides an easy test to derive strength by three points loading, so that failure of the brick/mortar interface is caused by flexure rather than by direct tension, as is the case with pull test specimens. Khalaf's preliminary results show that the new test method is capable of determining the values of the flexural bond strength for brickwork where the plane of failure is parallel to bed joints but further validation and finite analysis is required. It is also of note that the gravitational force aided the penetration of mortar into the brick on the lower face as it was observed by Khalaf that failure occurred most commonly on the upper face of the mortar joint with this test there is also a notable reduction in the coefficient of variation. Baker (1982/1) details testing to measure the flexural bond strength comparing Australian, American and British standards and available research tests with his own invention as was in the late 1970's. As a result Baker concludes that none of the standard tests are as accurate as his own. Gabby (1989) reviewed three flexural bond strength tests from USA and Canada and decided that more research was necessary. Analogously Van Der Pluijm et al (2000) concluded that continued research, especially with more brick-mortar combinations, was necessary in this field. In addition Van Der Pluijm, et al urged caution recommending that data sets be obtained with one type of failure, because combined failure modes often lead to diffuse post-peak data, as these experiments, should reveal important conclusions with regard to understanding the failure envelope and post peak behaviour.

Overall there is a continued request for further investment in masonry research to improve understanding of the complex issues within this area.

2.6 Testing masonry strength

There have historically been various methods of testing masonry strength (assessing the flexural strength of bonds being just part of the overall strength of any masonry), and a number are listed here. However, as this thesis is focusing on the flexural bond strength namely the B wallette and the Bond Wrench Test methods in particular the others are only mentioned here in passing so that the reader can investigate further should they wish to do so. It should also be noted that this list is not exhaustive.

One measure of the strength of masonry is to measure it using the internal fracture method. This method assesses the force required to pull a section from a brick. This was developed by Chabowski et al. (1980) and was based on previous work by Malhotra (1972). However, this was found to be somewhat unreliable by De Vekey (1991) and has been subject to further investigation by Hui and De Vekey (1998). I do not propose to discuss this test further as it is somewhat beyond the realms of this thesis and, as yet, no firm conclusions seem to have been reached in this regard.

With regards to bond strength, there are two bond strengths to test depending on whether we are concerned with in-plane (tensile) or out-of-plane (flexural) strength. For each of these there are a number of tests.

The main tests relating to tensile stress include the couplet test with steel end plates attached using adhesive, couplet tests using clamps, couplet tests using bolts through holes, the "Sheffield" test and the crossed brick couplet test. In comparing these methods it has been stated (Riddington et al. (1998)) that the different tests produce differing stress distributions in the joints and therefore produce differing bond strength values. There is therefore no agreement as to which method is the most reliable. Further, the bond strength at the edge of the joint may be different from that over the main area of the joint and therefore, if a test produces a non-uniform stress distribution with the maximum tensile stress at the edge of the joint, then this is unlikely to represent the actual bond strength and is therefore somewhat compromised as a test.

As an aside it should be noted that Riddington et al. (1998) went on to say that as failure in bond strength test is reached at low levels of stress then any non-linearity of the material is insignificant and therefore not simulated in their analysis. It should also be noted that if strain softening does exist then it has been shown that the difference between the load at which failure is initiated and the final failure load increases with the degree of the non-uniformity of the stress distribution as well as the amount of strain softening used in the analysis.

My intention is not to describe all of the bond strength tests in detail here as I assume that the reader is aware of them but instead will merely focus on the various arguments as to their relative merits or otherwise.

In comparing the tensile bond strength tests, it is argued that the couplet test using steel end plates attached with adhesive is flawed due to the fact that the steel plates bend and, if this is not accounted for, it will cause an underestimation in the bond strength. Thicker steel plates can be used to negate this problem but it is argued that this is somewhat impractical. However, this test is the only one considered here that ensures that failure occurs away from the edges of the joint and this is a point in its favour.

It is argued that the couplet test using clamps is unlikely to produce constant or reliable results unless the clamping force is controlled and its effect of the stress distribution accounted for. This is due to the fact that the tensile stress is highest in the joint closest to the point below where the clamping bolt acts.

The couplet test that uses bolts through holes has a similar problem in that the tensile stress varies across the joint and also varies with the bolt diameter.

The "Sheffield" test (as devised by Taylor-Firth, A. et al. (1990)) causes bending of the test units and, as a result, high tensile stress develops at the ends of the joint and compressive forces develop in the middle of the joint and therefore the stress distribution is not uniform and causes results to be very much less than ideal – either too high or too low depending upon where they are measured.

Finally, the crossed brick couplet test: One form of this test is used in the American Standard but again, as with most of the tests above, there is bending of the structure causing a non-uniform stress distribution.

As a result of this there is a strong case to argue that the couplet test using steel end plates attached with adhesive is the best. However, as that test is somewhat impractical to carry out, it is argued that the couplet test using bolts through holes is the best. This is due to the fact that it is easy to do, can produce consistent results and, provided that a stiff enough bolt is used, the variations in stress along the joint is not as great as in the other tests.

In comparing the flexural bond strength tests, it is argued that the four point loading stack prism test, though giving a maximum tensile stress that matches that which is calculated using simple bending theory, is inefficient as a result of the quantity of materials required.

Finally we come to the bond wrench test. This has been widely adopted and a detailed description of the process follows. However, at present I merely wish to comment generally on the suitability of the test for measuring flexural bond strength. It is said that similarly to the Miltenberger, Colville and Wolder-Tinsae test, high clamping forces close to the joint can significantly affect the maximum tensile stress acting across the joint. In addition, if the width of the bond wrench is less than the width of the unit being tested then this will affect the stress distribution. Therefore, it cannot be concluded that the bond wrench test will produce results close to those, which would be calculated by theory unless these two issues are negated.

Masonry is a material which exhibits distinct directional properties, so a failure criterion, because of the material anisotropy, cannot be postulated in terms of principal stresses, like the failure of an isotropic material and as Frunzio et al

(2000) concluded to define a failure criterion for masonry in a plane stress state, a three-dimensional surface is required in terms of the principal stresses and their respective directions relative to the bed joints. Although, laboratory studies on the bed joint shear behaviour of masonry including the effects of normal load magnitude and shear load history presented by Atkinson et al (1988) along with similar studies on the in-situ behaviour of joints in existing structures are also presented the outcome of both laboratory and field studies depict that peak and residual shear strengths are well represented by the Mohr-Coulomb failure criterion. Investigations by Jukes and Riddington (2001) show that if shear strength characteristics as defined by the Coulomb line are wanted, a test arrangment should be used that minimises bending, and the level of precompression stress should not exceed the level where mortar non-linearity becomes important.

Baker (1982/2) attempts to justify the continued investment into masonry research as the Flow (rheological value) of Mortar was observed to be a sensitive and important parameter influencing the flexural-bond strength of brickwork; as the apparent erratic behaviour of the flexural-bond strength of brickwork as it ages points to a complicated interaction of shrinkage cracking, hydration of cement and carbonation of lime that needs more detailed investigation.

By using fine sand instead of course sand we can achieve up to two times higher compressive strength of the masonry and up to five times higher modulus of elasticity according to Bokan Bosiljkov (2000). The significance of the sand grade is greater according to De Vekey et al (1989) which lead to the suggestion of pre contact trials and or some system of quality control on site. De Vekey et al used full sized walls in addition to small laboratory sized specimens for this research.

In the UK, during the mid eighties test provisions were falling far short of the ideal for testing of masonry, Gairns et al (1987) made recommendations for the standardisation of site testing as the existing approach had resulted in the blurring of the distinction between the necessity for tight control of test procedures and the desirability of the masonry tested being representative of that used in the construction. Gairns et al remarked that the recommendations by Anderson and Morton for site control testing of masonry, if implemented would go a long way towards alleviating the problems exhibited in this situation.

Hui & De Vekey (1998) introduced the concept of an in situ pull-out test for brick strength, investigated the effectiveness and scope of such a device. The investigations by Hui & De Vekey found the test is viable for non isolated bricks (i.e. numbers greater than two conjoined together), even for calibration, can be used as an in situ evaluation test as it has sufficient sensitivity to give a broad indication of brick unit strength but given the known variability of the compressive strength of the clay bricks, there was a suggestion that the sensitivity of the test would thus be increased by increasing the numbers of replicate pull-out values for each determination. Ultimately Hui & De Vekey recommended that more research needed to be undertaken to confirm the suitability of the test and provide a wider resource for calibration.

De Vekey (1988) gives a comprehensive review of Non destructive test (NDT) methods applicable to masonry structures which are defined, classified and reviewed in the context of the type of information required to suit different problems, as to which tests are appropriate and to which application also when they should be used. Flat Jack is becoming the accepted test for masonry structure investigation as reported by De Vekey (1991) although it can measure stress to within 5% but was less reliable for elasticity/strength determinations.

The effect of using woven or welded wire mesh bed joint reinforcement was observed to increase the capacity of a wall according to Drobiec and Kubica (2002). Suction has a great influence upon the strength of the hardened mortar in the mortar joints, Kjær (1991) discovered that it is possible to obtain the double strength for the mortar in the joints compared with mortar moulded in a steel mould (ISO test), where there is no suction at all.

Analogously the evolution of calcium hydroxide in both cement pastes and mortars was found to increase by increasing the water-cement ratio from 0.30 to 0.50 which according to Larbi and Bijen (1990) will also increase the bond strength.

An experimental investigation of the bond wrench testing apparatus using the procedures outlined in ASTM Standard C 1072 - 86 was undertaken by McGinley (1994) where it was found that erroneous results can be the result of apparatus setup may produce strain, and therefore stress distributions in masonry specimens that differ significantly from the linearly varying distribution that is assumed. For this reason, McGinley urged caution when applying the restraining bolts and throughout the entire set up process.

Investigations into thermal conductivity by O'Rourke (1995) found that Expanded Blast Furnace Slag (Ebfs) mortars performed better than traditional mortars and the results indicated that there is a potential for Ebfs to replace the sand component of mortar. Bricklaying is still done by hand and as G. Peirs (1998) observed mechanical bricklaying will not be developed until certain problems of thermal insulation are solved.

Ribar, J.W. and Dubovoy, V.S. (1989) found that a High Initial Rate of Absorption (IRA), in other words a high rate of initial suction, can significantly reduce the positive effect of a rough bedding surface texture thus reinforcing the need to dampen brick to reduce its dewatering effect on mortar.

There are problems with the bond wrench as Samarasinghe et al (1999) discovered two major ones the geometrical configuration of the wrench, which results in a high concentration of stresses near the centre of the tension face and the location of the bottom clamps, which induce tensile stresses in the vicinity of the brick/mortar interface. Samarasinghe et al predicted a possible bond failure at a stress level as low as 40% below the actual bond strength.

Bowler (1991) reviewed the possible methods to determine workability of mortar the flow table, plunger test, determination of Flexural and Compressive Strength of Hardened Mortars and determination of water absorption coefficient due to capillary suction.

Sarangapani et al (2002) investigated moisture transport in some local burnt clay bricks. Their findings on moisture loss from mortar due to brick suction and its influence on the water/cement ratio of the mortar, noted, that there was a wide variation in the rate of initial rate of absorption. This rate of absorption slowed down once it achieved a sufficient amount of moisture. A high osmotic effect between the bricks and mortar was observed especially when the bricks were dry. Recommendations that for proper hydration conditions for the mortar and for better bond strength particularly saturated bricks should be used in construction, eliminating moisture barriers being are ineffective.

There has been a consistent trend since the mid 1980's with more than 50 percent of all masonry mortars used in Europe are ready-mixed of ready-to-use mortars. The reason is they provide consistent high quality and predictable masonry mortars the silo system provides high quality, ready to use mortar on the job site and has gained wide acceptance all over Europe, as commented on by Schmidt and Nelson (1990) who noted the continuous growth of masonry construction within modern construction in Europe, with the simultaneous demand for higher quality mortars continues to increase.

Porosity and pore size distribution are commonly acknowledged as crucial factors in bond formation, Wijffels and Adan (2004) indicated that calcium silicate brick characteristics affect bond strength evolution a factor being dimensional changes due to carbonation, considering the time scale of the observed phenomenon.

Sand characteristics are the most important factor affecting the amount of plastic shrinkage, Yool and Lees (1998) discovered that plastic shrinkage increased when the sand contained higher amounts of clays, but non clay fines had an effect, albeit smaller.

2.7 Development of masonry standards

Primarily to meet the Essential Requirements of the Construction Products Directive, and also to take into account the draft Eurocode EC 6 task groups were established according to Fisher (1991). The remit of these product standard task groups was to identify the tests related solely to the specification of physical properties they needed in order to specify their respective product properties. The idea of promoting greater understanding and removing communication barriers is a key element addressed by Merlet (1991). The Euronorms according to Merlet are to provide a common language in the products trade annotated with key definitions, properties, testing procedures and time classification requirements.

The prEN series initially was received with caution and at the time various papers highlighted specific areas of concern. Roberts (1991) noted that specifically for autoclaved aerated concrete (AAC) units, there was nothing in the new proposed prEN documents which will significantly harm the manufacturing base and concluded that AAC would still routinely be widely specified throughout Europe.

Analogously, Rademaker (1991) noted that although Calcium Silicate is produced in eight of the CEN member countries; its attributes, level of importance and uses are quite different. Rademaker commented that the actual draft does reflect these different perspectives and is sufficient for each of the different countries involved. Fried and Roberts (1998) investigated aspects of the structural design of wind loaded walls and how the UK design philosophy now meshes with that of the rest of Europe.

Eurocodes were not the only standards changing in the nineties, McNeilly et al (1991) noted changes to the Australian code could include recognition that practical brickwork produces coefficients of variation higher than is currently recognised. Historically McNeilly commented that current provisions give an incentive to keep the number of specimens in the test sample below, rather than equal to or slightly greater than 10.

Lees (1991) concluded that it was not likely that the implementation of European standards for mortars would lead to significant changes in UK practice apart from that a wider range of cements would become available. Similarly Edgell et al (1990) investigated EC6, ISO and BS5628 and compared the relative similarities and differences; subject to further research it was concluded that the standards were all relatively similar. Conversely, Herrnkind (2002) did not predict such small changes to concrete; concluding that the effect of the new standards would necessitate the user of the new standard would experience changes in test procedures and the actual recording of the results of tests.. Peirs (1998) forewarned the masonry industry to take care not to get immured in National or European Codes and considered that the study of building physics was a more urgent need at that moment. In time Piers also commented that discussions on the strength of masonry were not actually of interest to the public.

2.8 Bond wrench test

The British Standard BS EN 1052-5: 2005 (2005) specifies the method for determining the bond strength of horizontal bed joints in masonry using a bond wrench.

In short, a couplet of bricks is rigidly held and a clamp attached to the top unit. A bending moment is then applied to the top brick until the unit rotated from the mortar joint directly beneath it by the force applied. Following testing the bond strength is then calculated.

The British Standard provides requirements for all aspects of the test with regards to the bond wrench itself, the manufacture of the couplets, and the method for calculating the bond strength and what details are required to be reported on.

The procedure that was carried out, broadly followed the method as dictated by the British Standard with a single type of mortar (in our case thin joint glue mortar) and four types of brick – standard red brick, Aircrete coursing units, concrete bricks and yellow bricks – being used.

The British Standard states that loads should be applied slowly so that failure occurs in 2 to 5 minutes.

It has been noted by Van Der Pluijm (1995) that in the majority of flexural bond strengths the actual bond surface was smaller than the gross cross-sectional area of the brick. This implies that the loading may not be symmetrical with respect to the loading of the actual bond surface and as a result it can be argued that the full surface area of the brick should not be used when calculating the stresses but rather some smaller area. He recommends that only 80% of the cross-sectional area should be used.

It is also noted from our experiment that when the bond between the brick and mortar failed rather than the brick itself, the majority of the failure was of type A1 that is a failure in the upper face of the joint. It has been suggested by Khalaf (1998) that this is due to the fact that the lower face is in a more favourable position for developing a good bond during laying and curing compared with the upper face due to both gravitational force which helps mortar flow into the pores of the lower brick and works against the mortar being absorbed into the upper brick face.

Further, McGinley (1994) has investigated the effect of loading rates has on the results of bond strength. His investigations suggest that there is some small variation in measured bond strength with variations in the loading rate. His results suggest that the lower the loading rate the smaller the coefficient of variation than with the higher rates suggesting that more consistent results could be obtained if a low and uniform loading rate is used.

Finally, Van Der Pluijm et al. (1995) have investigated the influence of manual load application. Their conclusion was that if the bond wrench is manually loaded with a lever arm of 1 metre, the magnitude of shear and torsional stresses is so small that the influence on the measured bond strength can be neglected.

Based on the assumption that the measured flexural bond strength depends on the height, the stiffness and the fracture energy of the specimen Van Der Pluijm (1995) compared the bond-wrench method to the 4-point bending tests and observed that the same results were achieved. Van Der Pluijm did put a limitation on this as taller specimens are likely to experience a redistribution of stresses. Fried et al (1988) describes the necessity for an economical method of determining and controlling the flexural properties of masonry on construction sites as recommended by Anderson & Morton (1986). This PhD investigates and develops a suitable portable method encompassing research conducted in the intervening years. The BRE (1991) developed the BRENCH test which is tool for assessing the strength of masonry on and off site.

Anderson & Morton (1986) highlighted that further correlation between in-situ and laboratory testing is required. In practice there is already a recognized method of using a large partial safety factor for materials which in masonry design accounts for many of the variables and uncertainties as discussed by Anderson & Morton. Therefore the masonry materials proposed for a project can be tested in flexure in the laboratory at the design stage and then the bond specimens which are built by the bricklayers on site during the construction many of the inherent uncertainties will be eliminated. Anderson & Morton (1986) confirm that the Bond Wrench is a satisfactory and conservative way of obtaining a flexural strength of masonry in relation to the strength obtained by wallette testing.

Analogously Brown and Palm (1982) justify the use of the Bond Wrench for testing flexural bond strength and furthermore reinforces the point that tooling of bed joints provides a stronger and more uniform set of test results. Later Lovegrove (1989) described the Bond Wrench as a relatively quick and easy test which, although intended primarily as a laboratory tool, can be adapted for use on site: either as a means of quality control or to indicate the level of strength remaining in old walls. Thus is a suitable tool as a standardised method as was recognised by Anderson & Morton (1986) and Fried et al (1988). Hughes and Zsembery (1980) state that so long as the design of the bond wrench is based on the same principles the results generated will be comparable.

Hamid and Hakam (1998) conclusion based their investigations on the bond wrench test technique as an appropriate method to determine the modulus of rupture of grouted masonry walls. Further endorsement was received from Riddington et al (1998) who observed that of the flexural test methods; the bond wrench test was the most suitable. Although caution was exhibited by the same authors that care needed to be taken with the way the bricks were clamped in so not to adversely affect the stress across the joint. A suitable procedure was suggested by Schierhorn (2001) and by Van Der Pluijm, and Vermeltfoot (1995).

2.9 Conclusion

It can be concluded, based on the works that have been reviewed here, that:

- Flexural bond strength between masonry units and the mortar is the most critical factor in the strength of non load-bearing masonry walls. Bond strength is influenced by several factors, such as material properties, geometric properties, environmental factors and workmanship.
- Most of the factors influencing the flexural bond strength masonry are known, but quantifying their effects is still a major stumbling block.

3. Bond Wrench Designs

This chapter describes the background to the development of the bond wrench test and the process in which the design was constructed.

Following proposals in the 1960's for a bond wrench test detailed by Pearson (1963), it was not until Hughes and Zsembery (1980) who further developed the technique, for a low cost scaled down understanding of flexural bond strength. They described a basic bond wrench in the form of a long lever, which is clamped to a brick unit at one end while the other end is free. When a gradually increasing force is applied at the free end the unit to which the wrench is attached to, is rotated free from the mortar joint immediately below it. The measure of the bond strength between the unit and mortar is calculated from the final load or resultant moment applied. Hughes and Zsembery (1980) suggested three ways in which the force can be applied relative to the design:

(1) "Dead-Weight" - where a mass hook or container is hung at the free end and a filled with lead shot or an alternative fluid mass

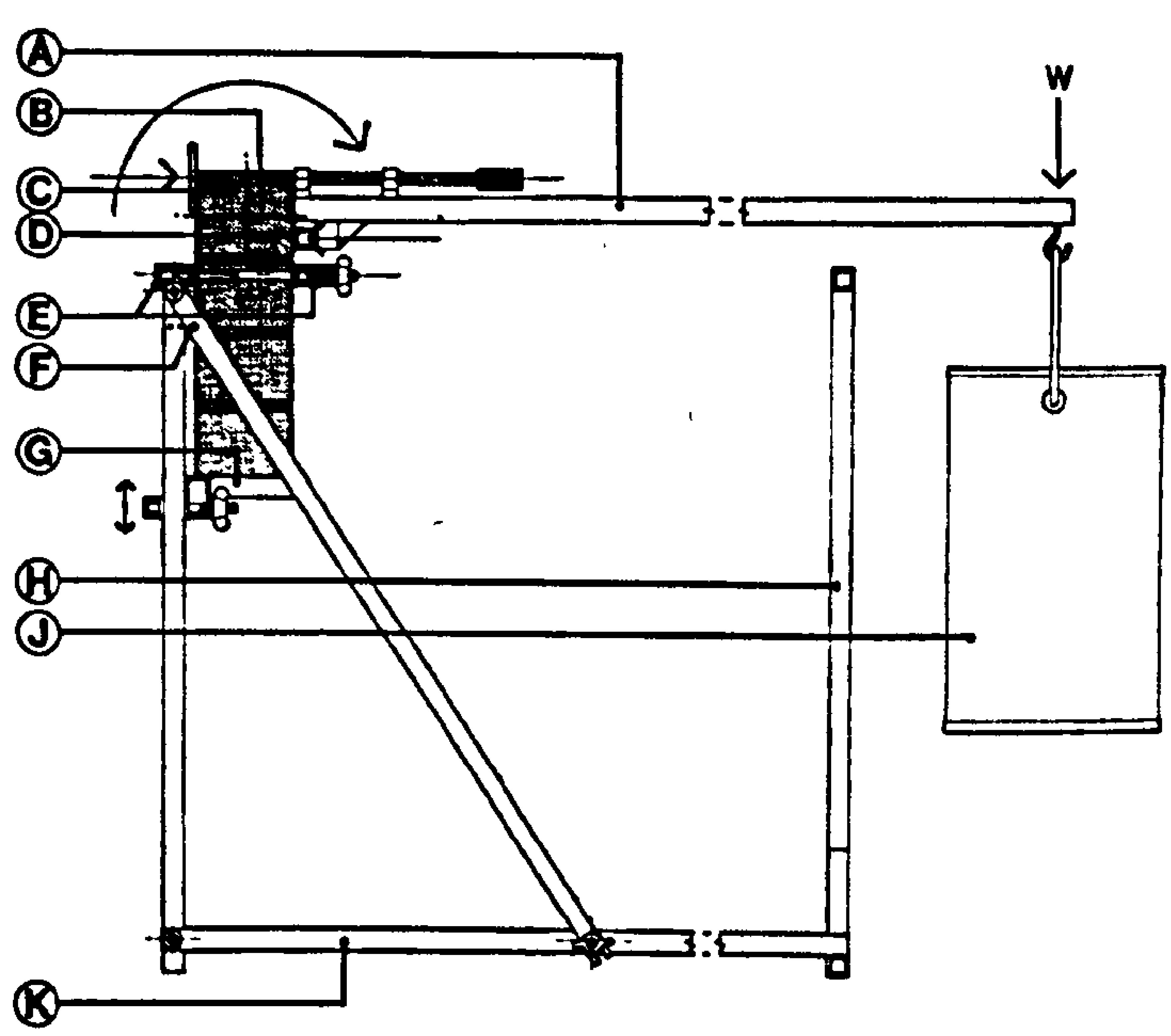


Figure 3.1 – Bond wrench proposed design – Dead weight – [Hughes and Zsembery (1980)]

A: Lever-arm of Bond-wrench, B: Adjustable draw-head mechanism, C: Specimen,
D: Compression face of Bond-wrench, E: Clamp on specimen retaining frame,
F: Rear face of clamp (concealed), G: Support bracket for specimen,
H: T-Piece to restrain Bond-wrench, J: vessel to contain applied load, K: Base of specimen retaining frame.

(2) "Beam Balance" - Permanent mass hung along the length of the bond wrench, which at the outset of the test gradually moves from the masonry specimen outwards, until failure.

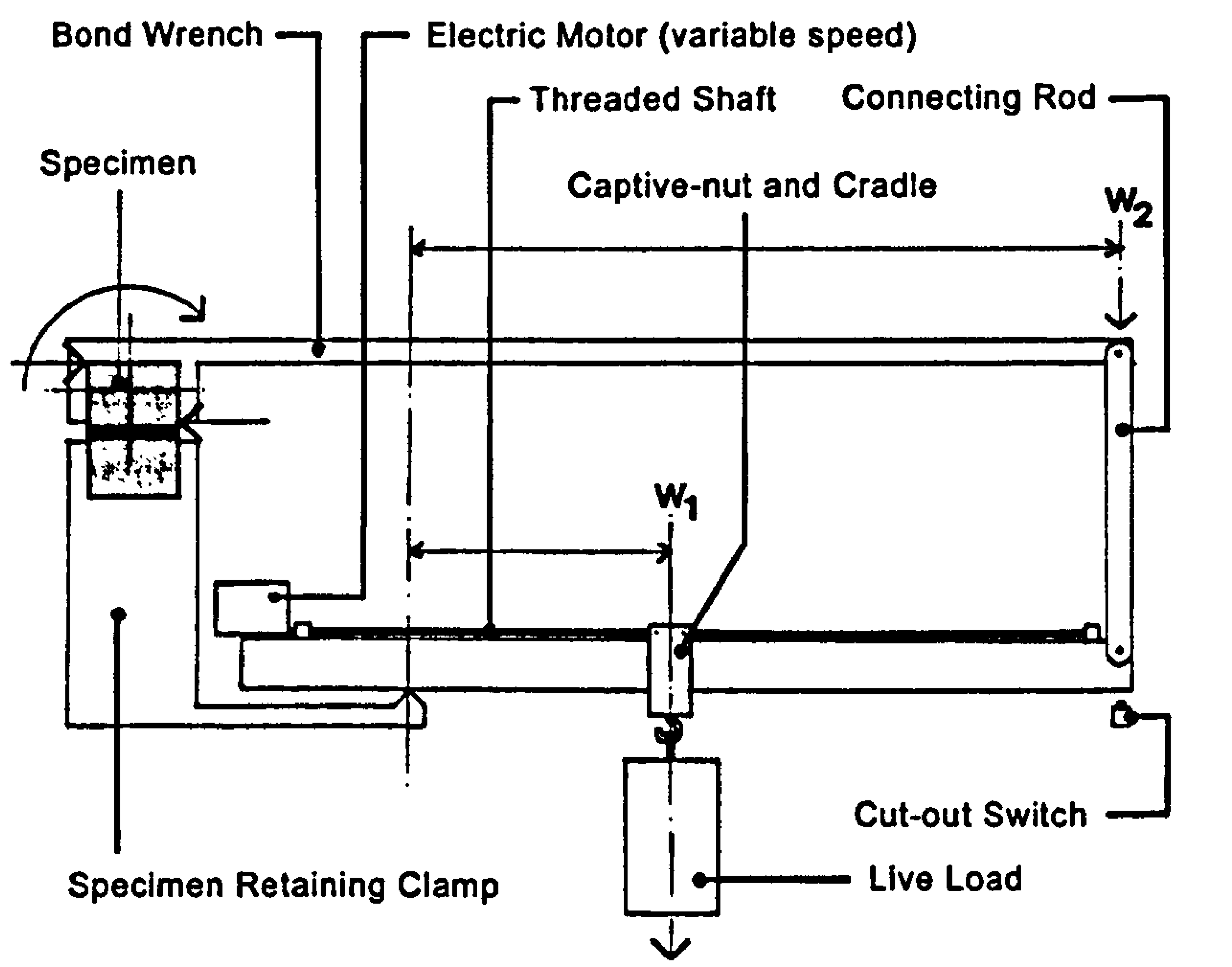


Figure 3.2 – Bond wrench proposed design – Beam balance – [Hughes and Zsembery (1980)]

(3) "Hydraulic Jack" – where a force is generated using a hydraulic jack acting from a reaction point. These three systems are practical but are only really satisfactory in a laboratory situation due to the large mass or the reaction that is required.

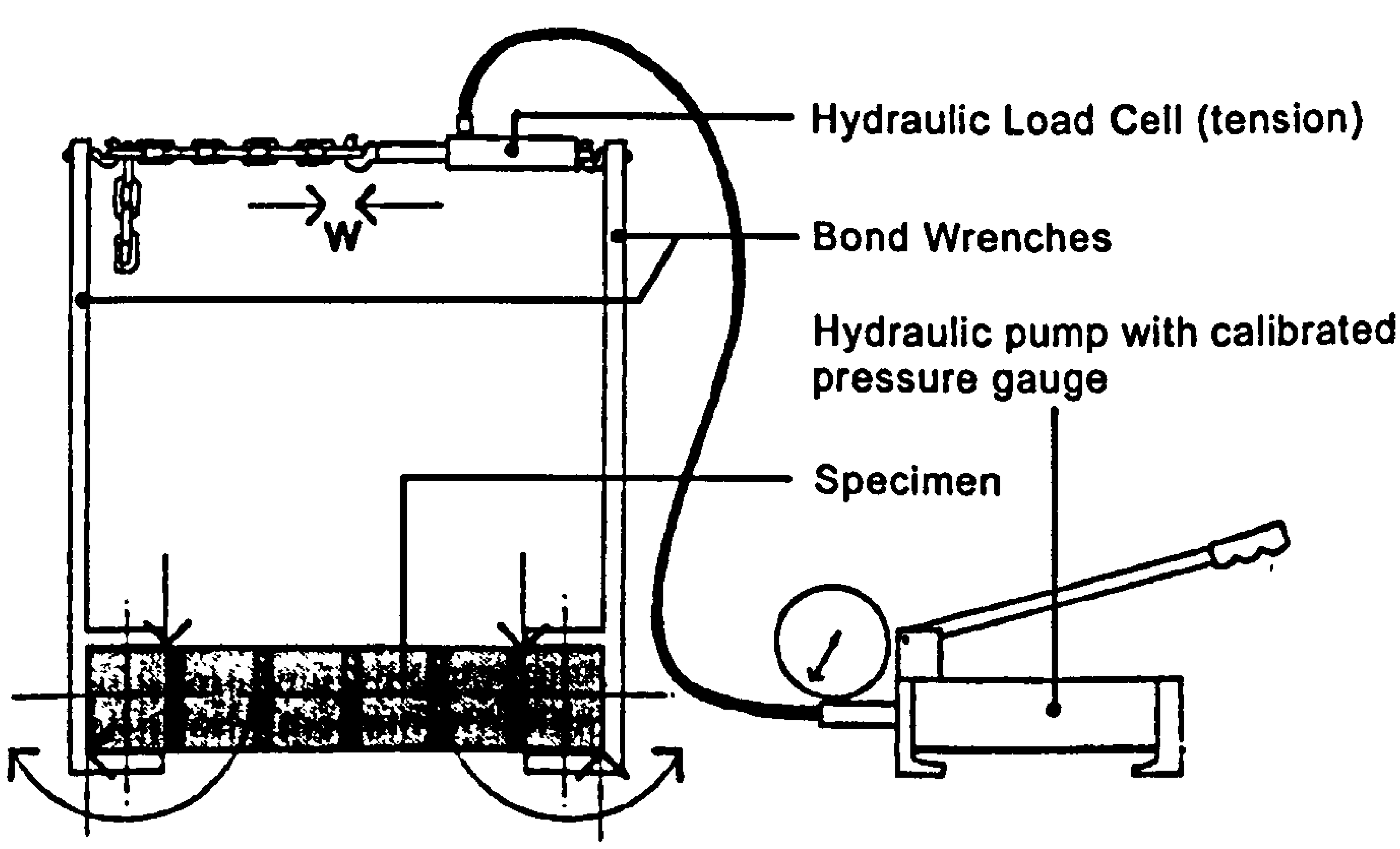


Figure 3.3 – Bond wrench proposed design – Hydraulic jack – [Hughes and Zsembery (1980)]

A disadvantage of these entire wrench designs is that the dead weight of the lever arm generates a bending moment as soon as the wrench is attached which makes it impossible to measure weakly-bonded specimens.

The preliminary bond wrench testing was carried out using an existing bond wrench test rig present in the laboratories. It was used in past research work by Colin Anderson and Anton Fried. The wrench has never been named and to aid identification it will be referred to as Kingston University Bond Wrench (KUBW).

During the preliminary testing stages the KUBW was used on a range of early and advanced age testing of couplets and stack bonded prisms. The results found that due to the awkwardness in use and heavy weight (21kg) of the KUBW the bond between the units and mortar was adversely affected. This prompted an investigation into ways of improving the design. Owing to the impracticality of updating the KUBW, the manufacture of the new bond wrench was started.

The new British standard BSEN 1052-5: 2005 details the design criteria for a wrench, focusing on details at the point of contact between wrench and units, whilst, the overall design has been left for open interpretation.

Initially, some preliminary investigations were conducted into the various designs of Bond Wrenches. As a result the BRE Brench was chosen as a geometric starting point. Then during the design stages certain improvements to the initial design were implemented.

From this point on, the new bond wrench will be known as the Reutter Wrench.

3.1 Structural principles of the bond wrench test

Except for counterweighted or tension versions, all wrenches apply some vertical dead load and a small bending moment when first clamped to the specimen. At the start of a test the vertical load at the joint plane is the sum of the dead weight of the upper unit and the dead weight of the bond wrench, while the moment results from the dead weight of the bond wrench acting at its centre of gravity. As load is applied to the free end, both the bending moment and the vertical load are increased.

The maximum tensile stress F_s may be calculated (assuming a triangular stress block), in N/mm^2, as follows:

$$F_s = \frac{M}{Z} - \frac{W}{(b \times d)}$$

where:

M	=	bending moment at failure, N x mm
Z	=	section modulus of joint, in cubic millimetres = $b.d^2/6$
W	=	maximum compressive force applied to the joint, N
b	=	the mean width of joint at the line of fracture, mm
d	=	the mean depth of joint at the line of fracture, mm

Where the dead weight or Brench system is used, the specimen is built from solid or perforated units laid on a full bed of mortar and a triangular symmetrical stress block is assumed the expression for the failure stress is given by:

$$F_s = \frac{(W \cdot Lg + W_1 L_1 g) \times 6}{b \times d^2} - \frac{(W \cdot L \cdot g + W_1 \cdot L_1 \cdot g)}{(b \times d)}$$

Where additionally:

W	=	load at failure applied at the extremity of the moment arm
L	=	lever arm for the applied load
W_1	=	load due to the deadweight mass of the apparatus, W_{bw}, plus the clamped unit W_u acting at the centre of gravity.
L_1	=	Lever arm for the mass of the wrench at the centre of gravity.

Although the triangular stress block is assumed, it has been shown by work by Fried (1991) and Samarasinghe et al (1999) that the effective Young's modulus in the tension zone is lower than that in the compression zone thus the stress block is not linear and the neutral axis is displaced towards the compression face. However, the degree to which this occurs must vary with material and so it is not normally allowed for in standard bond wrench assessments.

3.2 BS EN Specification for bond wrench test

During the development of the Bond Wrench, the current British Standard European Norm BS EN 1052-5 was still in its preliminary stage of being standardised and was only formalised from 2005. The standard describes the apparatus, testing procedure and results to be obtained for the analysing formula. Its description was used as a guide but not as an exact design blueprint. The following parameters and procedures are a synopsis taken from the standard:

The standard describes the test rig in three parts:

1. Support frame

   A suitable support frame and clamp which holds in place the unit beneath the top bed joint of the stack bonded specimen without applying any significant bending moment to any lower units. Shown in Figure 3.2.1 with Area A shown in greater detail in Figure 3.2.2

2. Bond wrench parameters

   The bond wrench is described as: *A lever which has a clamp at one end which can be applied to the top unit of the stack bonded specimen. The lever arm should be at least 1 m in length. The tensile stress applied to a specimen due to the weight of the lever and clamp should not exceed 0.05 N/mm^2.*

3. Testing procedure

   A means of applying downward force to the lever arm without shock and a means of measuring this force with an accuracy of ± 1 %.

   An example of a suitable clamping arrangement is shown in Figure 1. The specimen should not be subjected to any torsional stress, either from the weight of the lever or the applied force. Where highly perforated bricks with thin shells are to be tested, the faces of the clamp will need to be as large as is practicable so as to avoid local crushing of the units under the action of the clamping force.

Weighing device capable of weighing a masonry unit to an accuracy of ± 1%.

Apparatus capable of measuring the dimensions of the specimens to an accuracy of ± 1 mm.

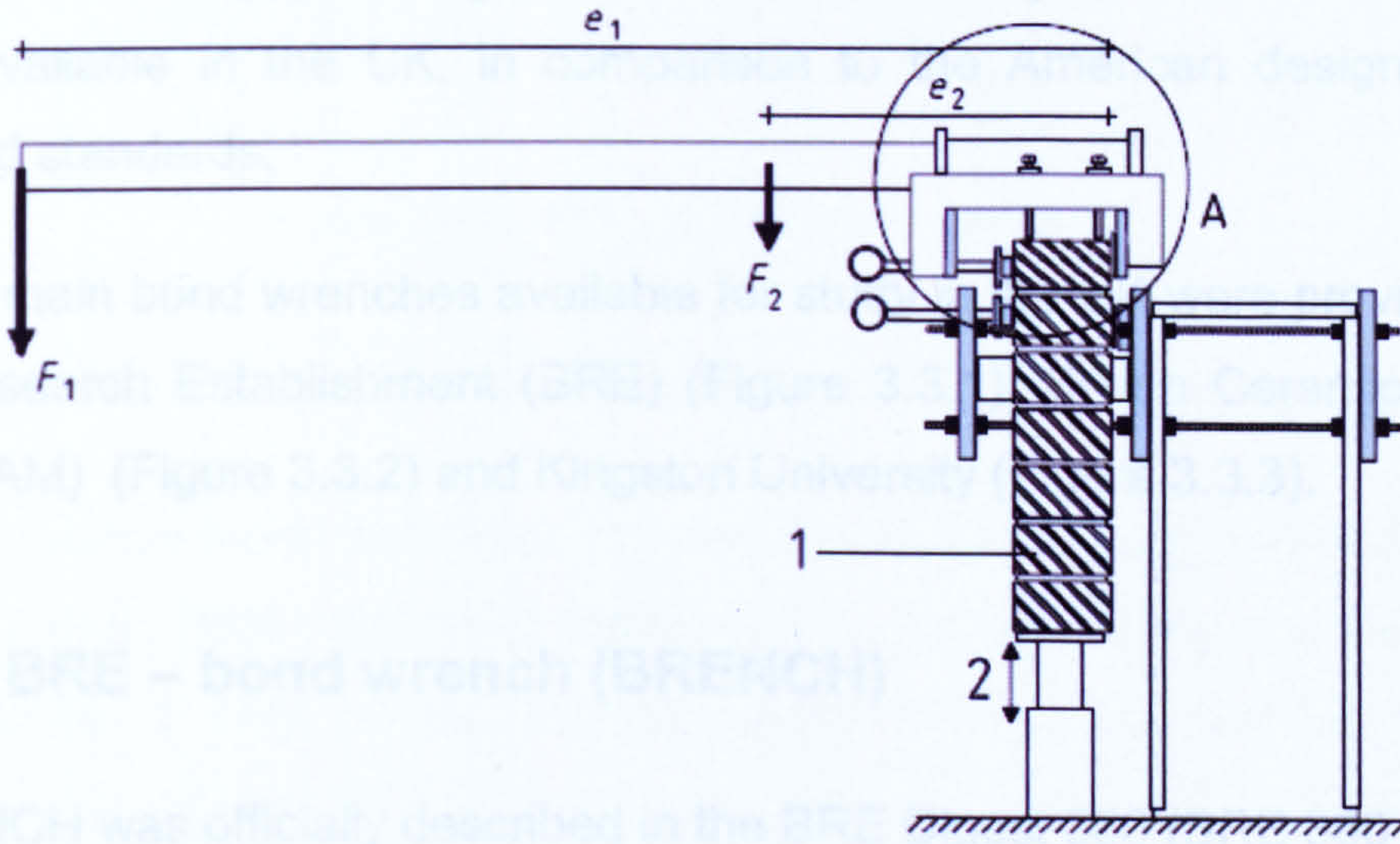


Figure 3.2.1 – BS EN 1052-5: 2005 – Suitable support frame and clamp

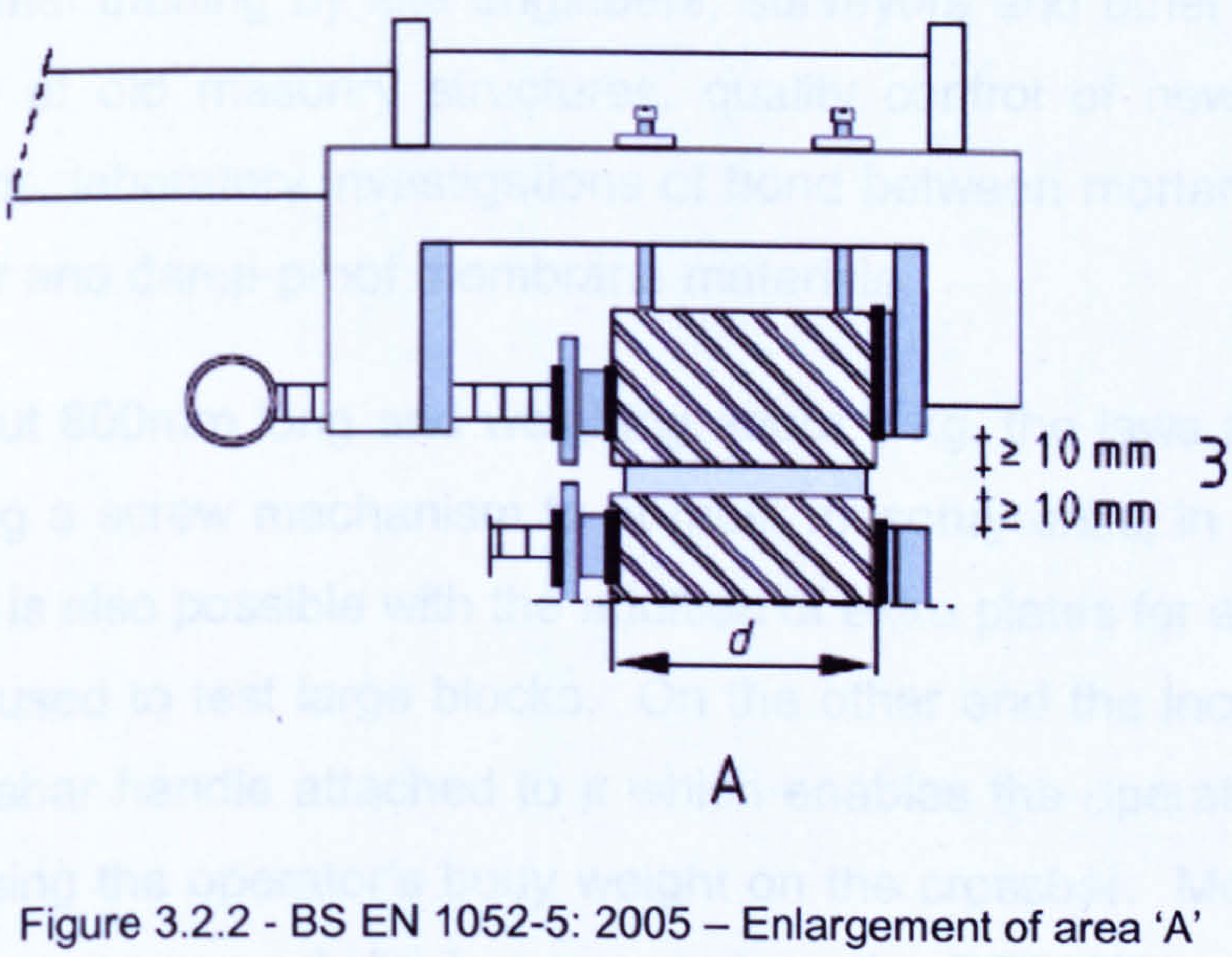


Figure 3.2.2 - BS EN 1052-5: 2005 – Enlargement of area 'A'

3.3 Existing bond wrenches designs

First developed by Hughes and Zsembery (1980) they mention that: "A large degree of flexibility in the design of individual test apparatuses based upon the Bond Wrench principles is possible without invalidating the comparability of the results they provide". This statement summarises the inevitable outcome that there is not one standard geometry set up for a Bond Wrench. At the same time, Baker (1982/1) comments that since Australia, America and Britain have adopted a standard test method, but each standard being different from each other. Unfortunately, this makes it difficult to relate results obtained by the respective standards.

Utilizing this vast array of designs available, an investigation was carried out with designs available in the UK, in comparison to the American design shown in papers and standards.

The three main bond wrenches available for study in the UK were provided by the British Research Establishment (BRE) (Figure 3.3.1), British Ceramic Research Ltd. (CERAM) (Figure 3.3.2) and Kingston University (Figure 3.3.3).

3.3.1 BRE – bond wrench (BRENCH)

The BRENCH was officially described in the BRE Digest 360 (BRE 360 1991) as a portable, safe bond wrench which needs no ancillary equipment and which can be used with minimal training by site engineers, surveyors and other technical staff for site testing of old masonry structures, quality control of new work, testing mortar variations, laboratory investigations of bond between mortar and units and between mortar and damp-proof membrane materials.

Measuring about 800mm long and weighing about 9 kg, the jaws at one end are adjustable using a screw mechanism to fit most masonry units, in either width or length ways. It is also possible with the addition of extra plates for a larger surface area it can be used to test large blocks. On the other end the incorporated load cell has a crossbar handle attached to it which enables the operator to manually apply a load using the operator's body weight on the crossbar. Monitoring of the load cell is by an easy read display mounted on the BRENCH body. With the display clearly visible the operator can adjust the loading rate and read off the maximum load result that causes failure to the bond before resetting the display for another test. The measuring device gives a reading of the applied load in N, Kg or lb.

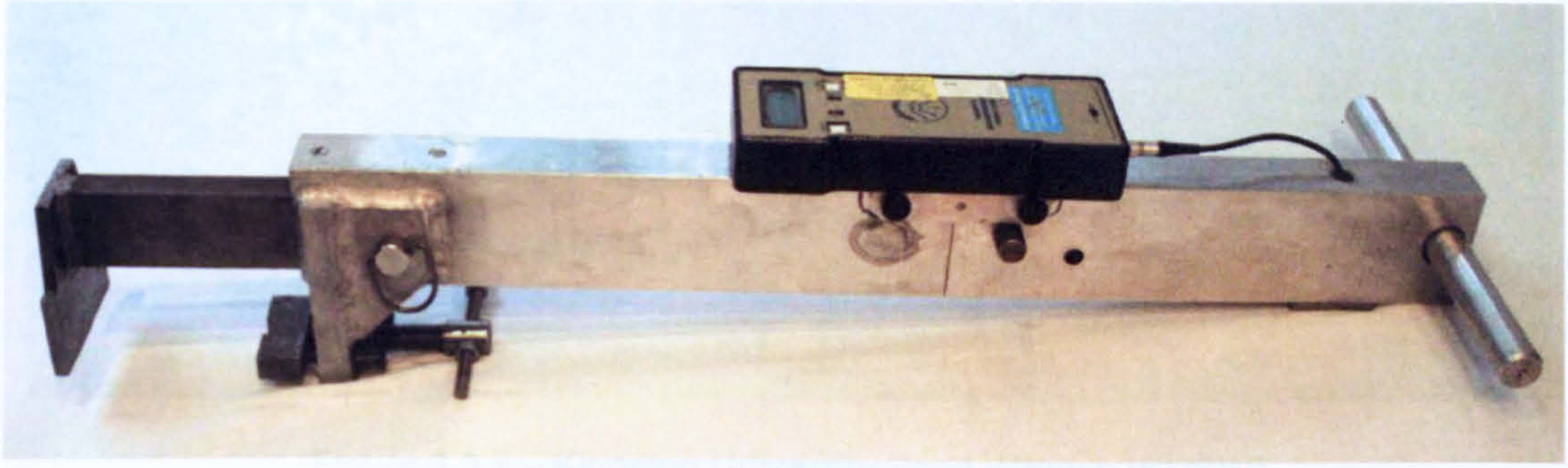


Figure 3.3.1 – BRE bond wrench – (BRENCH)

3.3.2 British Ceramic Research Ltd – CERAM bond wrench

This bond wrench most resembles the diagram in the current European Standard (BS EN 1052-5: 2005) shown in Figure 3.3.2. Unfortunately, the nature of the design makes it only usable for laboratory testing, as part of a research programme.

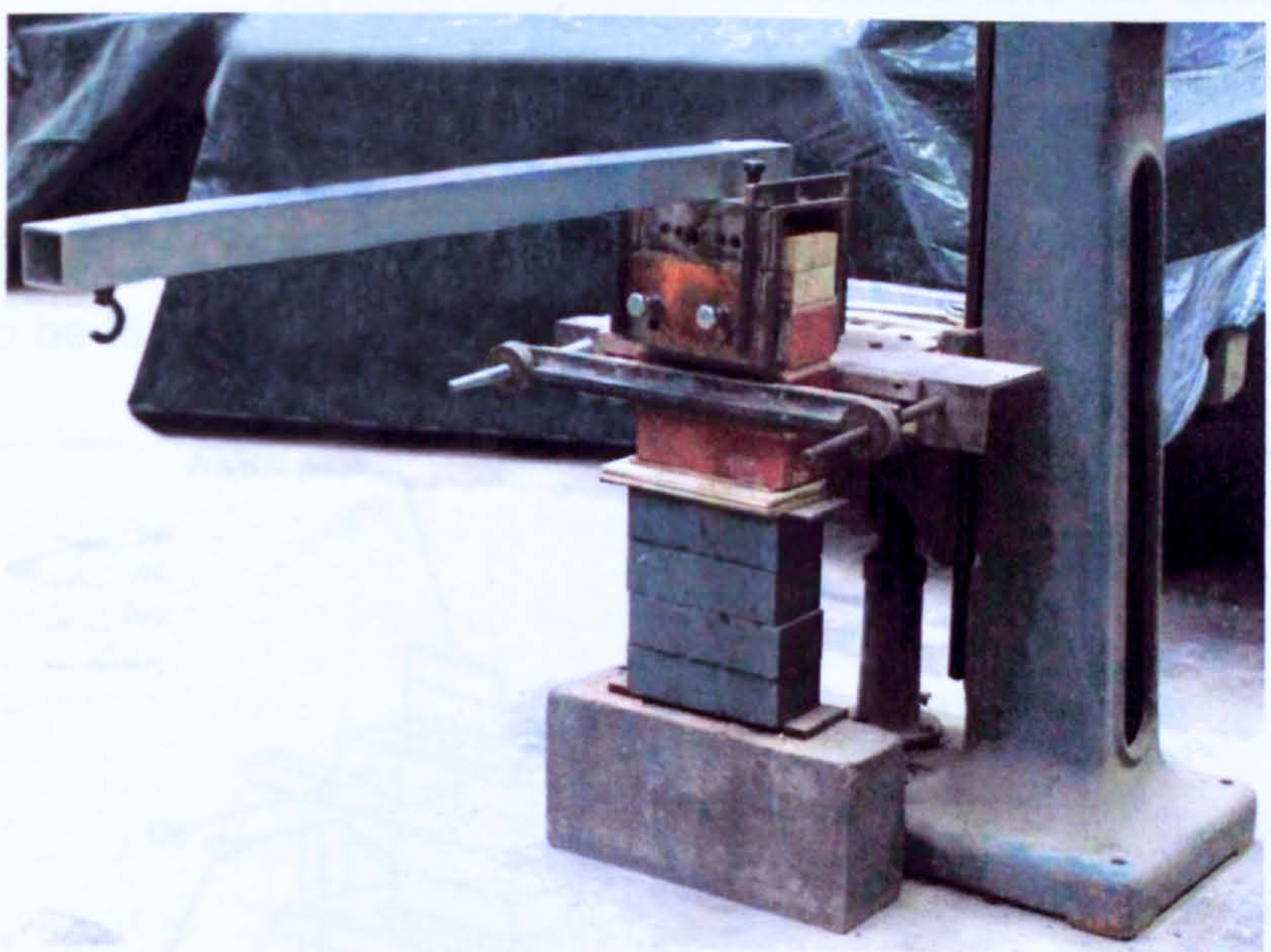


Figure 3.3.2 – CERAM bond wrench

3.3.3 Kingston University Bond Wrench

The bond wrench shown in Figure 3.3.3 is 1 m long and weighs 21 kg and is counter balanced. Originally made for London's South Bank University the construction is made of welded steel tubing which is extremely robust but very difficult to handle.

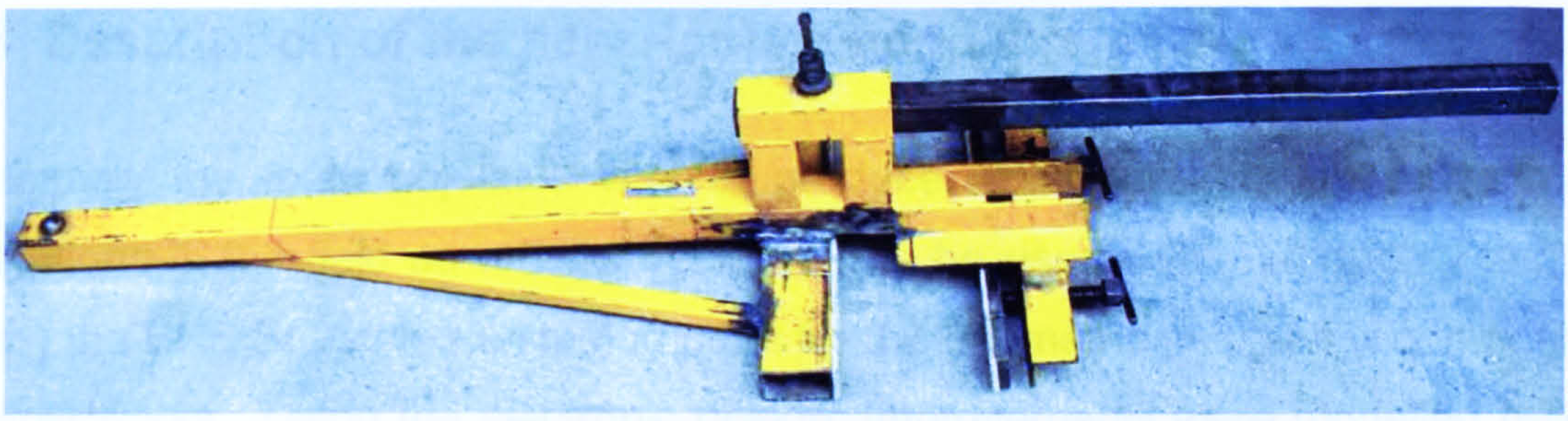


Figure 3.3.3 – Kingston University Bond Wrench (KUBW)

Looking further into other bond wrench designs that originate from outside the UK, the following two were chosen as a representation of differing international designs.

3.3.4 American ASTM bond wrench design

The American bond wrench is described in the ASTM C-1072 standard, which details a break down of parts needed to manufacture and the design. Not only does it specify the bond wrench but also the bottom clamping base. As seen in the schematic diagram Figure 3.3.4 the arm looks to be very short and with the constrained geometry looks only to be usable on brick sized units. Blocks would not be able to be tested.

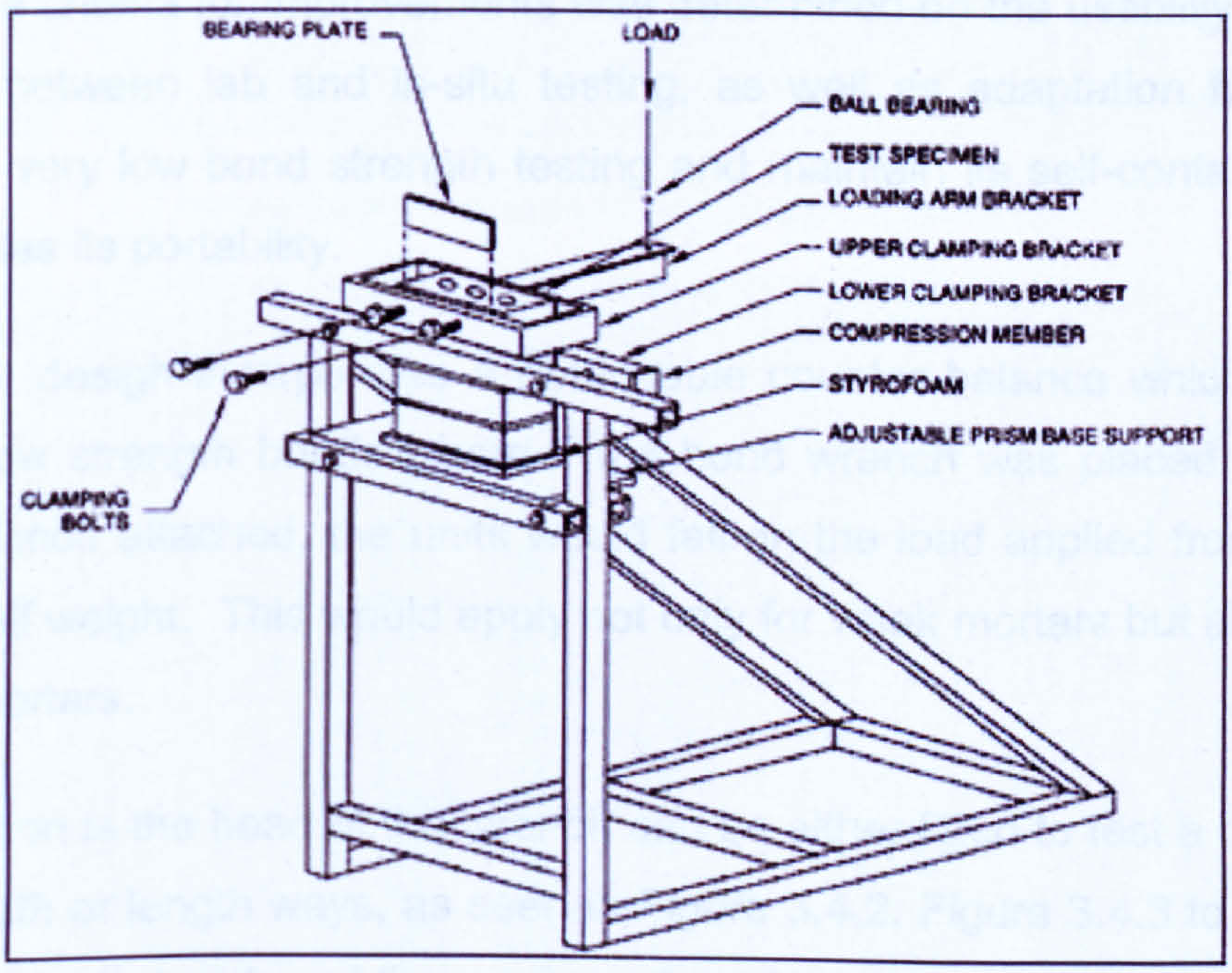


Figure 3.3.4 – American bond wrench

3.4 Description of the new Reutter bond wrench

Principally the main objective was to produce a wrench with applications for operations in the field as well as being able to be used within laboratory testing. Using the BRE Brench as a starting point for the geometric design it was modelled in *Solidworks.* Using the electronic design, improvements were modelled before the manufacture of the Reutter wrench and further mechanical improvements were developed. These improvements were based not only on preliminary testing but also due to general improvements in equipment and materials available.

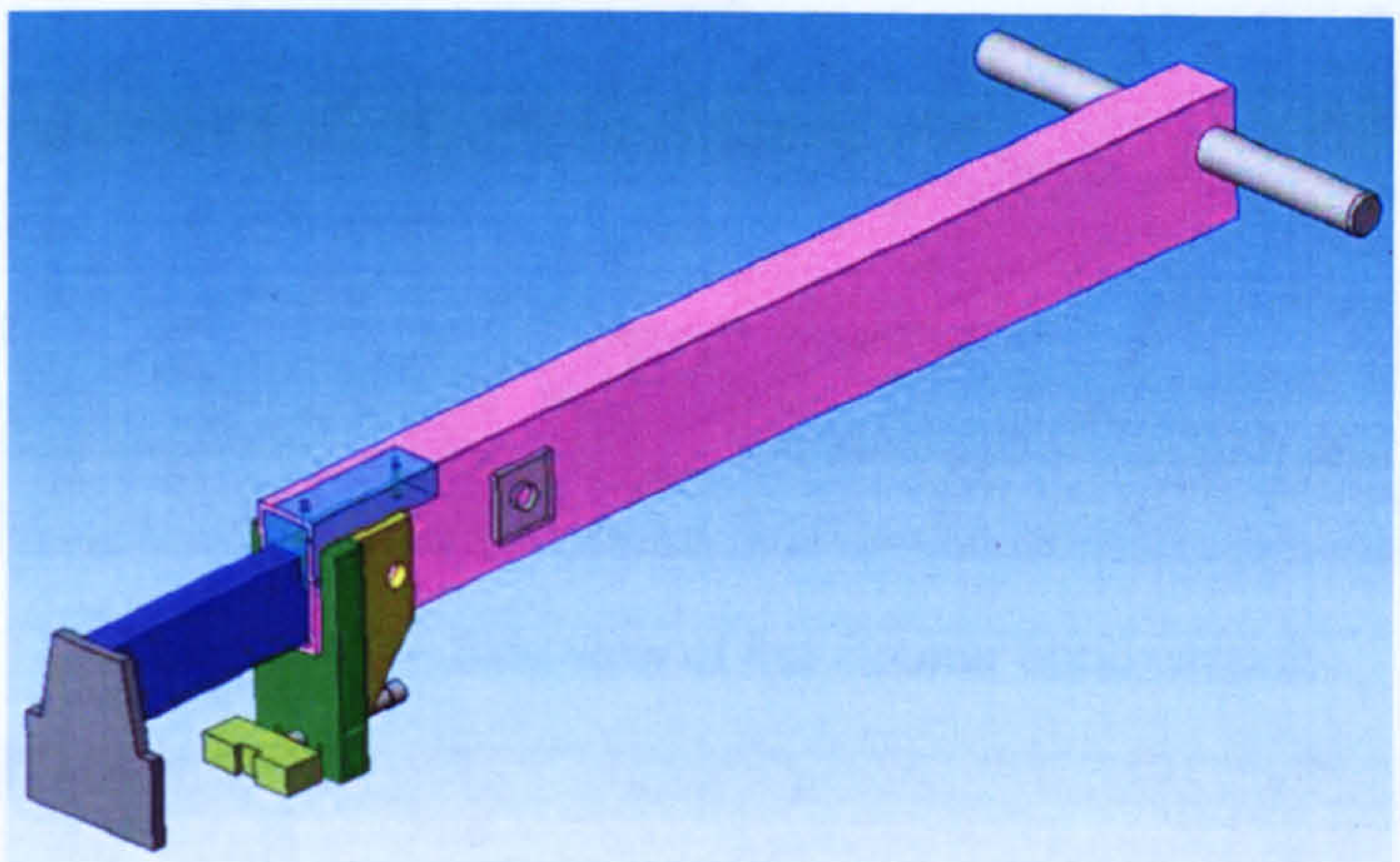


Figure 3.4.1 – Solidworks model of BRENCH

Basically the criteria for improvements was determined on the usability in terms of correlating between lab and in-situ testing, as well as adaptation for use with samples of very low bond strength testing and maintain its self-contained nature which enables its portability.

The Reutter design incorporates a detachable counter balance which allows for testing of low strength bonds where if the bond wrench was placed without the counter balance attached, the units would fail on the load applied from the bond wrench's self weight. This would apply not only for weak mortars but also for early testing of mortars.

Another option is the head of the wrench can be either fitted to test a brick's bond strength width or length ways, as seen in Figure 3.4.2. Figure 3.4.3 to 3.4.5 show the Reutter bond wrench and the configuration of how it is used during testing.

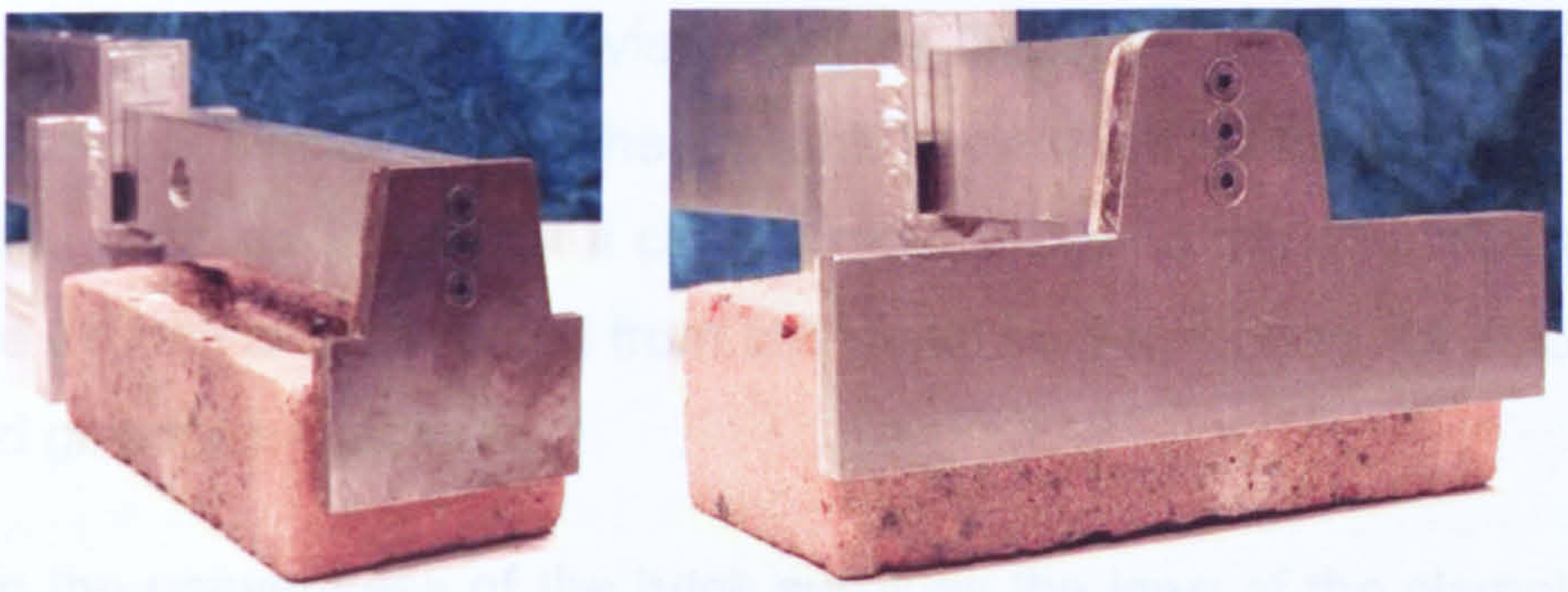


Figure 3.4.2 - Head adjustments for Reutter Wrench

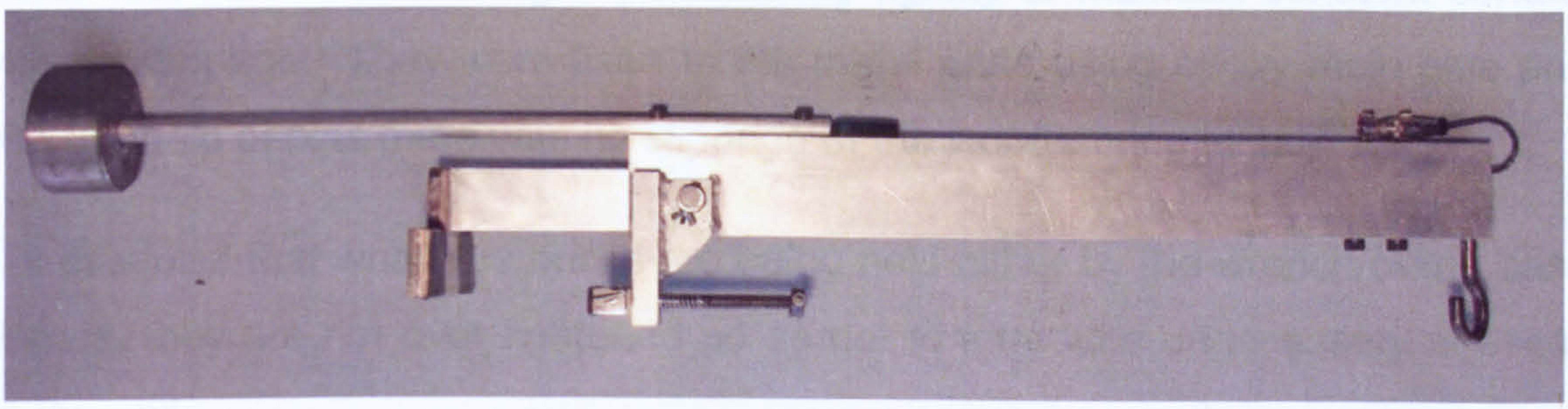


Figure 3.4.3 – Side view of the Reutter bond wrench

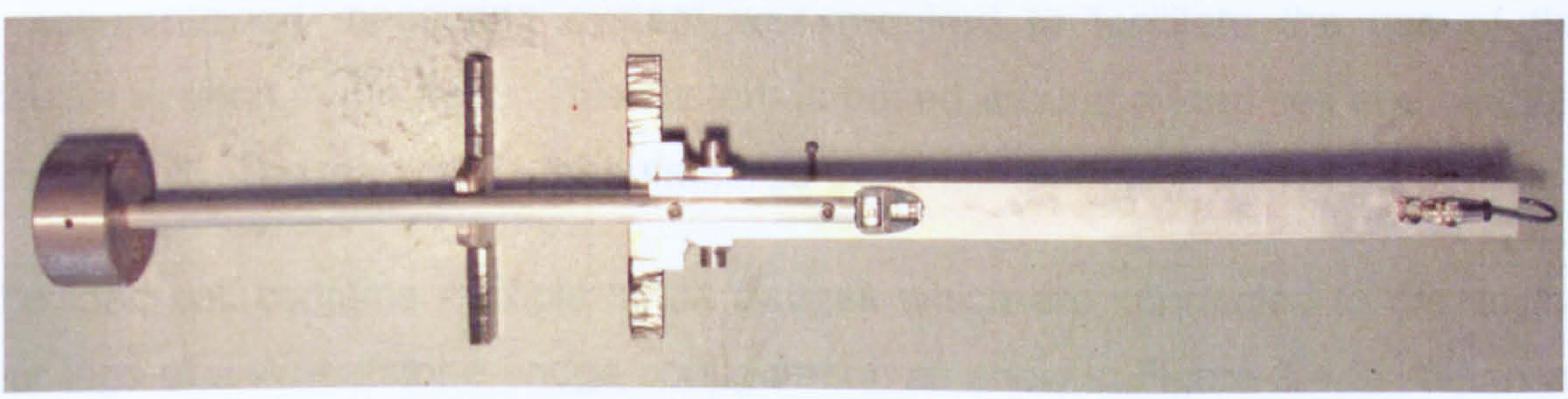


Figure 3.4.4 – Top view of the Reutter bond wrench

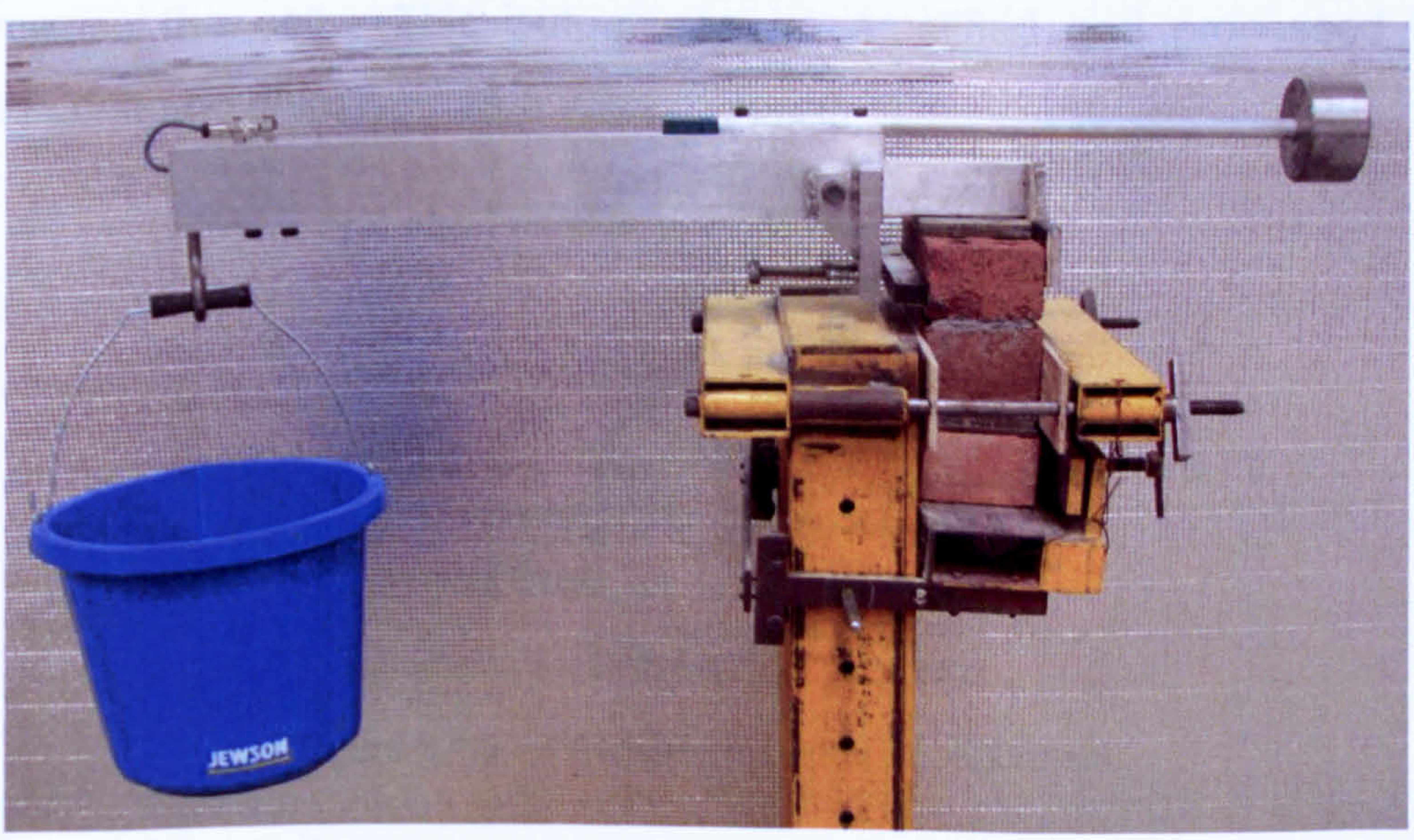


Figure 3.4.5 – Test being carried out with the Reutter bond wrench

As mentioned in the literature review chapter the basic principle of all previous bond wrenches is similar in that the top unit is clamped by the wrench whilst the unit below is clamped in so that it cannot move. Due to the nature of the forces applied the wrench is constructed from stiff metal so that it does not deform during testing and give false readings.

To take up the unevenness of the brick surfaces the jaws of the clamping part of the bond wrench were coated with a layer of 3mm plywood. Plywood was chosen for this role because it's soft enough to take up the imperfections of the units under test as well as having the necessary rigidity to maintain constant contact with no slippage. They were fixed to the metal parts using epoxy resin glue and with the help of pins there was no slippage of the wood during tests.

It is essential that when the bricks are being held either by the wrench of the base clamps, they are not over tightened so as not to introduce unnecessary stresses on the units.

A self-contained measuring system was required to facilitate the use of the Reutter wrench in the field. This system is based around a load cell and suitable display unit. The load cell is manufactured by "Thames Side – Maywood".

The load cell contains multiple strain gauges which are connected to create the four legs of a Wheatstone-bridge configuration as show in Figure 3.4.3. When an input voltage is applied to the bridge, the output becomes a voltage proportional to the force on the cell. This output can be amplified and processed by the electronic unit and displayed as a value of force.

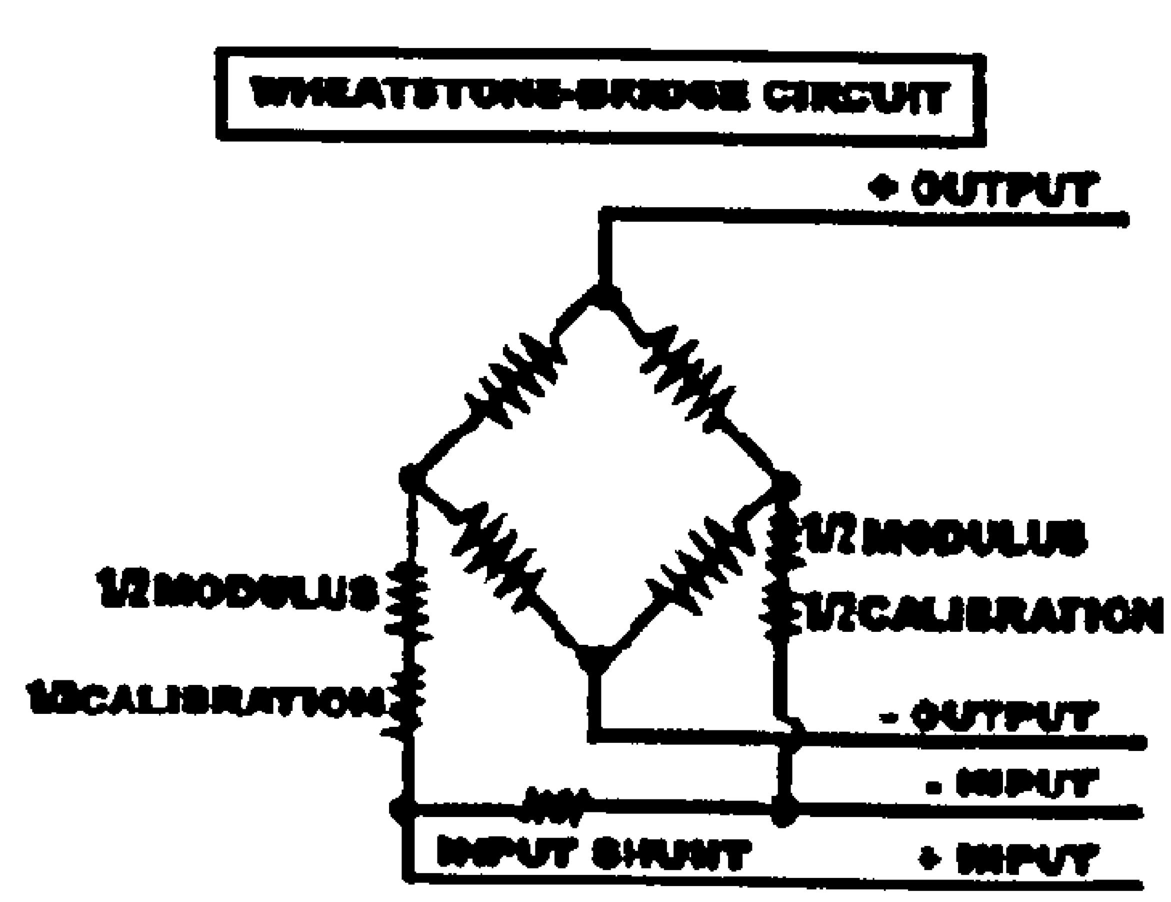


Figure 3.4.6 – Wheatstone bridge Configuration

3.5 Mechanical construction of the Reutter bond wrench

Finding ways of improving the design were worked on with weight being the main criterion for concern. The materials used in the construction were aluminium and steel. Due to the weight limitation to enable maximum usability as a main priority of the design, aluminium was used in parts that required good rigidity and strength although not to the same degree as mild steel would have provided.

Situated on the rear of the assembly arm is the load cell. A hook from which the load is applied is screwed into the bottom of the load cell in a position so as not to touch anything else.

The signal is fed from the load cell output via a waterproof connector to the electronic display unit.

Figure 3.5 – Front end of assembly with brick unit

3.6 Construction of the electronic display unit (EDU)

The Electronic Display Unit (EDU) translates the signals received from the load cell and displays them as a unit of force.

The unit used for displaying the reading is the XT1200LL which is manufactured by *Thames Side – Maywood*. A manufacturer's specification is found in APPENDIX A2.

The model used is the DC version and as seen in the specification has an input voltage of 11-30 volt.

During the design stages of the EDU's power supply management system three functions were identified:

1. Convert AC – DC to power the unit in the controlled environment laboratory

2. Contain suitably powered batteries for extended use in the field

3. Provide a charging mechanism for the batteries

The transformer chosen was a *TRACO POWER* supply model TXL 025-24S purchased from RS components (stock number: 449-3125). It was small enough to fit inside the casing. Since the main casing also acts as a heat sink the power supply was able to be very small since the heat generated will dissipate into the main casing. The EDU is shown below in Figure 3.6.

Figure 3.6 – Electronic display unit and casing

3.7 Bond wrench calibration procedure

3.7.1 Stage 1

To find the mass and the position of the centre of gravity (C of G), of a bond wrench: The mass of the wrench W_{bw} and of the target unit type W_u are measured by weighing to the nearest 10 g. After clamping the target unit in the jaws the position of the centre of gravity is found by balancing on a knife edge. This must be carried out for each position of the jaws (i.e. each unit depth) for which a calibration is required. Both the ASTM and the Australian Code require the weight of the top brick, in an actual test, to be taken into account in the calculation of the centre of gravity and the dead weight compression load on the bed joint. This requirement means that either these measurements are carried out with a unit in the jaws and that a separate calibration has, strictly to be carried out for each density of unit catered for or that the bond wrench is calibrated empty, the unit is weighed separately and the parameters are corrected for in a separate calculation. Three separate determinations are carried out for each parameter and the mean is taken.

3.7.2 Stage 2

First, measure the lever arm for the load point.

For deadweight bond wrenches using the filled container system, further calibration is not necessary since the load is derived from the mass of the container at failure.

For electronically measured bond wrenches a deadweight loading calibration of the measuring system is carried out. The device is clamped to a suitable support and, after resetting the electronics to zero, a load-hanger of known mass is suspended from the measuring handles: Known masses, up to a maximum of 70-100 kg in approximately 10 kg steps, are then added to the hanger and the reading noted. This process is then reversed to zero mass and the procedure repeated. A best-fit line is then drawn through the results and a calibration chart or spreadsheet is produced.

3.7.3 Stage 3

To relate bond wrench readings to stress: This is a paper exercise using the formulae given above to plot a graph of stress versus the bond wrench reading.

3.7.4 Calibration of load cell

A linearization method was used to calibrate the load cell and EDU, where 10 calibration points were entered to generate a curved function between the signal input and the value displayed. The process from calibration using this method works only if each increment displayed is greater than the previous one.

The EDU was zeroed as the starting point with the load cell being free from any load. Spread over 10 calibration points the load distribution ranged from 0-500N as this range is up to the highest expected value that can be obtained from a single test.

Each time a greater load was applied the exact total weight was adjusted to the desired value and then set. The weights used were calibrated by NPL and were still within calibration dates. Once all 10 calibration points were set and linearised the calibrated weights were used to check the validity of the calibration. It was found that a tolerance of ± 0.5% was present between what the calibrated weights were set to be by NPL and that of what was displayed on the EDU.

3.8 Variability of bond wrench measurements

Such is the variability of masonry bond that failure is common with no additional applied load to a bond wrench and yet, in some specimens, with a nominally similar specification, the same device can support the whole weight of a 100 kg operative at the end of a 1 m moment arm.

The bond wrench has been extensively studied and is used routinely in Australia to type-test potential unit-mortar combinations and, in the USA, to allow quality assurance checking of bond in large masonry contracts. In UK it has been used more as an investigative tool in cases where there is some doubt as to the bond being achieved in already-built or weathered masonry. In a paper by De Vekey et al (1994), some data from bond wrenches used for these three applications was analysed to look at the variability of the technique. The achievable running average of variability for deadweight wrenches used on bespoke stack bond specimens was under 20% coefficient of variation (COV). Where the wrench was used for investigation of existing structures, in both UK and Australia, the running average rose to around 50% COV. There are probably several reasons for this discrepancy the main ones being:

- Commercial brickwork is likely to have a lower standard of workmanship than specimens made for laboratory tests.

- The in situ samples were normally of brickwork, which was suffering from some problem which could have selectively reduced the bond, e.g. fire damage, weathering and under-specified mortars

- It was apparent that the coefficient of variation (COV) was influenced by the average bond strength. COV increased with lower bond strength specimens, which are often encountered in these circumstances.

The last factor in the list above was investigated statistically. It was found that the standard deviation was relatively constant for a population of data and those variations of the coefficient of variation were due to variations of the underlying mean. This is particularly noticeable where the wrench was used to do in situ tests on mortar joints which were at the low end of the strength range due the use of underspecified mortar where the variability climbed to above 50% compared with laboratory tests of strong joints where it could sometimes fall to around 15%.

Another area of investigation has been the stack prisms used for type testing and quality control. These are usually in the form of couplets, six brick units high (five joints) or 11-brick unit-high for ten joints, although other heights have also been used. For larger units, couplets are the only practical option since anything larger would be very easily damaged. Possible reasons advanced for such differences are:

- The different level of deadweight prestress during curing
- Damage to subsequent joints due to bending moment applied to the joints below the one tested
- Bias induced by the bond wrench itself
- Inequalities in the bond, particularly for units with one large frog or different sizes of frog
- Different curing conditions for different volumes of masonry.

Several authors have investigated the effect of different stack heights, but there is no clear evidence that this influences the test provided that the clamping system is arranged such as not to apply any bending moment to the joints below the tested joint. In the work of Hughes and Zsembery (1980), there was a direct comparison between a 9-high, 4-high and 2-high stack prisms. Additionally a prism test was initially carried out on the 9-high prisms leaving seven remaining joints for bond wrench tests. (Note: this was a slightly questionable exercise since it could be argued that the initial beam test would fail at the weaker joint and thus give an inevitably lower value than the remainder). The results, summarised in Table 3.7, indicate that the beam test did indeed give a lower result and that there was no difference between 9-high and 4-high stack specimens. Oddly the couplets gave a similar result to the beam test but this may have been due to curing differences of the different volumes.

3.9 Evaluation and comparison to other bond wrenches

During a study in the US a number of different bond wrench devices were distributed around the country to various laboratories, to measure the reproducibility of the test. The result was a very poor comparison. On examining the possibilities for the poor correlation between each bond wrench, it was found that most of the laboratories had no prior experience in using any bond wrench mechanism. The study was flawed and in time disregarded.

There has not been a great deal of investigation into details of the individual rigs. Equally as important is that by using a vice type device there is a possibility of applying some load too close to the joint and getting compression. Van Der Pluijm (1995) using finite element analysis has tried to analyse what goes on at the interfaces.

Evaluating and comparing bond wrench designs can be very difficult without a point of reference. As seen different designs incorporate different features with only some being counterbalanced but the main interface where the bond wrench meets the brick in the front end geometry has to meet the criteria stipulated in the standard.

The Reutter bond wrench meets the requirements stipulated in BS EN 1052-5:2005 for the front end geometry; furthermore the testing procedures are detailed in Chapter 4.

4. Methodology

Extensive research was carried out to establish the flexural bond strength of masonry using both the BS5628 wallette and the new BS EN 1052-5: 2005 bond wrench test methods. As part of the research programme all properties of the building units prior to building, as well as wet and dry properties of the mortar itself were ascertained. The methodology used for this research is described in this chapter thus forming a basis for subsequent chapters.

With the transition from the British Standards to the European Norm both the new and the old were conducted where possible, as a comparative study.

4.1 Properties of wet mortar – Workability

Workability is a term used to describe the consistency and texture of the mortar mix prior to bricklaying. Ideally, a mortar stays plastic (workable) for several minutes after being placed in contact with building units to allow precise positioning by the builder. Builders, through experience, develop a feel for the right consistency and workability for the mortar depending on conditions of use.

There are many different ways to ascertain the workability of mortar, greatly depending on the location of testing and the purpose of the intended findings. The majority of tests are only applicable for use in laboratories and in the hands of an experienced user.

Benningfield (2006) conducted detailed research into the rheological properties of mortar using almost all known workability tests.

The properties of mortar in the fresh state were assessed through a series of four tests. The superseded dropping ball and flow table tests, detailed in BS4551, were used as a comparison to the current plunger penetration and flow table European standard tests. Testing was conducted immediately after the mixing process, and the procedures are described in the following sections.

4.1.1 Flow table – BS 4551-1: 1998

Constructed of a brass table top 254 mm in diameter, with an edge thickness of 7.6 mm; mounted and a vertical shaft 15.82 mm, as illustrated in Figure 4.1.1.1. Through turning of the handle the flow table is raised by a cam being allowed to fall 12.72 mm. The method is detailed in BS 4551-1: 1998.

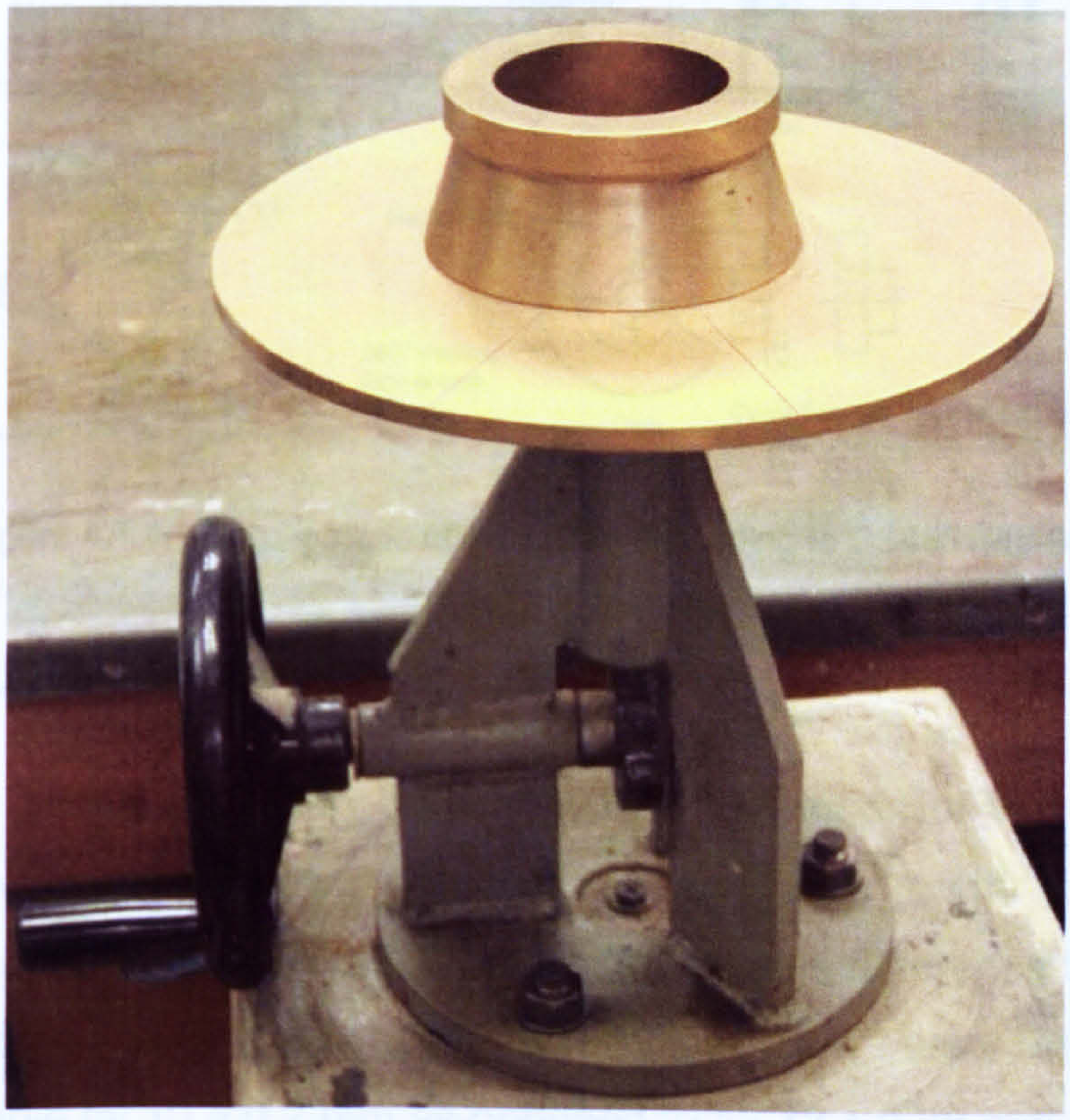


Figure 4.1.1.1 – Photo of flow table according to BS4551-1:1998

After fifteen rotations of the handle the spread of the mortar is measured using a calibrated calliper. The flow of the mortar is calculated as the resulting increase in average diameter of the mortar, measured on four diameters at equal intervals, expressed as a percentage of the internal base diameter of the mould, and reported to the nearest 5 %.

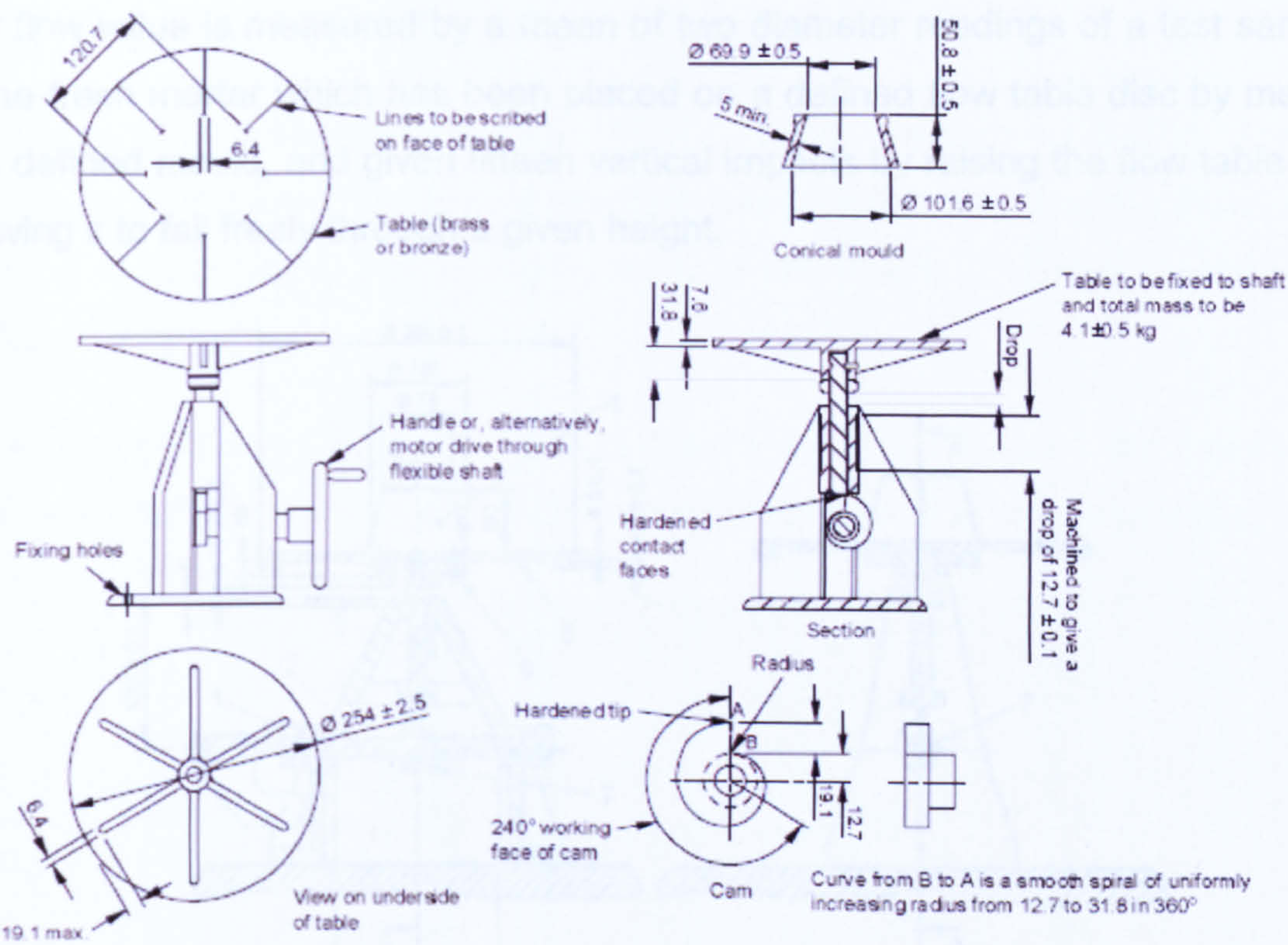


Figure 4.1.1.2 – Schematic of flow table according to BS4551-1:1998

4.1.2 Flow table – BS EN 1015-3: 1999

Carried out in accordance with BS EN 1015-3; "Methods of test for mortar for masonry – Part 3 Determination of consistence of fresh mortar (by flow table)". Similar in test method to the old BS 4551 with the main difference being: the cam design and subsequently the fall height. The lifting cam raises the lifting spindle and the flow table by 10 ± 0.2 mm as opposed to 12.72 ± 0.38 mm in the previous standard.

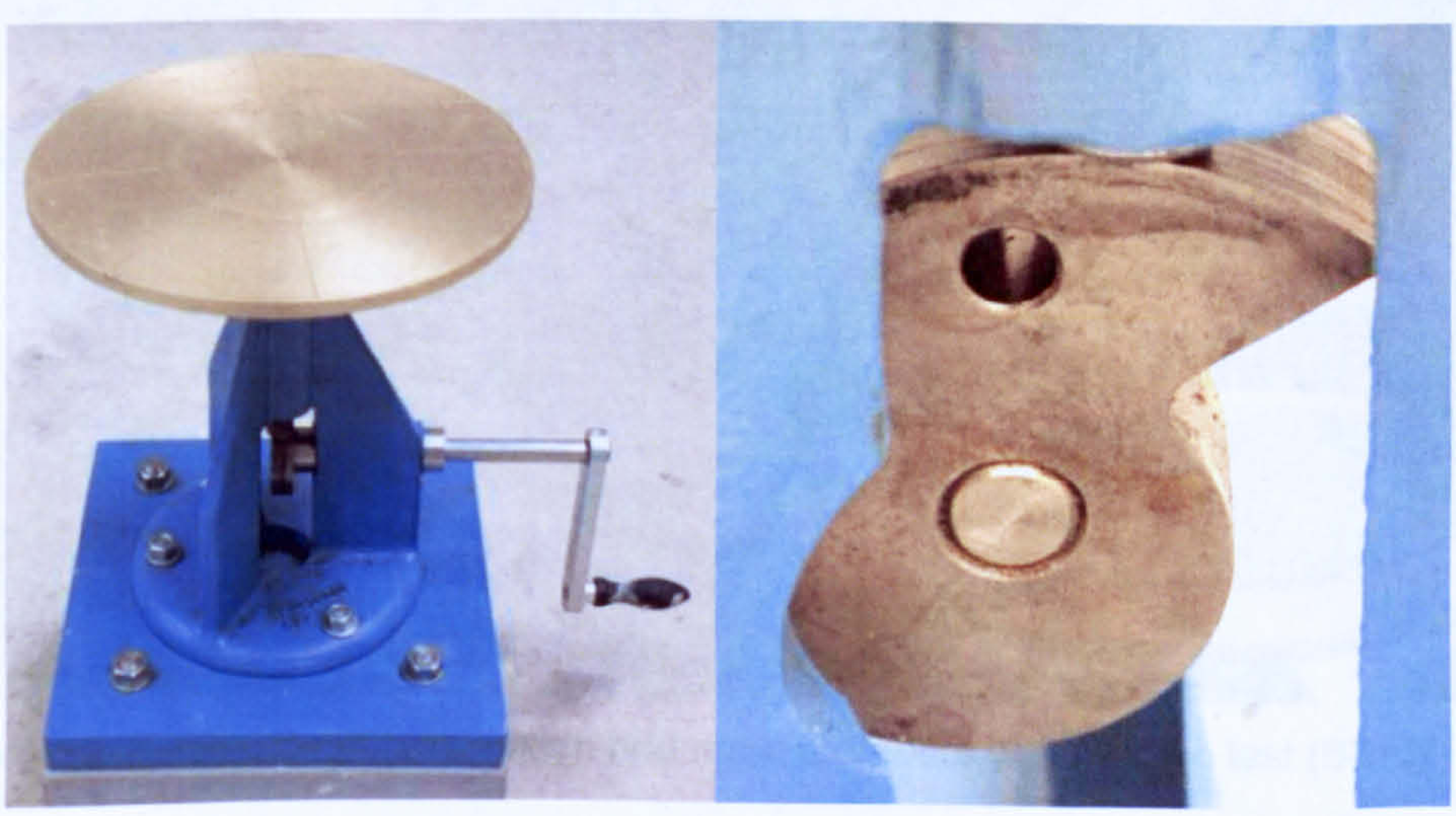


Figure 4.1.2.1 – Photo of flow table and zoom in into the cam

The flow value is measured by a mean of two diameter readings of a test sample of the fresh mortar which has been placed on a defined flow table disc by means of a defined mould, and given fifteen vertical impacts by raising the flow table and allowing it to fall freely through a given height.

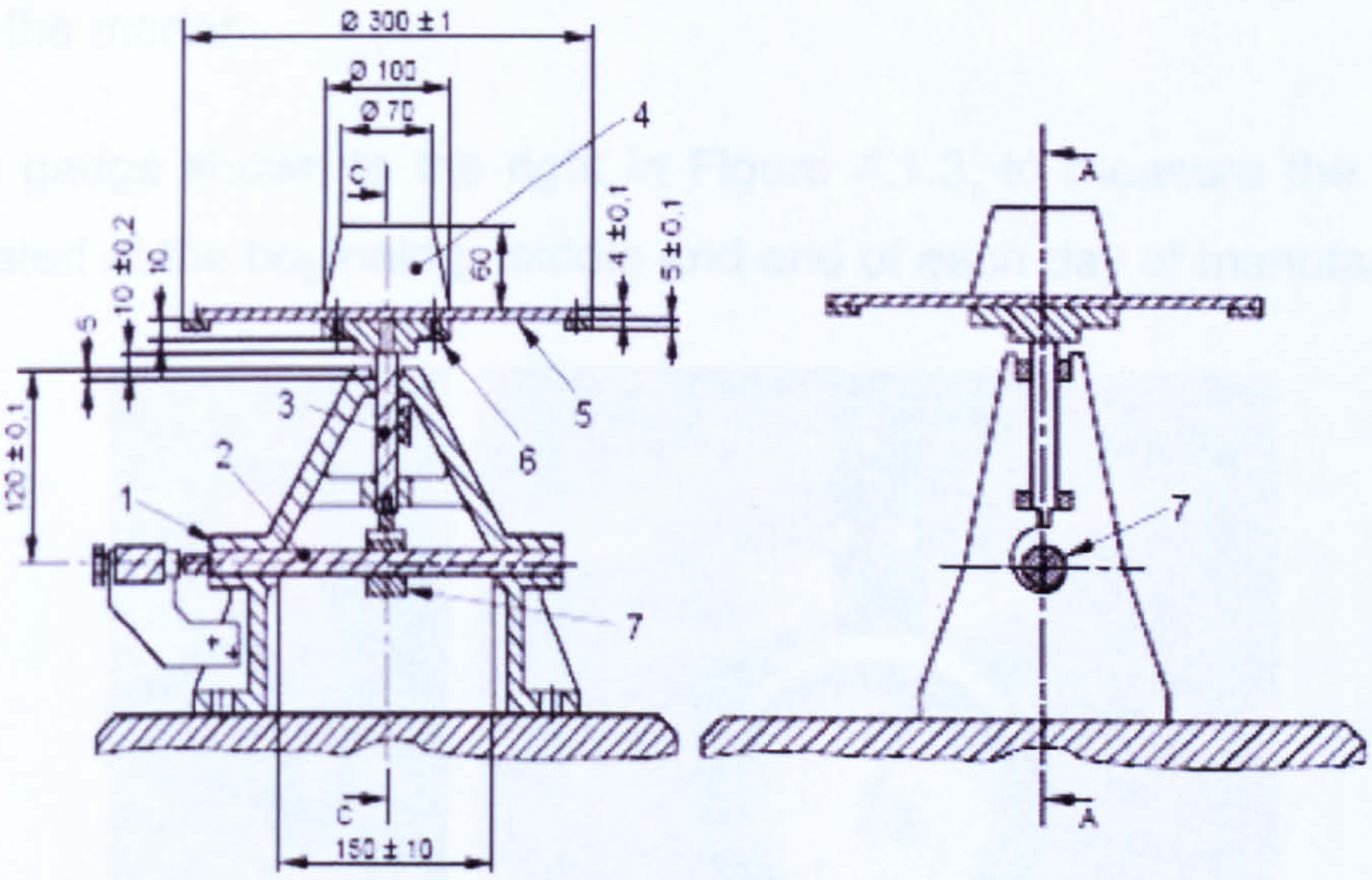


Figure 4.1.2.2 – Schematic of flow table according to BS EN1015-3: 1999

Key 1: Stand, 2: Horizontal shaft, 3: Lifting spindle, 4: Truncated conical mould, 5: Disc, 6: Rigid table plate, 7: Lifting cam

Figure 4.1.2.3 – Photos of preparation and measurements of flow table test (BSEN1015-3)

4.1.3 Drop ball – BS4551-1: 1998

Carried out in accordance with BS 4551–1 (1998) Methods of testing mortars, screeds and plasters. The aim of this exercise was to determine the indentation depth a methrancrate ball dropping from a set height 250 mm breaking the surface of the mortar.

The depth gauge shown to the right in Figure 4.1.3, to measure the indentation was calibrated at the beginning, middle and end of each day of manufacture.

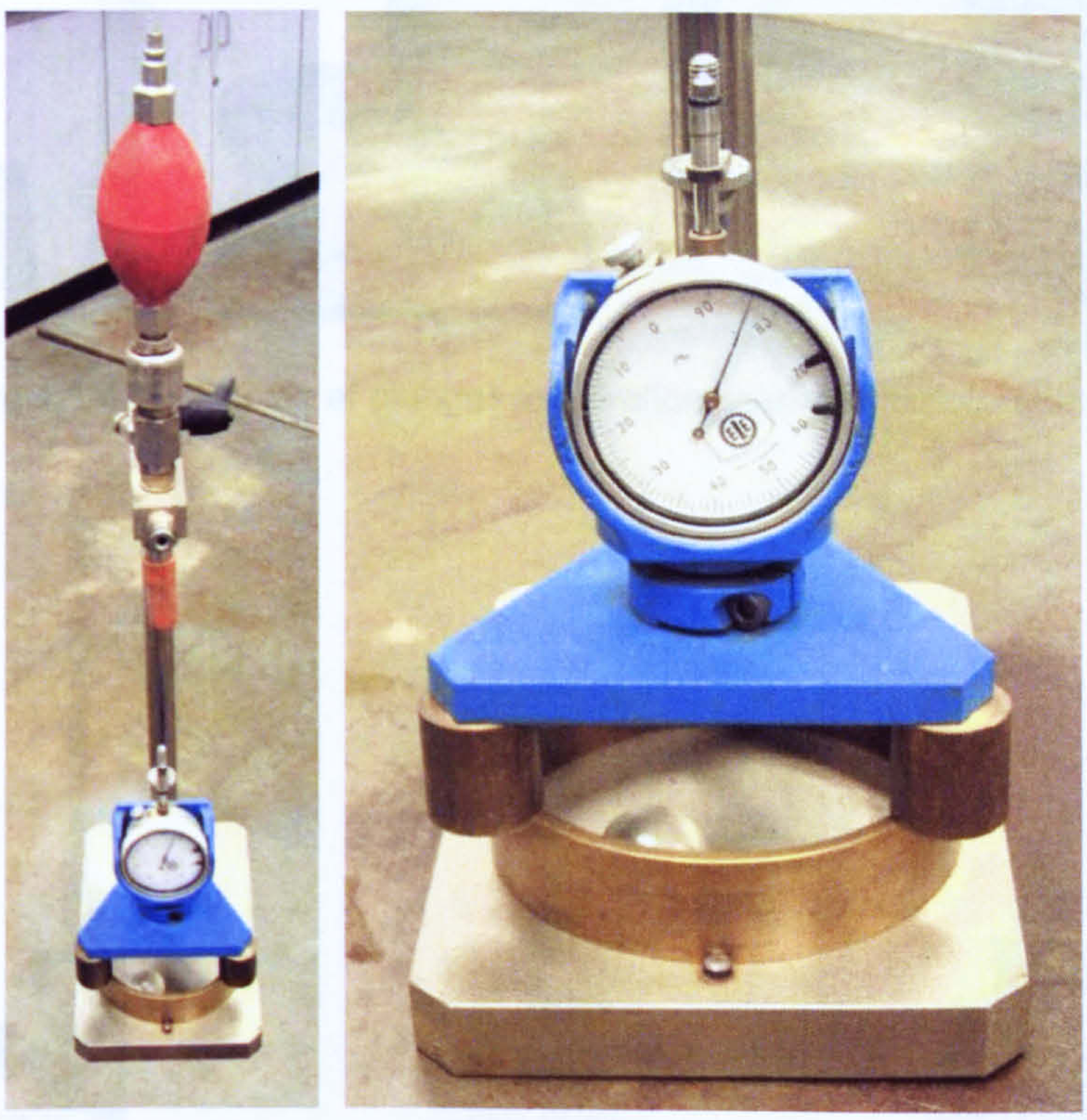


Figure 4.1.3 – Photos of dropping ball assembly and depth gauge

4.1.4 Plunger penetration – BSEN 1015-4: 1999

Carried out in accordance with EN 1015-4: 1999 Methods of test for mortar for masonry - Part 4: Determination of consistence of fresh mortar (by plunger penetration). The aim of this exercise was to determine depth the plunger dropping from a set height penetrates the surface of the mortar.

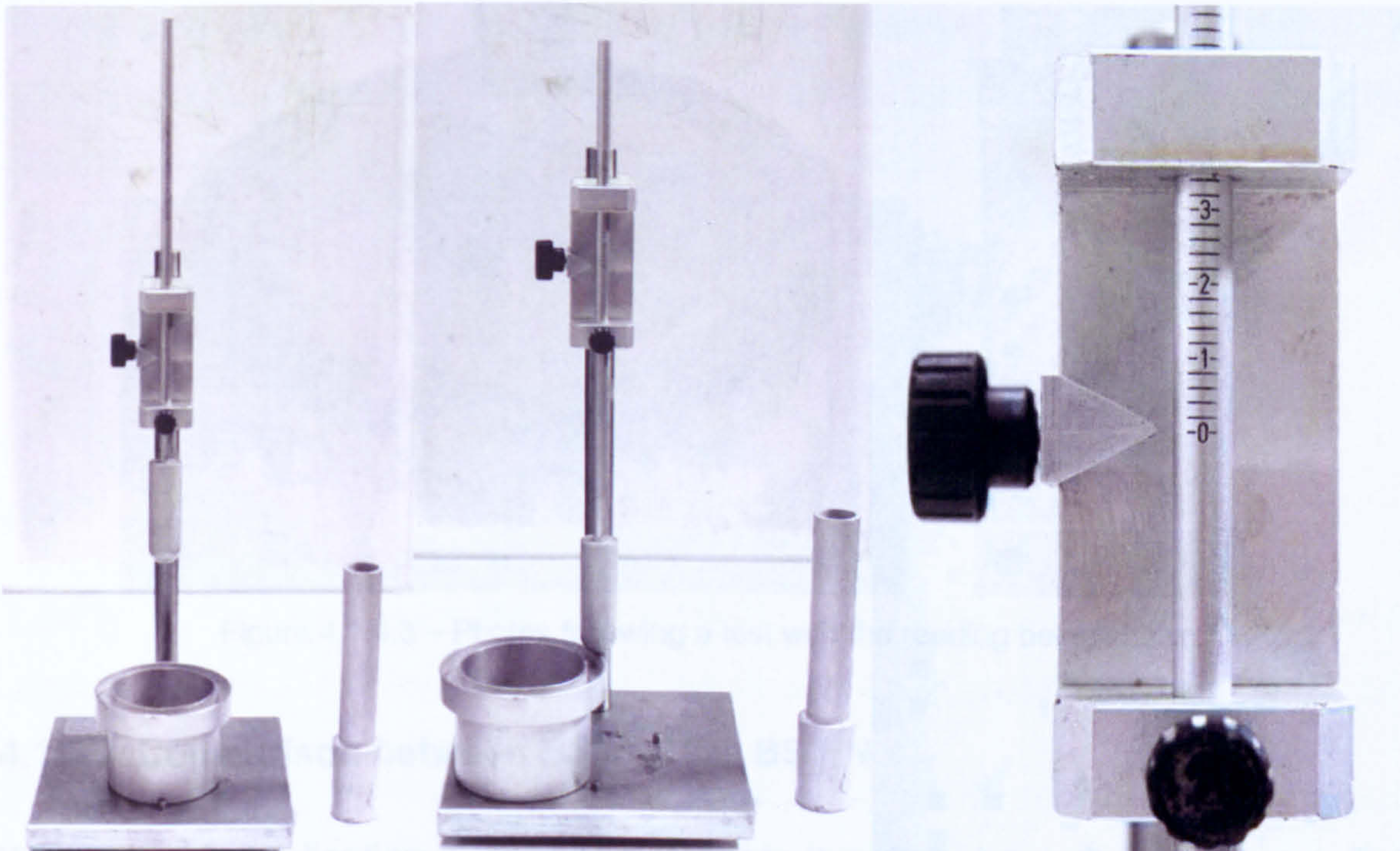


Figure 4.1.4.1 – Photos of plunger penetration assembly being calibrated

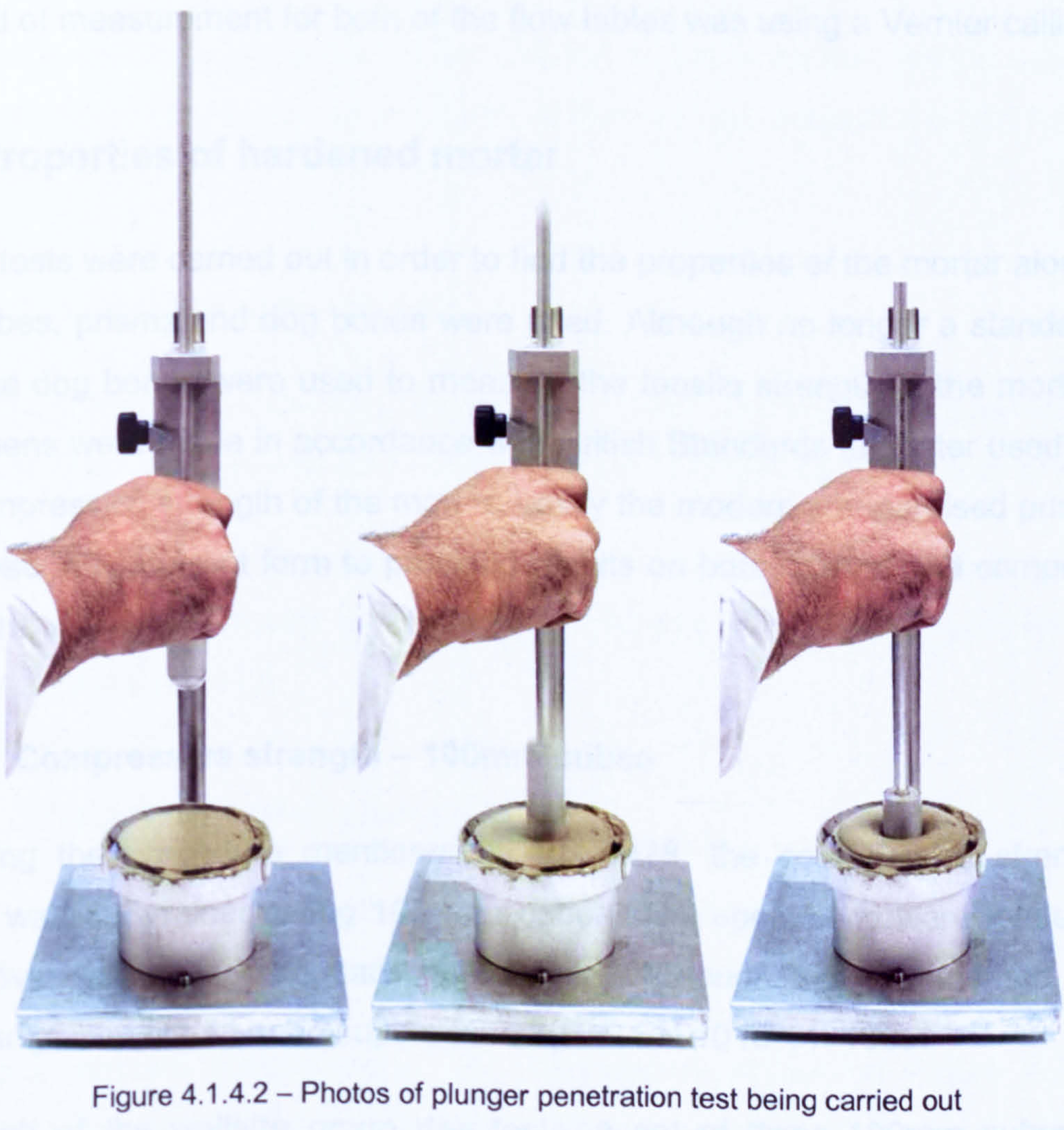


Figure 4.1.4.2 – Photos of plunger penetration test being carried out

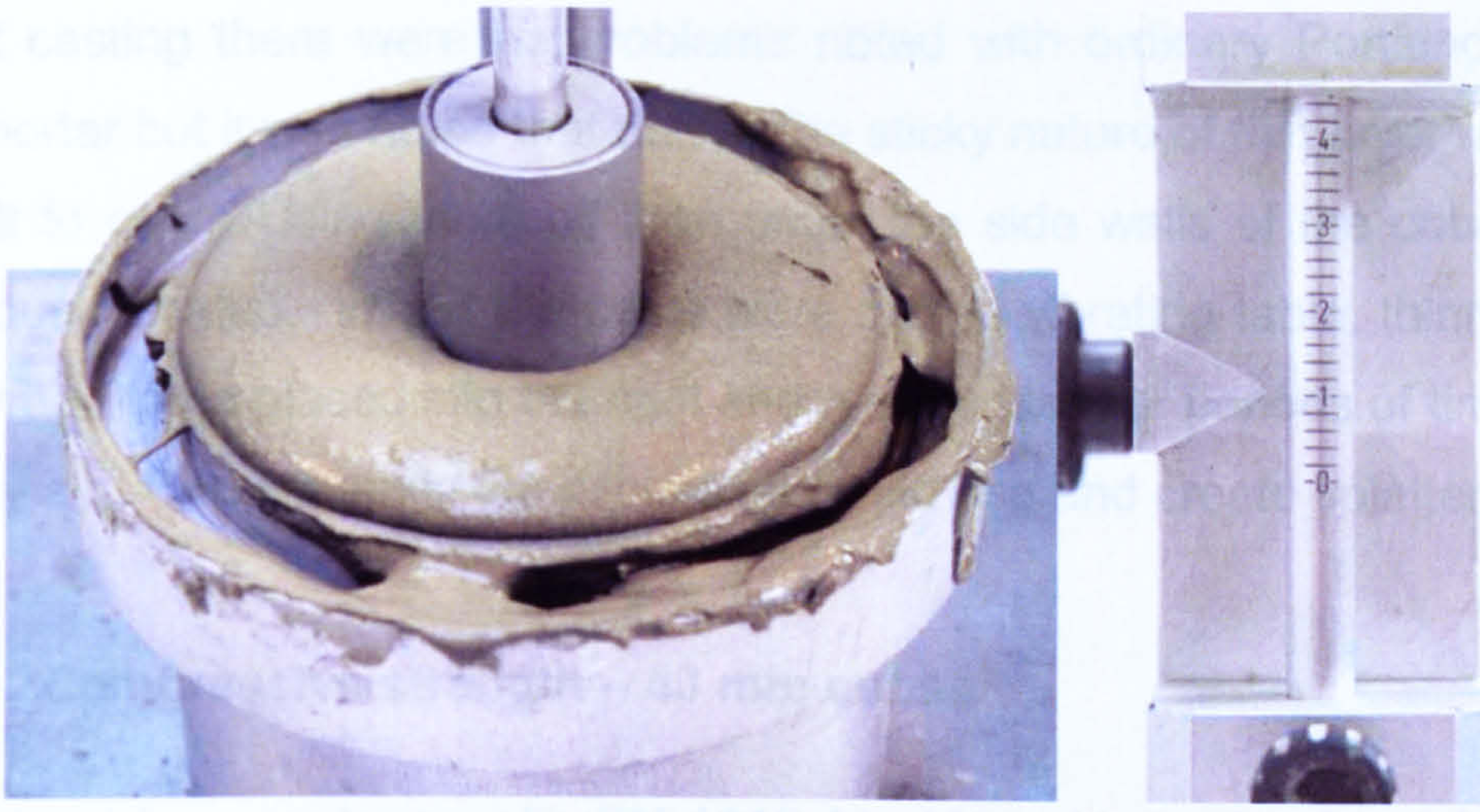


Figure 4.1.4.3 – Photos following a test with the reading being shown

4.1.5 Comparison between BS and the BS EN

With the standardisation of BS EN standards the dropping ball and old cam flow table were superseded by the plunger penetration and new cam flow table. The method of measurement for both of the flow tables was using a Vernier calliper.

4.2 Properties of hardened mortar

These tests were carried out in order to find the properties of the mortar alone. For this cubes, prisms and dog bones were used. Although no longer a standardised test, the dog bones were used to measure the tensile strength of the mortar. All specimens were made in accordance with British Standards and later used to test the compressive strength of the mortar. Lastly the modern standardised prism test was used in its current form to provided results on both flexural and compressive strength.

4.2.1 Compressive strength – 100mm cubes

Following the procedure mentioned in BS 5628, the compressive strength of mortar was determined using 100 mm cubes. The specimens were loaded at a rate governed by the standard until failure. Although this BS method is still commonly used, it has been superseded by BS EN 1015-11: 1999.

For each of the wallette group day tests, a set of three 100mm cubes were manufactured.

Whilst casting there were no problems noted with ordinary Portland cement or lime mortar but it was noted that due to the sticky nature of thin layer mortar it was difficult to cast. Using more oil than usual the side walls of the cube had to be generously coated. Whilst the casts were on the vibrating table, thinner layers of mortar had to be placed into the cast and required longer periods of time to bubble out any air. Consequently the excess oil would rise and create splatter.

4.2.2 Compressive strength – 40 mm cubes

Carried out in accordance with EN 1015-11: 1999. *Methods of test for mortar for masonry - Part 11: Determination of Flexural and Compressive strength of Mortar.*

For each of the wallette group day tests a set of three 40mm prisms were manufactured, giving 6 readings after the prisms have been broken in two following the flexural test on the mortar.

Due to the smaller surface area it was difficult for the automatic testing machine to detect early age compressive strengths of lime mortar. Instead the test had to be performed manually.

4.2.3 Flexural strength – prisms

Carried out in accordance with EN 1015-11: 1999. *Methods of test for mortar for masonry - Part 11: Determination of Flexural and Compressive strength of Mortar.*

Similarly to the problems experienced with moulding the 100mm cubes excess oil had to be used to ensure a uniform prism shape with no void, perforations or bubbles in the specimen.

4.2.4 Direct tensile of dog bones

There is no British or European standard, using this test for mortar testing. The theory and technique behind it is simple and used in other fields of engineering.

Dog-bone shaped specimens of the dimensions shown in Figure 4.2.4.1 – Schematic diagram of dog bone configuration; dimensions in mm were used. The specimen's cross sectional area is 25 x 25 mm in the narrow part of the dog-bone shape. Specimens were prepared by casting into moulds of the same shape and size. Tensile testing was performed using a automatic testing rig that applied a constant load until failure.

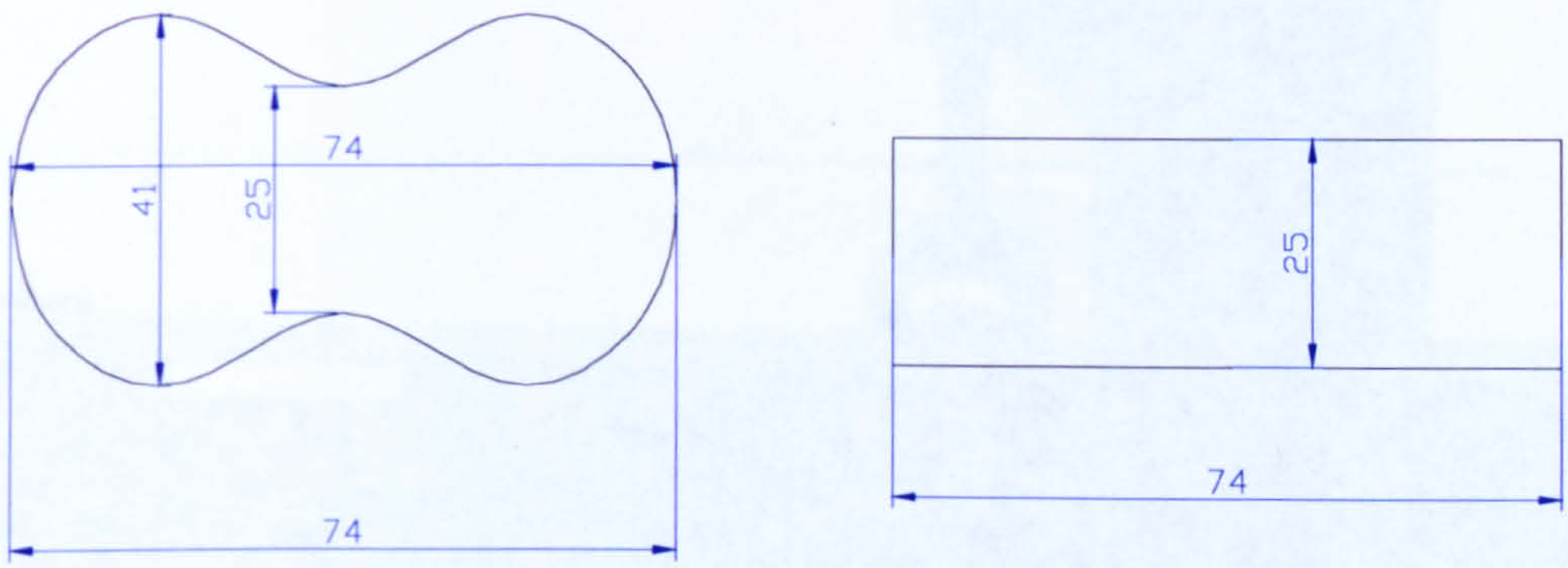


Figure 4.2.4.1 – Schematic diagram of dog bone configuration; dimensions in mm

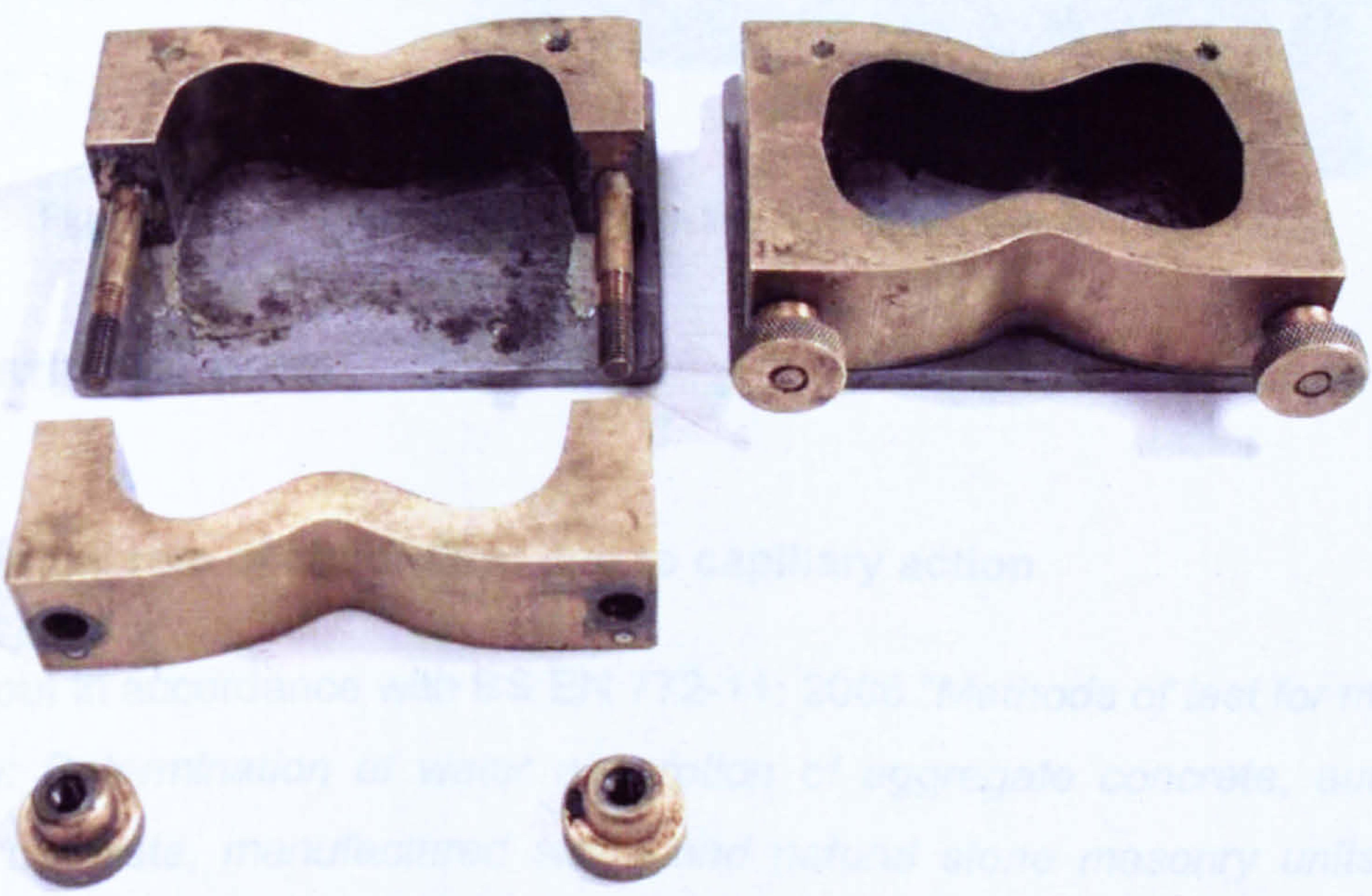


Figure 4.2.4.2 – Photos of dog bone moulds

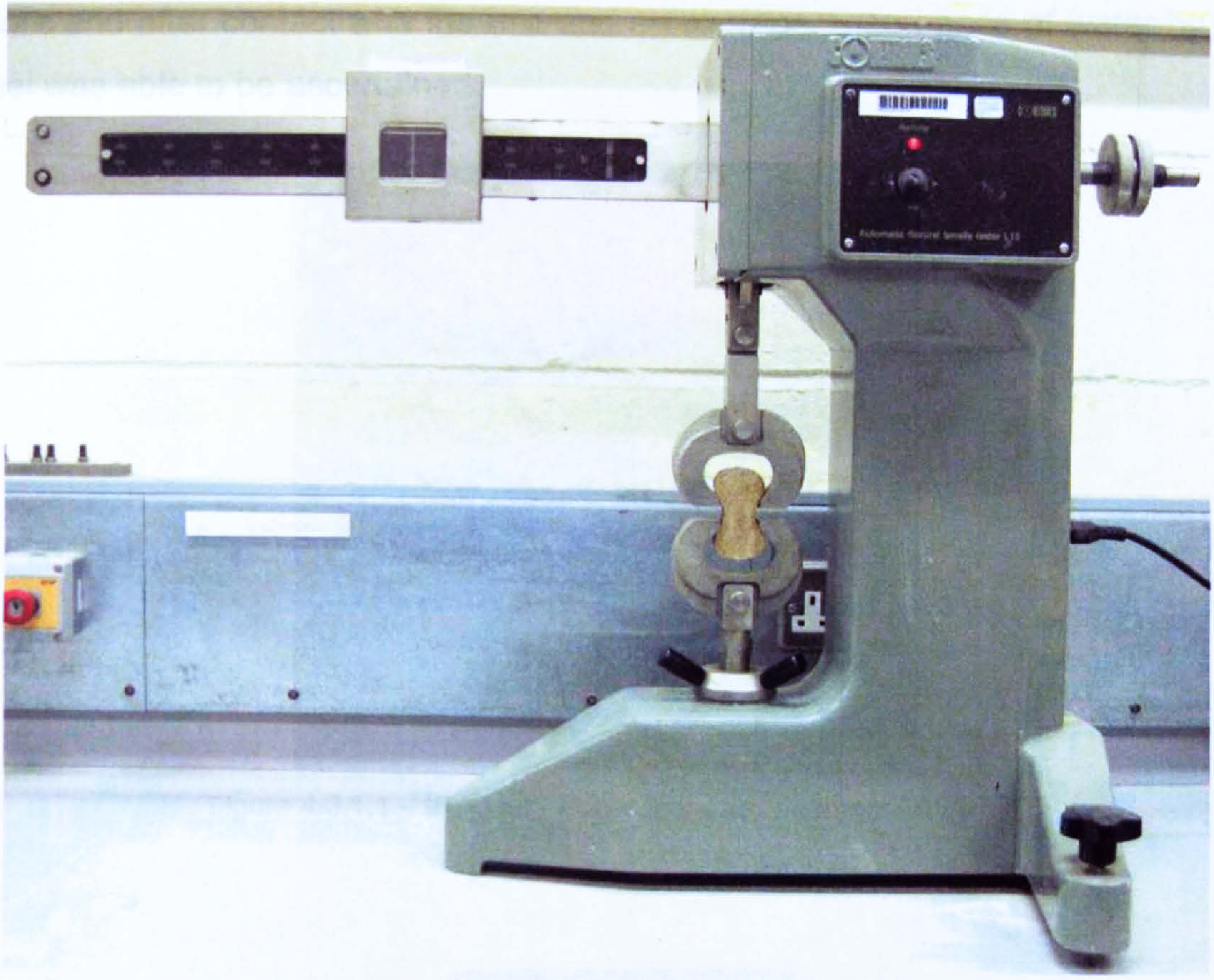


Figure 4.2.4.3 – Photo of dog bone testing rig with a specimen being tested

4.3 Testing of units

4.3.1 Initial rate of absorption due to capillary action

Carried out in accordance with BS EN 772-11: 2000 *"Methods of test for mortar for masonry: 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"*.

To increase the accuracy and better understanding of initial rate of suction or also known as water absorption; a spread of immersion times were used above and below the specified times.

The standard explains that after immersion in water for a specified time the sample should have the excess water wiped off the surface before weighing. Since this seemed to be too ambiguous in not knowing how to wipe an improved method was devised. As seen in Figure 4.3.1.1, the unit was placed on a clean and dry paper towel for 1 second before being weighed. The towel was weighed before and after contact with the unit and an average absorbance of water by the towel was able to be ascertained.

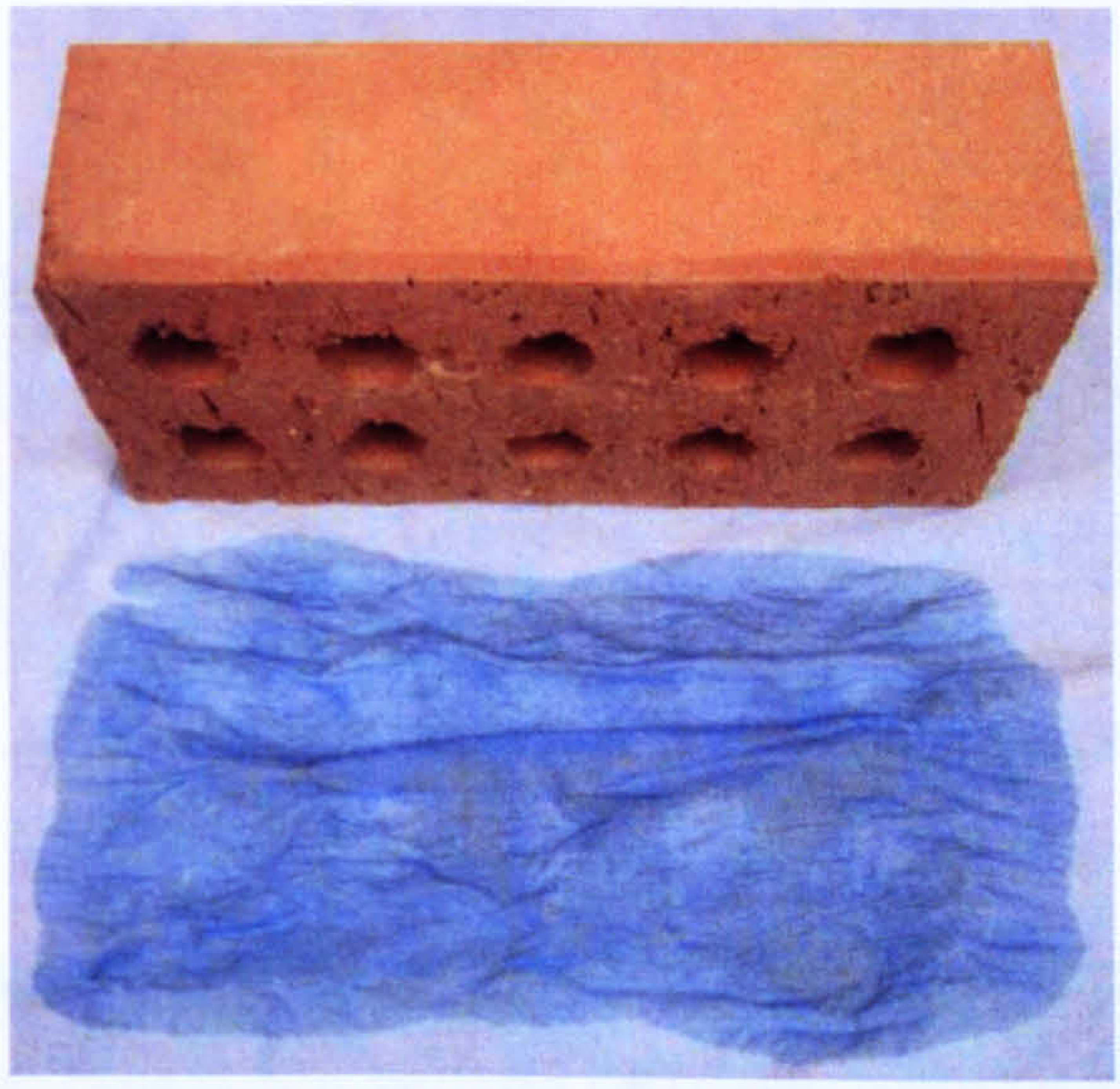


Figure 4.3.1.1 – IRA test - Paper towel after contact with unit

Figure 4.3.1.2 – IRA test – Brick being weighed

Following Figure 4.3.1.3 – Apparatus for measuring the water capillary suction of units each time a unit was taken out it was placed on a paper towel for 1 second and then immediately weighed.

Another addition was measuring the height of the watermark left after the immersion. Since the watermarks were all irregular, measurements were taken using a Vernier calliper at the centre of each side's length and shown in Figure 4.3.1.4 – IRA test – Measuring the height of the watermark

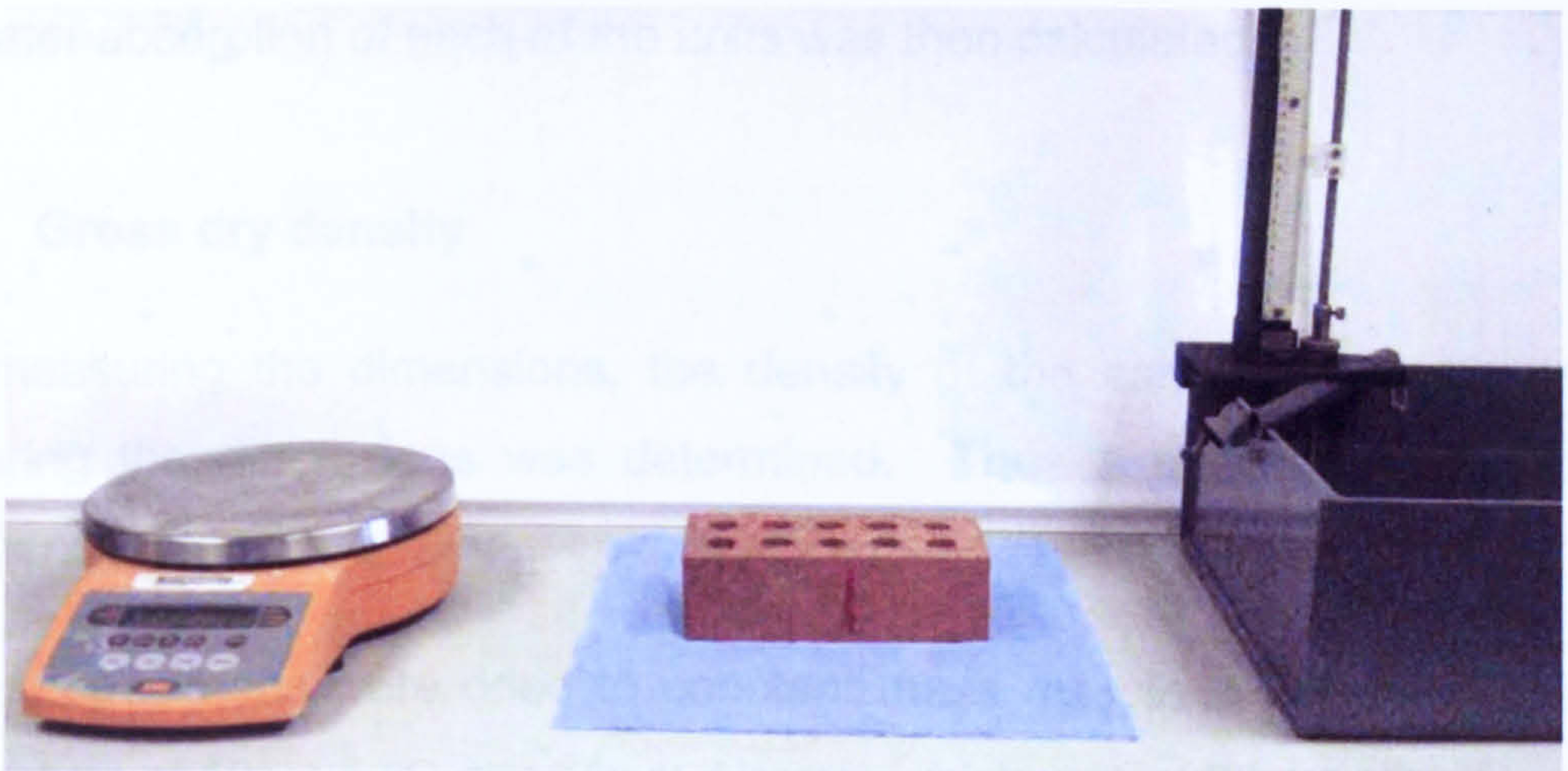


Figure 4.3.1.3 – Photo of apparatus for measuring the IRA of units

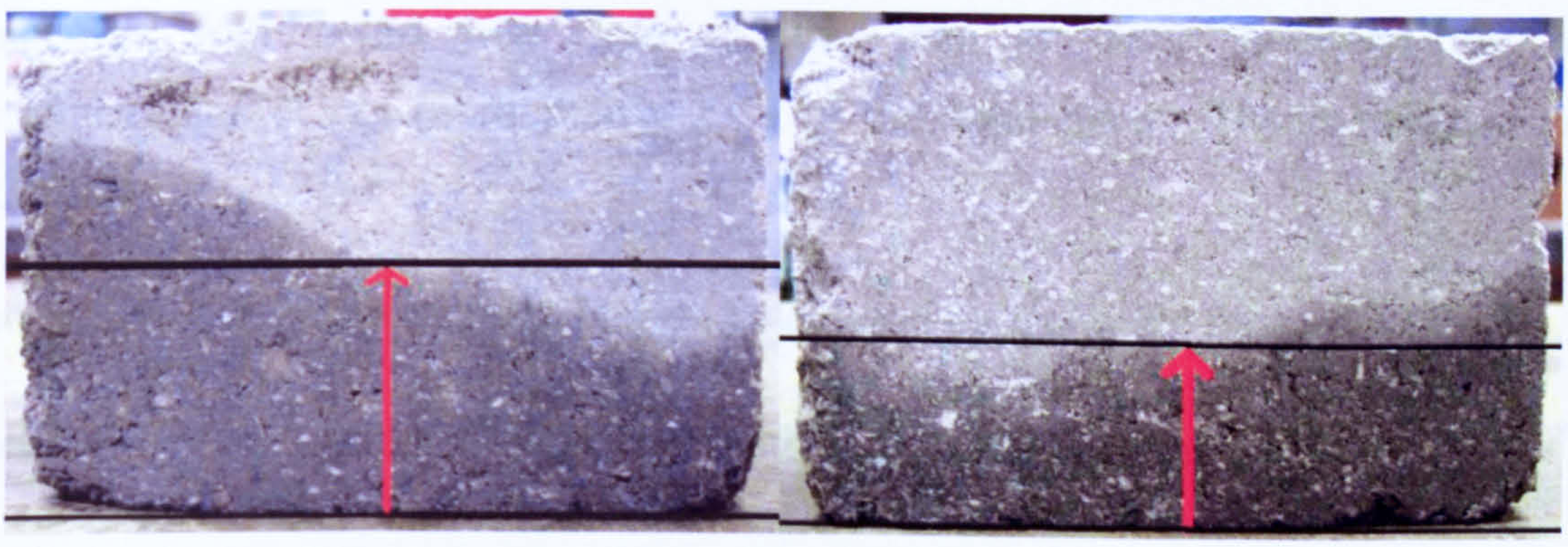


Figure 4.3.1.4 – IRA test – Measuring the height of the watermark

4.3.2 Water absorption – "Cold Soak"

Carried out in accordance with Annex C of BS EN 771-1: 2003 "Specification for clay masonry units"

Although this standard is for clay unit, for the purposes of comparison these tests were in addition carried out for the concrete and Aircrete units. The concrete units were oven dried at 105 °C and Aircrete at 70°C, to a constant mass.

Each unit was placed in the tank of water at room temperature and made full contact with all faces of the unit by resting the units on pieces of metal.

Following submergence for 24 h, the units were removed from the tank and momentarily placed on a new, clean and dry tissue before being weighed. The purpose of the clean and dry tissue was to see how much surface water was being absorbed each time from the units.

The water absorption of each of the units was then calculated.

4.3.3 Gross dry density

After measuring the dimensions, the density of the same specimens used for measuring the dimensions was determined. Thus a minimum number of six specimens were tested.

The test specimens were dried to constant mass $m_{dry,}$ in a ventilated oven at a temperature of 105 ± 5 °C apart from Aircrete which was at 70 ± 5 °C.

Constant mass is reached, if during the drying process in two subsequent weighings with a 24 hour interval, the loss in mass between the two determinations is not more than 0.2 % of the total mass. The mass m_{dry} was recorded

The volume (V) of the material is then calculated by using the formula:

Volume = length x width x height, the value is expressed to the nearest 10^4 mm^3.

Having calculated the gross volume $V_{g,u}$ of the unit from the unit dimensions subtracting the volume of perforations the following formulae found the gross dry density ρ_{gu} by dividing the dry mass ($m_{dry,u}$) by the gross volume ($V_{g,u}$) of the unit:

$$\rho_{g,u} = \frac{m_{dry,u}}{V_{g,u}} \times 10^6 (kg/m^3)$$

4.3.4 Compressive strength of units

Carried out in accordance with BS EN 772-1: 2000 "Determination of compressive strength of units". The units had a 2 mm thin piece of plywood placed on the top and bottom to negate any irregularities of the units. The loading rate was chosen in accordance with "Table 2" of the standard after testing an extra unit as an indicator.

4.4 Properties of wallettes

The standards specify a method for determining the flexural strength of masonry wallettes for both of the axes of loading. The two types of wallettes are known as B and P. The standards cover the specifics for the manufacture, conditioning and testing and further more the calculations for the analysis. As seen in Figure 4.4 – BS5628 – B and P Wallette, B wallettes test for the flexural strength of failure parallel to the bed joint, whilst P wallettes test for the failure perpendicular to the bed joints.

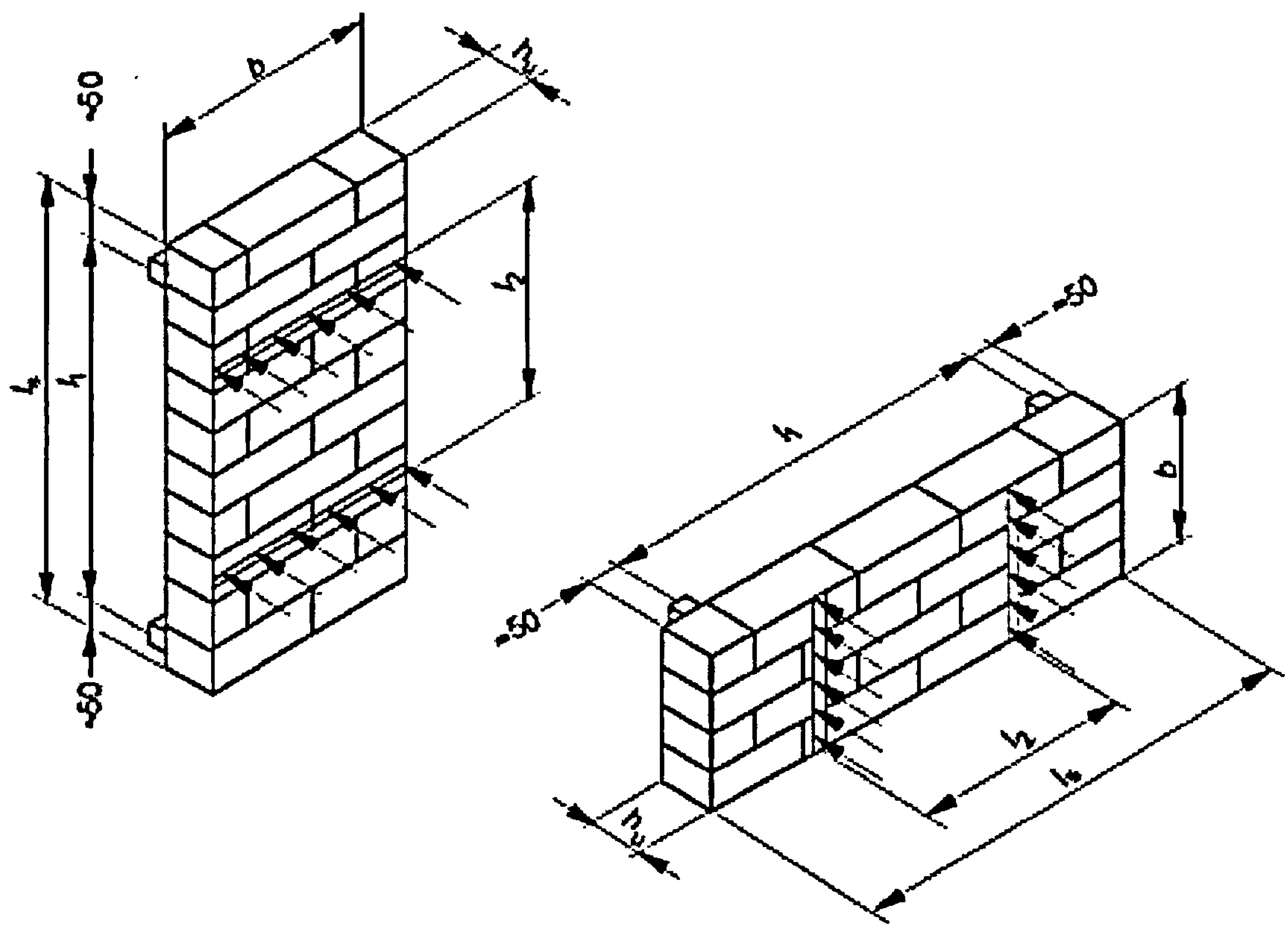


Figure 4.4 – BS5628 – B and P Wallette

4.4.1 Manufacture of wallettes

The wallettes were manufactured according to the methods described in BS EN 1052-2: 1999. The specimens were pre-compressed with three courses of bricks along the full length of the wallette and kept covered with a polythene sheet until the day of their testing.

The two methods used in building the wallettes were:

- "Bricky" tool for the OPC and NHL
- Specially designed scoop when building with thin joint mortar.

As seen in Figure 4.4.1.1 – "Bricky" Tool, this ingenious design enables the laying of a precise 10mm bed of mortar on the horizontal bed and vertical joint. The template enables constant reproducibility. The mortar joint left by the "Bricky" tool was of a raked form and was constant throughout the OPC and lime specimens.

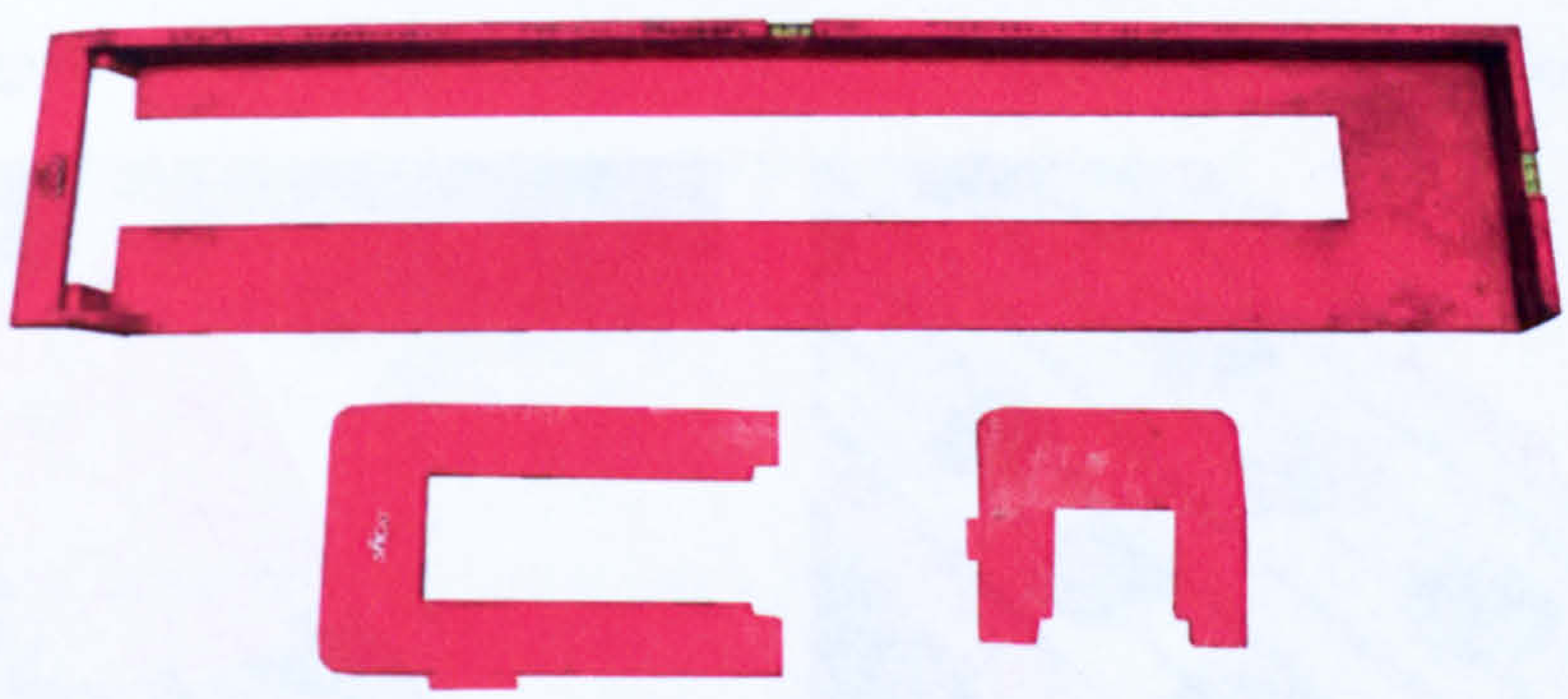


Figure 4.4.1.1 – "Bricky" Tool

The "Bricky" tool works on perpend joints as well and is illustrated below in Figure 4.4.1.2.

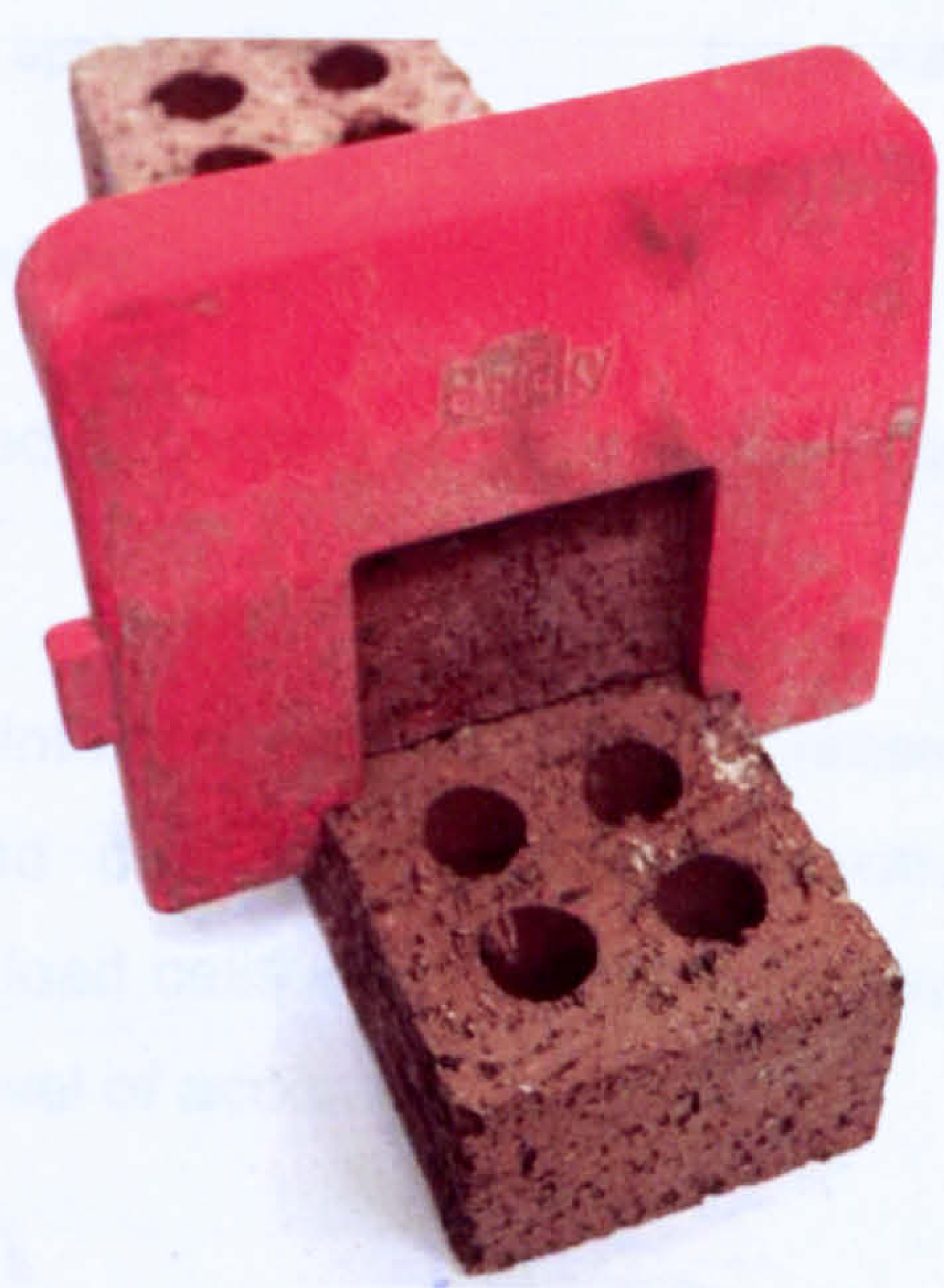


Figure 4.4.1.2 – "Bricky" tool in place for mortaring the perpend joint

The scoop for laying TLM is shown in Figure 4.4.1.3 and 4.4.1.4. Figure 4.4.1.4 shows the mortar contents within the scoop just after laying. Figure 4.4.1.5 and 4.4.1.6 illustrate the actions used for laying TLM.

Figure 4.4.1.3 – TLM scoop

Figure 4.4.1.4 – TLM scoop with mortar

Figure 4.4.1.5 – Scoop applying TLM

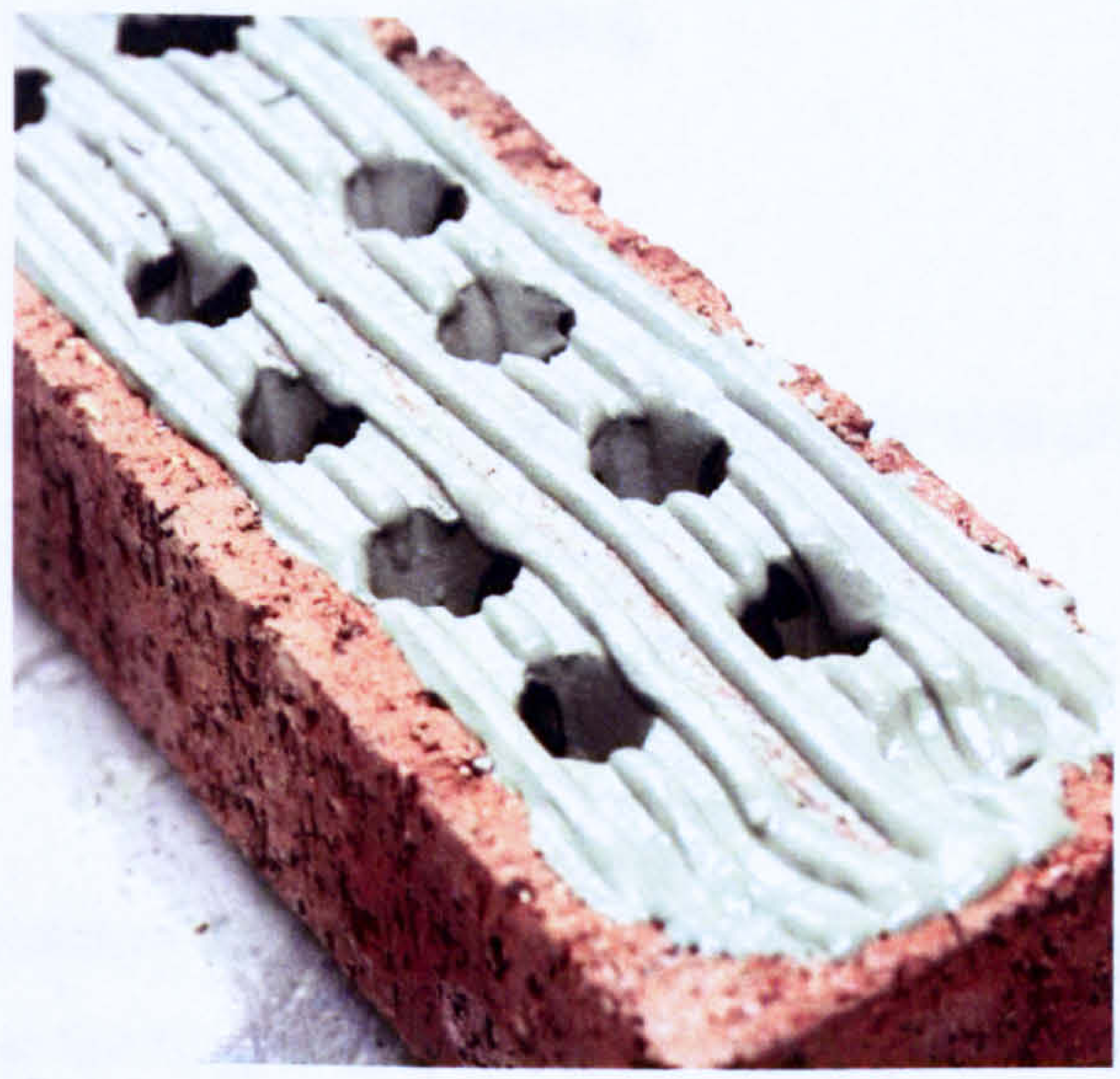


Figure 4.4.1.6 – Layer of TLM mortar

4.4.2 Testing of wallettes

The wallettes were tested according to the methods described in BS EN 1052-2: 1999.

The testing rig was maintained with constant dimensions for both the B and P configurations. The load cells and loading apparatus were all within close calibration periods. The load cells were changed depending on the expected load to further increase the level of accuracy.

4.5 Couplets

The standard for manufacturing specimens to be tested using the Bond Wrench give scope of choice in that either stack bonded prisms or couplets can be built to ensure at least 10 results per test. Couplets were chosen as the preferred specimen.

4.5.1 Manufacture

As with the wallettes the same method of manufacture was employed in building the couplets All couplets were individually pre-compressed with three bricks on top and then covered using a polythene sheet until the day of testing.

4.5.2 Testing

After a specified time the couplets were individually tested using the Reutt wrench and method described in BS EN 1052-5: 2005.

4.5.3 Classification of results

The test results include the mode of breakage at the interface between the unit and mortar. The descriptions of failures according to BS EN 1052-5: 2005 are as follows:

- A1: Failure at interface between mortar and upper unit
- A2: Failure at interface between mortar and lower unit
- A3: Failure at interface between mortar and both units
- A4: Tension failure within mortar bed
- A5: Tension failure within unit near interface
- A6: Failure at interface between mortar and frogged unit
- A7: Crushing/shearing failure of unit where clamped

Diagrammatically the modes of failure descriptors represent the following form of breakage:

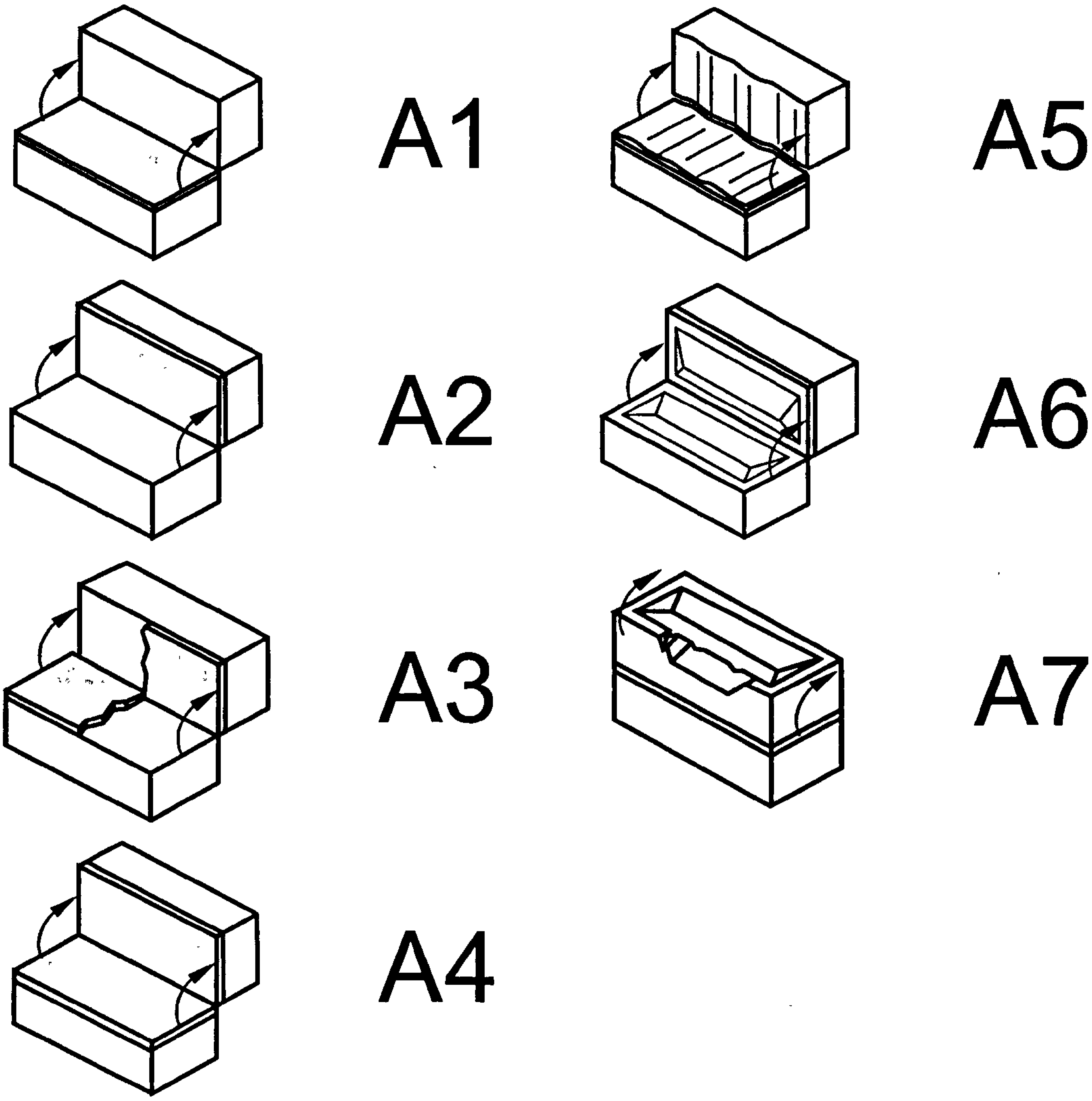


Figure 4.5.3 – Diagrammatic classification of couplet failures

5. Data Discussion

Investigating the comparison between the BS EN 1052-5:2005 bond wrench procedure with BS 5628-1:1992 wallettes, tests to ascertain properties of the constituent materials and the mortar were carried out. Where available, testing was conducted in accordance with procedures in the relevant British Standards (BS) and European Norms (EN).

Testing of the hard states of mortar was conducted prior or immediately after tests on wallettes or couplets. Wallette specimens were loaded with uniform applied stress and the crack patterns and bond breakages were noted and are detailed in Appendix E.

Predominantly, this chapter contains the means of the results data obtained during the testing program. The results are illustrated in tabular form, with brief comments on the data. Full details are contained in the appendices and a more detailed discussion of the results is presented in Chapter 6.

For the purpose of this chapter abbreviations for units and mortar will be used to enable quick identification of trends. The following table denotes the terms used:

RED	R
AIRCRETE	A
CONCRETE	C
YELLOW	Y

NHL	N
OPC	O
TLM	T

All trends start with the greatest significant value and end with the least.

5.1 Constituent materials of mortar

The purpose of ascertaining the properties of the material was to check the suitability in relation to BS and EN guidelines.

Each of the three mortar mixes had different variations of constituent materials. This section details the materials properties obtained through lab tests. Where data was not present manufacturers specifications were used.

OPC mortar consists of a 1:1:6 ratio mix of ordinary Portland cement, hydrated lime, and building sand respectively. In comparison NHL mortar is a 1:3 ratio mix of natural hydraulic lime and sharp sand. Conversely the constituents on thin layer mortar are different, depending on the manufacturer, but essentially contain polymer modified cement and finely ground sand.

Mortar strength is influenced by the range of properties associated with its constituent materials. For example, using sharp sand with a wider range of particle sizes, helps develop improvements in hard strength characteristics for NHL mortar. Similarly, OPC is dependant on the reaction between the sand and cement, hence the use of soft sand with predominantly smaller particles. In contrast TLM is a ready mix of a very finely ground powder containing sand. TLM is premixed and only requires the addition of water, to form a thinner mortar joint.

5.1.1 Sand

Sand is used as an aggregate in mortars. Aggregate for use in OPC mortar is most often referred to as "building (soft) sand" and is generally defined as a material mainly passing a 5.00 mm BS test sieve which may be either a natural sand or one obtained by crushing hard rocks or gravels. Sand for lime mortars such as NHL have a coarser texture with an evenly distributed range of larger particles. This is to provide a more closely bonded mortar which will be stronger as a result.

Two types of sharp sand and one type of building sand were assessed using methods detailed in BS 3921.

JEWSON BUILDING SAND		
Sieve	Sand	Passing
mm	g	%
2.36	0.0	100
1.18	1.5	100
0.600	33.0	89
0.300	193.0	24
0.150	65.0	3
Fines	7.5	0

Table 5.1.1.1 – Particle distribution for Jewson's building sand

Sands for OPC

Jewson soft building sand has a well graded particle size distribution because it is fine in nature; and therefore considered to be suitable for use with OPC mortar. The origins of the sand cannot be specified since the sand is a mix of similar sands but from different quarries.

Sands for lime mortar

JEWSON SHARP SAND		
Sieve	**Sand**	**Passing**
mm	g	%
2.36	63.5	79
1.18	18.5	73
0.600	16.0	68
0.300	43.0	53
0.150	134.5	9
Fines	24.5	0

TRAVIS PERKINS SHARP SAND		
Sieve	**Sand**	**Passing**
mm	g	%
2.36	39.0	87
1.18	54.0	69
0.600	58.5	50
0.300	95.0	18
0.150	48.5	2
Fines	5.0	0

Table 5.1.1.2 & 5.1.1.3 – Particle distribution for Jewsons' and "Leighton Buzzard" sharp sand

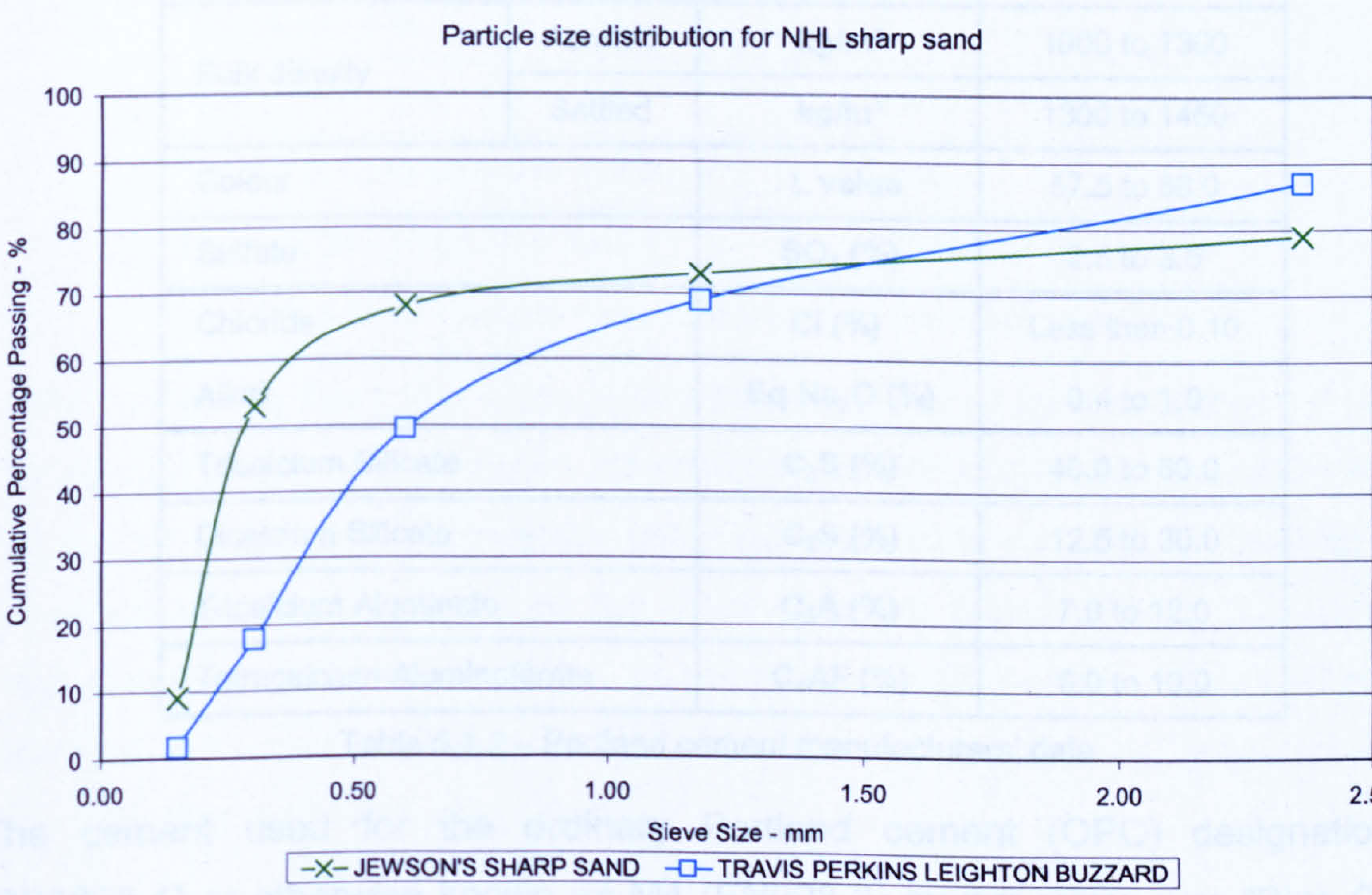


Figure 5.1.1 – NHL Sand particle size distribution

Jewson's Sharp sand did not attain the required particle size distribution because there were too many of the larger particles; and consequently determined to be unsuitable for use in Lime mortar. Although sourced from Jewson this sands origination was unspecified since it was a mixture.

As demonstrated by Figure 5.1.1, Travis Perkins sharp sand has the required particle size distribution because it was well graded owing to an even amount across the range with little fines; and hence was therefore considered better suited for use with NHL mortar. Originating from "Leighton Buzzard" this sand is of a coarser texture than the building sand and therefore provides a greater input into the bond strength.

5.1.2 Cement – ordinary Portland cement – 42.5

Typical properties of Blue Circle 42.5 Portland Cement			
Surface area		m^2/kg	290 to 390
Setting time – initial		mins	80 to 200
Mortar compressive strength - EN196-1	2 day	N/mm^2	21 to 31
	7 day	N/mm^2	40 to 50
	28 day	N/mm^2	52 to 62
Apparent particle density		kg/m^3	3080 to 3180
Bulk density	Aerated	kg/m^3	1000 to 1300
	Settled	kg/m^3	1300 to 1450
Colour		L value	57.5 to 68.0
Sulfate		SO_3 (%)	2.5 to 3.5
Chloride		Cl (%)	Less than 0.10
Alkali		Eq Na_2O (%)	0.4 to 1.0
Tricalcium Silicate		C_3S (%)	40.0 to 60.0
Dicalcium Silicate		C_2S (%)	12.5 to 30.0
Tricalcium Aluminate		C_3A (%)	7.0 to 12.0
Tetracalcium Aluminoferrite		C_4AF (%)	6.0 to 10.0

Table 5.1.2 – Portland cement manufacturers' data

The cement used for the ordinary Portland cement (OPC) designation iii (BS5628-1) or otherwise known as M4 (EN998-2) mortar mixes was "Blue Circle Cement" (part of the Lafarge group). This Portland cement was compliant with BS EN 197-7 CEM I 42.5. The manufacturer specified properties are in Table 5.1.2. According to the Blue Circle Cement data sheet the cement is predominantly made up of compounds of calcium silicate and calcium aluminate with a small proportion of gypsum. The finely ground mixture of raw materials which contain predominantly calcium carbonate, aluminium oxide, silica and iron oxide are burned or sintered at a temperature greater than 1400°C. The cooled clinker formed is ground under controlled conditions with the addition of typically 5% gypsum.

5.1.3 Lime – natural hydraulic lime– 3.5

Typical properties of St Astier Natural Hydraulic Limes (NHL)			
Surface cover		cm^2/g	9000
Setting time – initial		mins	80 to 200
Mortar compressive strength for 1:3 mix	7 day	N/mm^2	0.53
	28 day	N/mm^2	1.34
	6 months	N/mm^2	3.94
	12 months	N/mm^2	3.90
	24 months	N/mm^2	3.97
Density - volumetric weight typical		gr/litre	650
Whiteness index		-	72
Expansion		mm	< 1
Residue of quick lime after slaking		%	< 1
Available (free) lime after slaking		$Ca(OH)_2$ (%)	25 +

Table 5.1.3 – Natural hydraulic lime mortar manufacturers' data

In the standards there are a range of different types of lime available for use in mortar as a binder or plasticiser. Johnson (pers.com July 2005) advised that NHL 3.5 mortar is the most commonly used by builders in the UK for housing and conservation. Furthermore that the most common brand of NHL 3.5 currently most widely used in construction, is produced by St Astier. The number 3.5 classifies the limes maximum compressive strength using a 1:3 mix and water ratio specified in EN 459 after 28 days.

When mortar specimens are produced in accordance with EN 459 they should achieve a compressive strength after 28 days equal to 3.5 N/mm^2. Although this seems a good strength after such a short curing time, the mortar had a very short pot life and was starting to set soon after the designated mix procedure was complete. In building terms this mix was completely unworkable.

5.2 Properties of brick and block units

Work sized units were used for all unit types to maintain consistency and comparability by providing a direct method of comparison. It should be noted that Aircrete blocks have most commonly a work face dimensions of 440 or 620mm long by 215mm; in a range of thickness from 60mm to 355mm. The properties of all the units were tested according to the standards and the findings are shown in this section.

All units were used in an air dried state. This would not be the ideal method of building on-site but removes another variable caused by the possibilities of differing water contents

5.2.1 Gross dry density – BS EN 772-13:2000

The European standard specification for clay bricks relates to two groups of masonry units referred to as high density and low density. The units are detailed as:

- High Density (HD) units have a density greater than 1000 kg/m^3. Units that are exposed to the elements (facing bricks) have to be HD in order to maintain durability.

- Low Density (LD) units have a density not greater than 1000 kg/m^3. Units that are protected from the elements (internal bricks) can be LD.

Having calculated the gross volume $V_{g,u}$ of the unit from the unit dimensions subtracting the volume of perforations the following formulae found the gross dry density ρ_{gu} by dividing the dry mass ($m_{dry,u}$) by the gross volume ($V_{g,u}$) of the unit:

$$\rho_{g,u} = \frac{m_{dry,u}}{V_{g,u}} \times 10^6 (kg/m^3)$$

	Weight	Volume	Dry Density	Weight	Volume	Dry Density
	g	mm^3	kg/m^3	g	mm^3	kg/m^3
RESULT	Red Brick Unit			Yellow Brick Unit		
AVG	2501	1267240	**1973**	1933	1183651	**1633**
STDEV	10	19336	24	16	7467	13
COV	0.00	0.02	0.01	0.01	0.01	0.01
RESULT	Concrete Brick Sized Unit			Aircrete Brick Sized Unit		
AVG	2984	1419340	**2102**	900	1355646	**664**
STDEV	85	20445	33	32	37153	6
COV	0.03	0.01	0.02	0.04	0.03	0.01

Table 5.2.1 – Units – Gross Dry Density

All the units apart from Aircrete are HD which is expected since all the units apart from Aircrete are capable of being used as facing bricks. During testing Aircrete had to be weighed down since it floated and this is confirmed since the density of water is 1000 kg/m^3 and Aircrete is around 664 kg/m^3.

The concrete units have the highest volume, followed by Aircrete. Whilst due to perforations the volume red and yellow is lower. The weight of the units follows the same trend as density. Trends:

Weight	C – R – Y – A
Density	C – R – Y – A
Volume	C – A – R – Y

5.2.2 Absorption – BS EN 771-1:2003

All unit types are porous and absorb water to various degrees. The overall absorption is entirely dependent on the type of clay and method of manufacture.

Absorption of building units can be broken into two distinct categories which both deal with the ingress of water into the units.

- Absorption – covered in this section – takes account of the five and twenty four hour duration tests and which are not unit type specific
- Initial rate of absorption (IRA) – (section 5.2.3) takes account of the timing up to 30 minutes and is unit type specific

Extruded bricks are characteristically denser and less porous than bricks formed by moulding; since, the clay has lower moisture content than used for moulded bricks, prior to the baking / firing process. The intensity of the heat in the firing process is directly related to the water absorption, where the greater the heat the lower the characteristic water absorption. Manufacturers use the absorption test in their quality control criteria.

Absorption of a brick is expressed as a percentage, and defined as the ratio of the weight of water that is taken up into its body divided by the dry weight of the unit.

There are two ways to measure absorption:

- submerging the test specimen in room temperature water for a period of 24 hours – known as the "cold-soak" test
- submerging the test specimen in boiling water for five hours – referred to as the "five-hour boil" test – this test was not undertaken since according to current BSEN standards is only required for units used as damp proof coursing

A test to predict the durability by calculation of the saturation coefficient of units uses the ratio of the twenty four hour cold water and five hour boil absorption tests.

BS5628 gives a characteristic flexural strength of masonry based on the water absorption and mortar designation for clay bricks only. The water absorption test combined with Table 5.2.2.1, informed the testing of B and P wallettes.

The boiling water test is also referenced in the BSEN specification but only for determining the water absorption of bricks to be used as damp proof courses, test method BSEN 772-7 (BSI, 1998). The water absorption properties of bricks to be used for this purpose shall be declared and not exceeded by a test sample, although unlike the BS, no actual limits are given in the specification.

For all other bricks that are to be used externally and their face exposed, the BSEN specification requires that the water absorption shall also be determined but based on a 24-hour soak in water at ambient temperature. The method is described in Annex C of BS EN 771-1:2003 and the results for the test are given in Table 5.2.2.2.

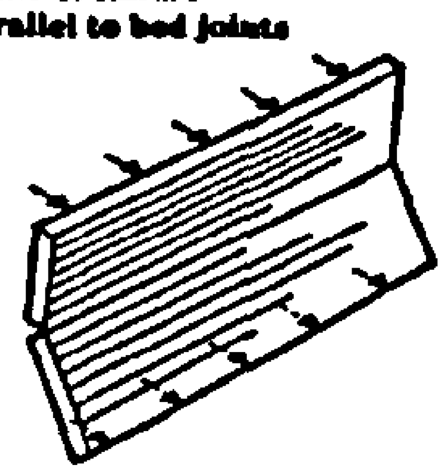
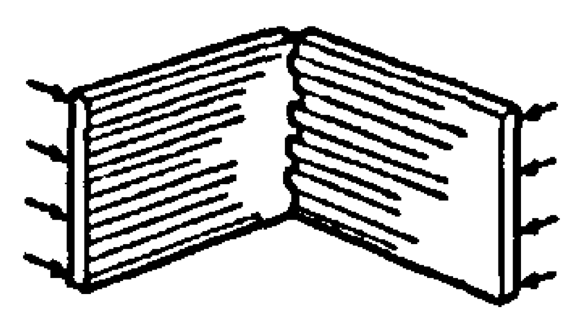
	Plane of failure parallel to bed joints 			Plane of failure perpendicular to bed joints 		
Mortar designation	(i)	(ii) and (iii)	(iv)	(i)	(ii) and (iii)	(iv)
Clay bricks having a water absorption						
less than 7 %	0.7	0.5	0.4	2.0	1.5	1.2
between 7 % and 12 %	0.5	0.4	0.35	1.5	1.1	1.0
over 12 %	0.4	0.3	0.25	1.1	0.9	0.8

Table 5.2.2.1 – BS5628 – Exert from Table 3 – Characteristic flexural strength of masonry

The notations: (i), (ii), (iii) and (iv) used in the table correspond to the mortar designation mix which is detailed in the standard.

All the units were oven dried at 105°C apart from Aircrete which was at a lower temperature of 70°C. Three consecutive equal measurement of dry mass (m_d) were taken before the absorption test was conducted. Following cooling to ambient room temperature (averaged at 22°C) each unit was immersed in order of the number written on the unit with the time of immersion noted.

All the units were placed on spacers ensuring full uninterrupted water contact with all faces during the length of immersion. The Aircrete units required to be weighed down since their density was less than the water. Following continuous submerging for 24 hours the units were removed from the tank in the same order as inserted.

Using a clean dry paper tissue for each unit the excess water was removed by letting the surplus water drip off from the unit and following that each unit was placed momentarily onto the tissue then straight onto the weighing scale.

The tissues used were weighed for consistency and it was found that an average of 9 grams was absorbed each time from the unit. Recording the wet mass (m_w) of each specimen the water absorption (w_m) was calculated using the formula below followed by the overall mean water absorption, all to the nearest 1%.

	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m
	g	g	%	g	g	%	g	g	%	g	g	%
Unit No	Red Brick Unit			Yellow Brick Unit			Concrete Brick Sized Unit			Aircrete Brick Sized Unit		
1	2513.5	2700.0	7	1949.3	2279.0	17	3047.0	3257.5	7	879.3	1257.0	43
2	2496.8	2666.0	7	1944.5	2279.0	17	2903.8	3126.0	8	955.3	1343.0	41
3	2506.8	2669.9	7	1921.5	2265.0	18	2990.8	3208.0	7	910.3	1313.5	44
4	2498.3	2670.5	7	1946.0	2290.0	18	2878.3	3103.0	8	865.3	1258.0	45
5	2483.5	2631.5	6	1913.8	2249.5	18	2979.3	3193.5	7	883.0	1291.5	46
6	2504.3	2678.0	7	1921.3	2262.0	18	3103.3	3313.0	7	905.8	1287.5	42
7	2498.3	2680.8	7	1946.8	2289.4	18	3048.1	3277.5	8	943.4	1339.3	42
8	2505.6	2679.7	7	1934.5	2273.6	18	2944.9	3159.4	7	917.7	1323.0	44
9	2503.5	2670.6	7	1939.7	2273.2	17	2969.1	3207.0	8	869.9	1269.3	46
10	2482.3	2657.9	7	1928.4	2273.2	18	3014.1	3225.0	7	935.0	1335.9	43
AVG	2499.3	2670.5	**6.9**	1934.6	2273.4	**18**	2987.8	3207.0	**7**	906.5	1301.8	**44**
STDEV	9.9	17.7	0.4	12.7	12.3	0.3	68.7	65.7	0.4	31.7	33.6	1.9
COV	0.00	0.01	0.06	0.01	0.01	0.02	0.02	0.02	0.06	0.03	0.03	0.04

Table 5.2.2.2 – Units – Absorption

$$w_m = \frac{m_w - m_d}{m_d} \times 100\ \%$$

Formula 5.2.2 – Absorption of units

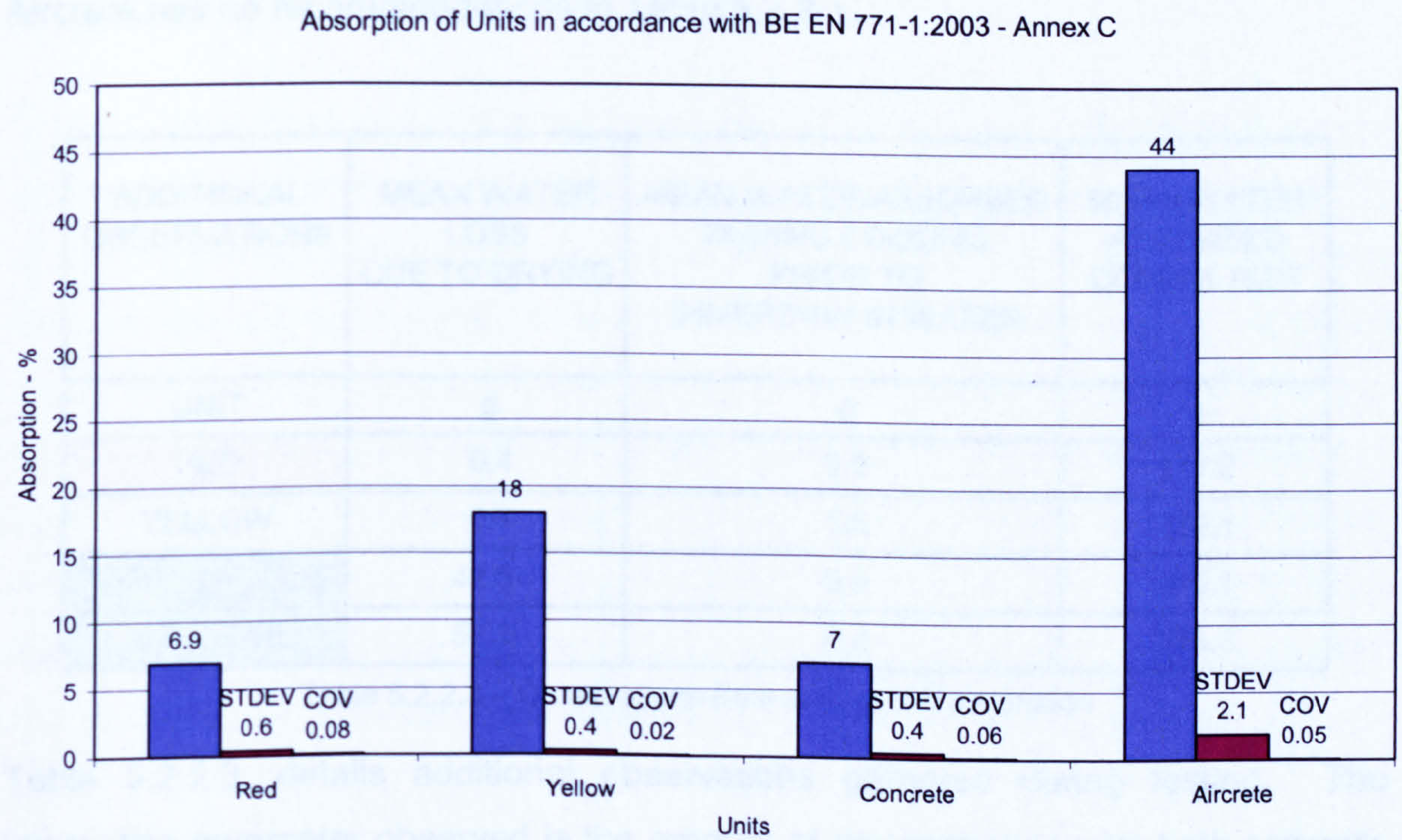


Figure 5.2.2 – Absorption of Units

Red and concrete units have the lowest absorption rate of approximately 7 % followed by yellow having 18% and Aircrete at 44%. The red and yellow bricks are both extruded clay units and with reference to Table 5.2.2.1 lie in two different water absorption brackets. The three ranges of water absorption are:

- less than 7%,
- between 7 and 12%
- greater than 12%.

According to Table 5.2.2.1; since, red has an absorption rate of 6.9 % it falls into the "less than 7%" bracket and using a designation (iii) mortar mix would yield characteristic bond strength of 0.5 and 1.5 N/mm^2 for B and P wallettes respectively. Yellow with an absorption rate much greater than 12%, on the same basis would be expected to gain 0.3 and 0.9 N/mm^2. This means that the characteristic flexural bond strength is expected to be higher for red units in comparison to yellow.

In the case of concrete bricks according to Table 5.2.2.1, a characteristic flexural bond strength for a designation (iii) mix should attain 0.3 and 0.9 N/mm^2 for B and P wallettes respectively; although this value is independent of water absorption. Aircrete has no recommendations in Table 5.2.2.1.

ADDITIONAL OBSERVATIONS	MEAN WATER LOSS DUE TO DRYING	MEAN WATER ABSORBED DURING COOLING PRIOR TO IMMERSION IN WATER	MEAN WATER ABSORBED DURING TEST
UNIT	g	g	g
RED	0.4	0.0	171.2
YELLOW	0.7	1.5	339.1
CONCRETE	42.5	5.0	219.1
AIRCRETE	51.3	8.0	395.3

Table 5.2.2.3 – Observations from testing unit absorption

Table 5.2.2.3, details additional observations gathered during testing. The interesting parameter observed is the amount of atmospheric water both concrete and Aircrete absorbed in comparison to the red and yellow units. All the units were cooling down to room temperature at the same time, yet Aircrete absorbed 8 grams of water. Since Aircrete has such a quick uptake this property would mirror itself when in contact with fresh mortar.

Concrete units absorbed 5 grams of water during cooling, whilst in the test absorbed almost 220 grams of water which was only 50 grams more than the lowest being red. This indicates that similar to Aircrete, concrete units have a quick initial uptake but the long term absorption is gradual.

Trends noted in Table 5.2.2.2:

Dry Mass	C – R – Y – A
Wet Mass	C – R – Y – A
Absorption	A – Y – C – R

5.2.3 Initial rate of absorption – BS EN 772-11:2000

All brick and block units are porous to varying degrees and will therefore absorb water in use. Due to brick suction water transport from mortar towards brick is taking place directly after bricklaying. This transport may cause changes in material composition nearby the interface and modification of the water distribution over the mortar-brick cross section.

Kjær (1991) states that the suction has a great influence upon the strength of the hardened mortar in the mortar joints. It is possible to obtain the double strength for the mortar in the joints compared with mortar moulded in a steel mould (ISO test), where there is no suction at all. Groot (1991) states that the development of bond appears to be largely influenced by the water content in the brick near the interface. Venu Madhava Rao et al (1996) further add that the moisture content of the masonry unit, at the time of casting has a significant influence on the flexural bond strength. In conclusion Venu Madhava Rao et al found that there is an optimum moisture content that leads to maximum bond strength but this can fall very rapidly as the moisture content increases beyond the optimum level.

Time	$c_{w,s}$	$c_{wi,s}$	$c_{w,s}$	$c_{wi,s}$
	$g/(m^2 \times s^{0,5})$	$kg/(m^2 \times min)$	$g/(m^2 \times s^{0,5})$	$kg/(m^2 \times min)$
sec	Red Brick		Yellow Brick	
30	90.52	0.99	129.14	1.41
60	38.40	**0.30**	246.27	**1.91**
90	86.13	0.54	194.30	1.23
120	90.52	0.50	234.80	1.29
240	103.69	0.40	225.52	0.87
300	76.71	0.27	193.05	0.67
sec	Concrete Unit		Aircrete Unit	
120	171.98	0.94	141.21	0.77
300	140.83	0.49	**121.37**	0.42
600	**98.77**	0.24	**119.01**	0.29
900	81.31	0.16	124.94	0.25
1200	68.13	0.12	**113.92**	0.20
1800	59.36	0.08	117.79	0.17

Table 5.2.3 – Units – Initial rate of absorption

The British Standard test described in BS EN 772-11:2000 give the method for ascertaining the initial rate of absorption (IRA) and coefficient of water absorption (CWA) due to capillary suction. The difference between the two types of tests is set in the formulas not in the method. The IRA is a measure for clay brick units and CWA for aggregate concrete, autoclaved aerated concrete and stone units. Table 5.2.3 provides data for IRA and CWA for all units.

The IRA and CWA were conducted on a sample of six units. The standard gives timing in seconds for post immersion weight for clay units at 60 seconds, concrete at 600 seconds and Aircrete at 300, 600 and 1200 seconds. The timing was taken over a broader range of values than the standard and is detailed in Table 5.2.3. The boxes with a thick border around them denote the standard timing requested when detailing the relevant unit types.

The following formulas were used to calculate IRA and CWA

$$c_{w,s} = \frac{m_{so,s} - m_{dry,s}}{A_s \sqrt{t_{so}}} \times 10^6 [g/(m^2 \times s^{0,5})]$$

Formula 5.2.3.1 - CWA - $c_{w,s}$ coefficient of water absorption due to capillary suction

$$c_{wi,s} = \frac{m_{so,s} - m_{dry,s}}{A_s t} \times 10^3 [kg/(m^2 x \times \min)]$$

Formula 5.2.3.2 - IRA - $c_{wi,s}$ initial rate of water absorption for masonry units

where:

$c_{w,s}$ = coefficient of water absorption due to capillary action - $g/(m^2 xs^{0.5})$

$c_{wt,s}$ = initial rate of water absorption for clay masonry units - $kg/(m^2 xmin)$

$m_{so,s}$ = mass of the specimen in grams after soaking for time t - g

$m_{dry,s}$ = mass of the specimen after drying - g

A_s = gross area of the face of the specimen immersed in water - mm^2

t_{so} = time of soaking - s

The yellow clay unit has a much higher sustained and different rate of suction than the red clay units, shown in Figure 5.2.3.1. Concrete initially has a higher capillary suction but in the region of 450 seconds, there is an equilibrium point reached by both Aircrete and concrete units. Following this time Aircrete sustains a level of suction averaging out at around 119 rate g/ $(m^2 xs^{0.5})$, whilst concrete gradually declines. The final suction rate for Aircrete, is double that for concrete as shown in Figure 5.2.3.2.

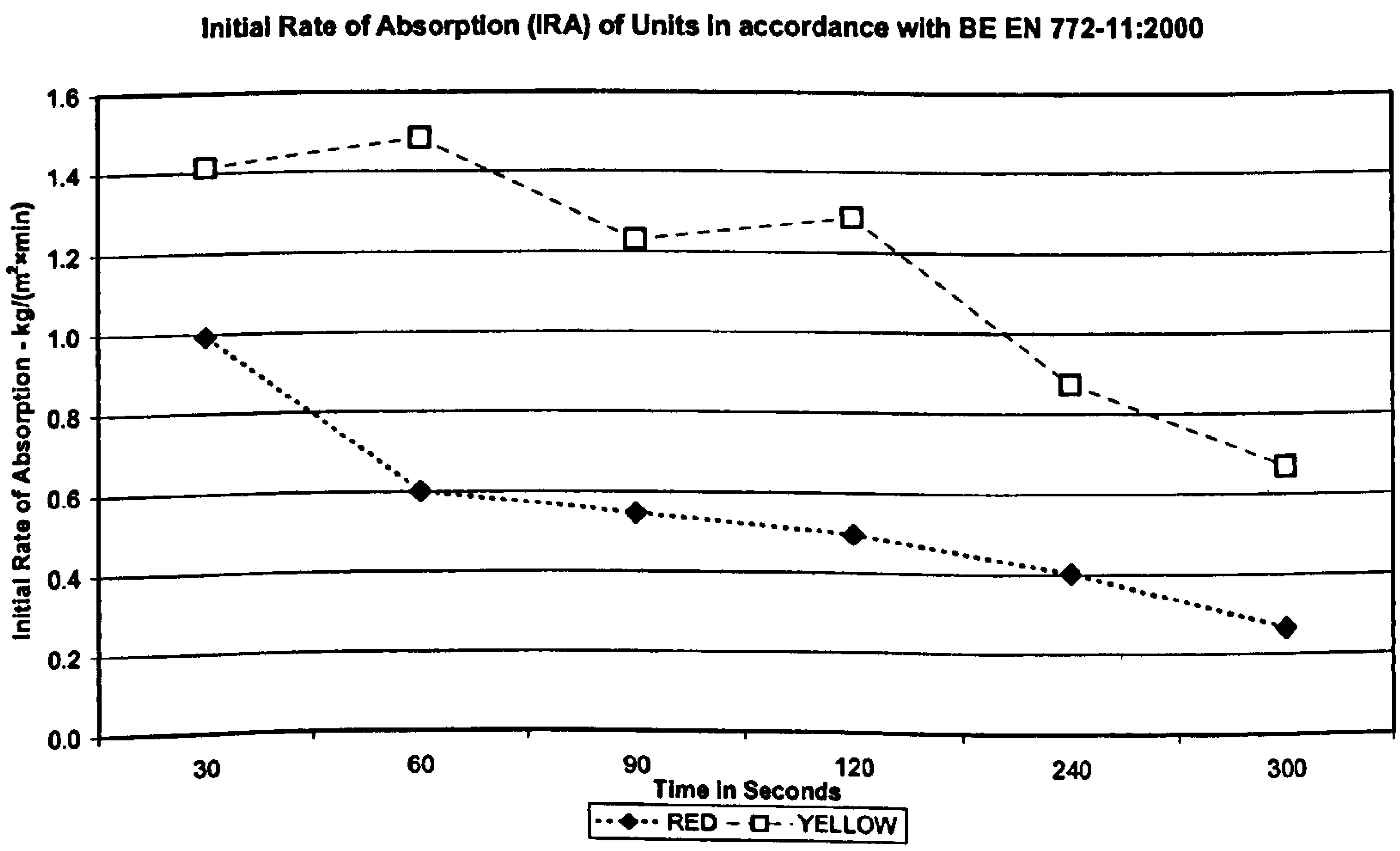


Figure 5.2.3.1 – Initial rate of absorption for red and yellow clay units

Since the timing of CWA is much greater in comparison to IRA and not comparable in formulas, Figure 5.2.3.3 uses IRA values from all units at 120 and 300 seconds. Yellow clay units have the highest IRA followed by concrete, Aircrete and red clay units.

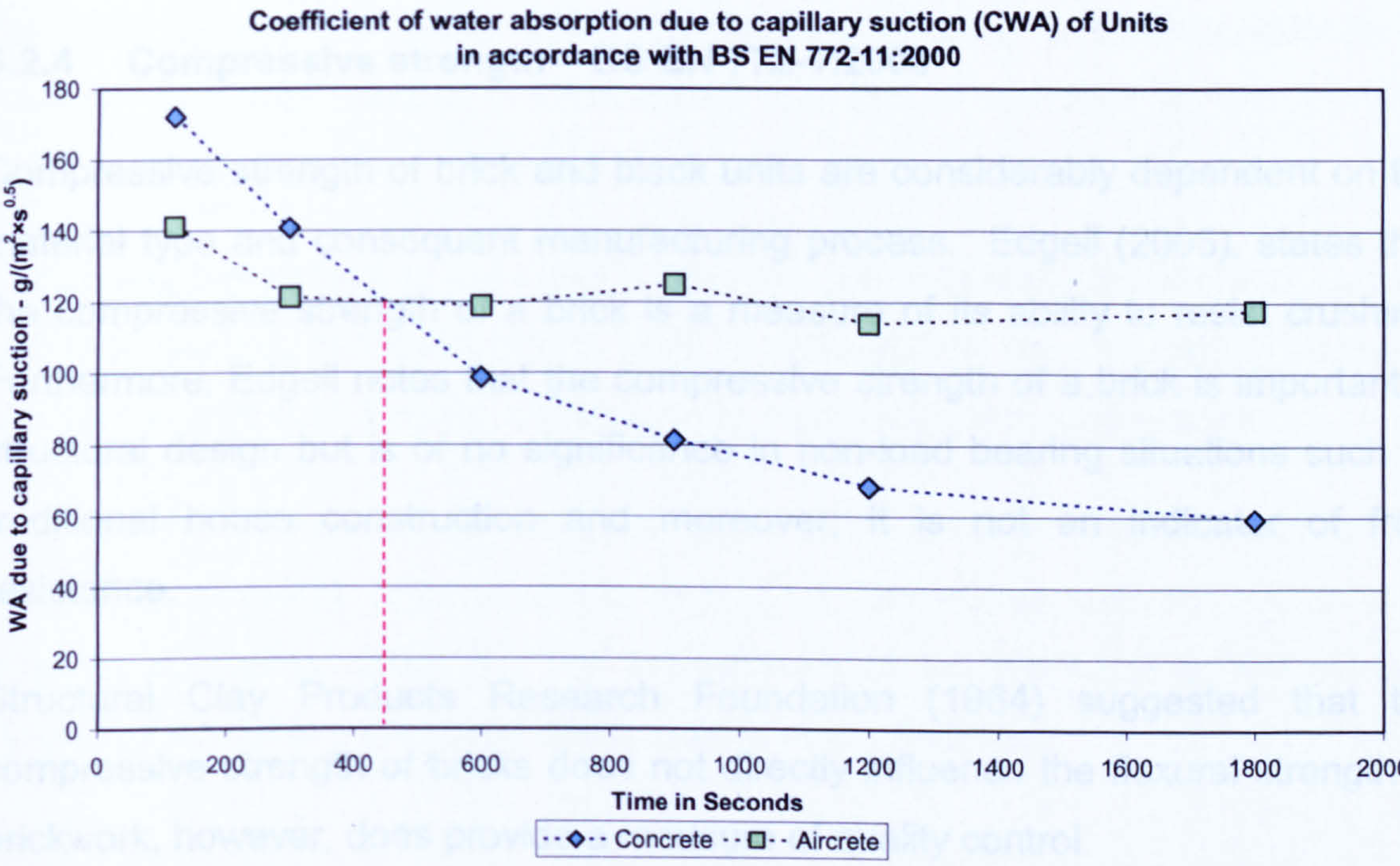


Figure 5.2.3.2 – Capillary suction of concrete and Aircrete units

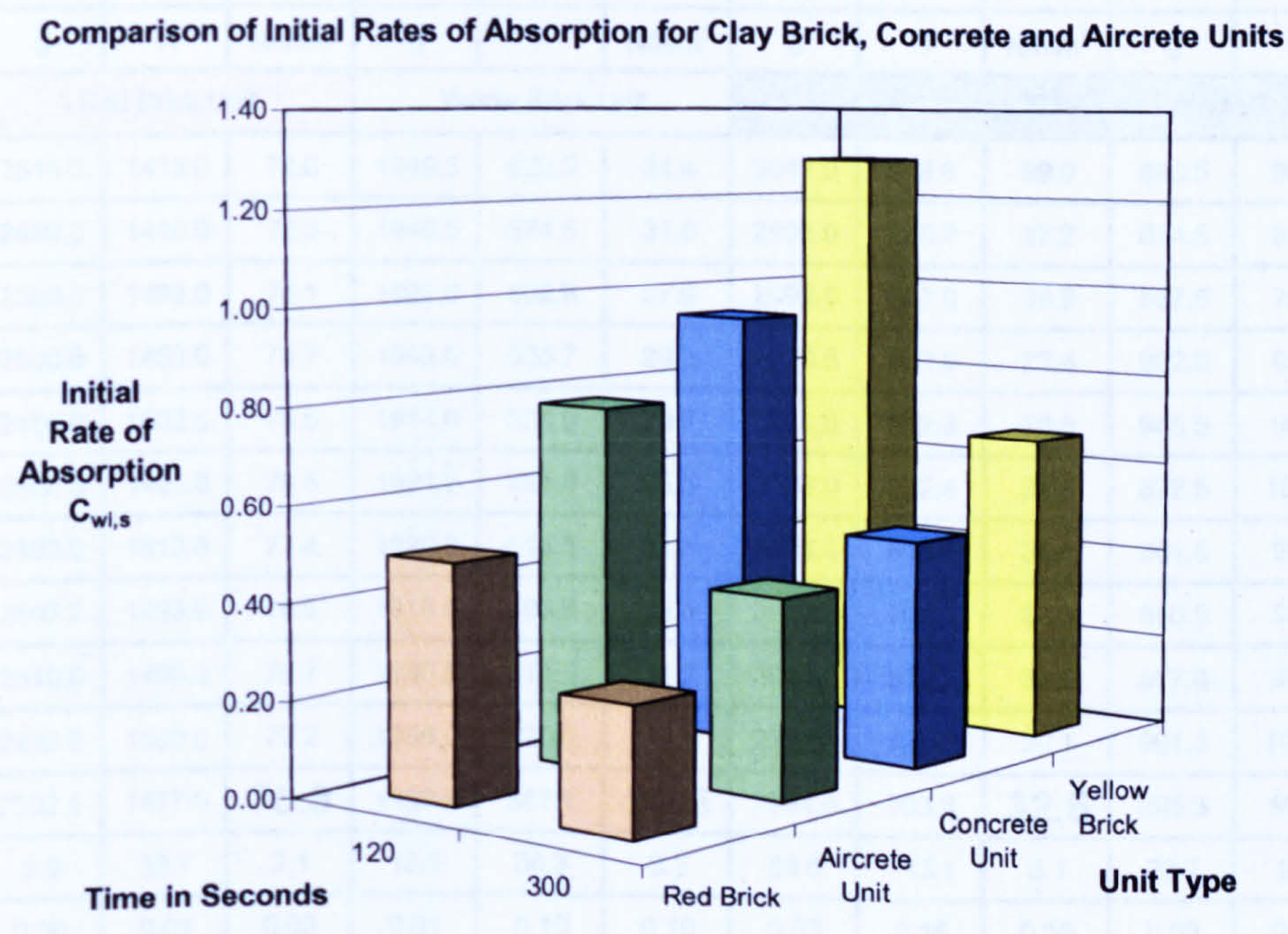


Figure 5.2.3.3 – IRA Comparison of all units for 120 and 300 seconds

The trends seen in the IRA and CWA graphs can be summarised as follows:

CWA <= 450 SEC	C – A
CWA >= 450 SEC	A – C
IRA	Y – R
COMPARISON	Y – C – A – R

5.2.4 Compressive strength – BS EN 772-1:2000

Compressive strength of brick and block units are considerably dependent on the material type and consequent manufacturing process. Edgell (2005), states that the compressive strength of a brick is a measure of its ability to resist crushing. Furthermore, Edgell notes that the compressive strength of a brick is important in structural design but is of no significance in non-load bearing situations such as traditional house construction and moreover; it is not an indicator of frost resistance.

Structural Clay Products Research Foundation (1964) suggested that the compressive strength of bricks does not directly influence the flexural strength of brickwork, however, does provide a measure of quality control.

	Weight	Load	Stress	Weight	Load	Stress	Weight	Load	Stress	Weight	Load	Stress
	g	N	N/mm^2	g	N	N/mm^2	g	N	N/mm^2	g	N	N/mm^2
No	Red Brick Unit			Yellow Brick Unit			Concrete Brick Sized Unit			Aircrete Brick Sized Unit		
1	2516.0	1413.0	72.0	1949.5	623.3	34.4	3047.0	846.6	39.0	893.5	92.5	4.5
2	2499.0	1410.0	72.3	1940.5	574.5	31.8	2905.0	580.9	27.2	874.5	81.2	3.8
3	2509.0	1499.0	76.1	1922.0	502.6	27.9	2992.0	667.9	30.9	857.5	75.8	3.5
4	2500.5	1450.0	74.7	1946.0	533.7	29.2	2879.5	502.9	23.4	902.0	95.4	4.7
5	2486.0	1502.5	78.5	1914.0	534.0	29.7	2980.0	622.8	28.8	945.5	90.1	4.3
6	2506.5	1490.0	76.5	1921.5	461.8	25.6	3103.0	772.4	34.8	872.5	106.2	5.0
7	2499.0	1510.0	77.4	1920.0	615.3	34.3	2993.0	698.4	32.5	901.5	90.6	4.4
8	2503.2	1493.0	76.5	1916.5	593.6	33.0	3010.3	706.9	32.3	886.9	89.4	4.3
9	2510.0	1499.0	76.7	1940.0	611.3	34.2	3044.0	813.5	37.6	897.6	96.7	4.6
10	2492.0	1509.0	77.2	1936.0	620.6	34.5	2991.8	825.2	38.1	901.3	102.9	5.0
AVG	2502.1	1477.6	**75.8**	1930.6	567.1	**31.5**	2994.6	703.8	**32.5**	893.3	92.1	**4.4**
STDEV	8.9	38.7	2.1	13.1	56.3	3.2	65.6	113.1	5.1	23.7	9.1	0.5
COV	0.00	0.03	0.03	0.01	0.10	0.10	0.02	0.16	0.16	0.03	0.10	0.10

Table 5.2.4 – Units – compressive strength

The compressive strength of the units was tested according to BSEN 772-1. Following conditioning to the required air dried state by drying the brick and concrete units at 105°C and Aircrete at 70 °C till constant mass was achieved. After the units cooled down the compressive test was carried out. Although the standard requires that the bed faces of units are ground to a parallel tolerance, the dry units were tested using plywood was as a packing to assist uniformity of loading. The total number of units tested was ten as specified by the standard and the results are given in Table 5.2.4.

Calculating the surface of the contact area the concrete and Aircrete units had full bed face contact, top and bottom. Due to perforations, the red having 10 holes and yellow units with 3 holes, consequently, had a reduced contact area.

Red had the highest compressive strength at 75.8 N/mm², double that of the concrete and yellow units attaining 32.5, 31.5 N/mm² respectively. Aircrete is weakest at approximately $^{1}/_{17}{}^{th}$ of the strength of the red units at 4.4 N/mm². Figure 5.2.4 shows a graphical interpretation of the findings.

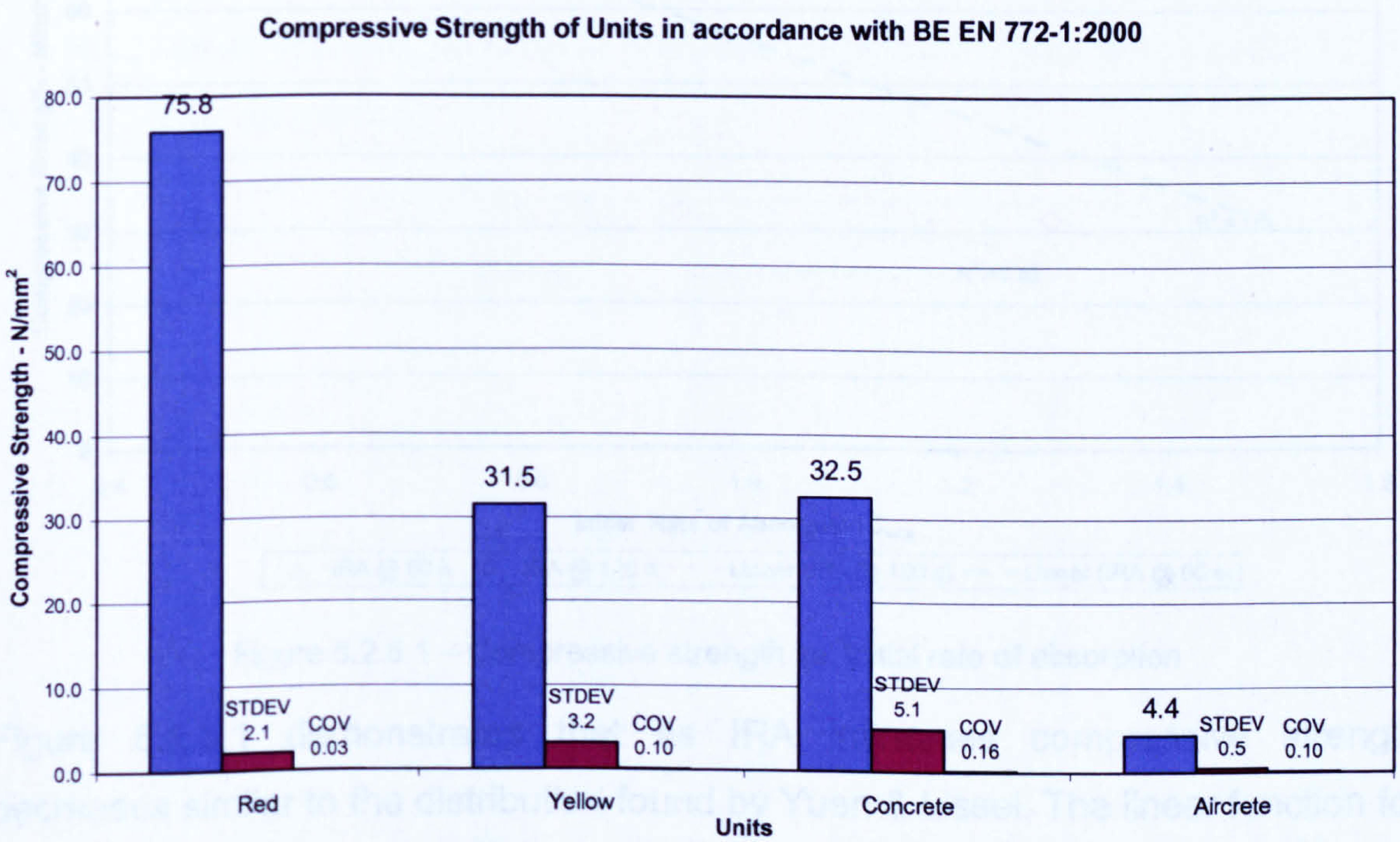


Figure 5.2.4 – Compressive strength of all units

Trends noted in Table 5.2.4:

Stress	R – C – Y – A
STDEV	C – Y – R – A
COV	C – Y – A – R

5.2.5 Observations and cross comparison

In recent research by Kaushik et al (2007) and Yuen & Lissel (2007) they noted that there was an inversely proportional relationship between compressive strength and initial rate of absorption, furthermore the same relationship was found between compressive strength and water absorption. Using the results from the unit property tests the same trends were found to be replicated. This is demonstrated by Figures 5.2.5.1 and 5.2.5.2.

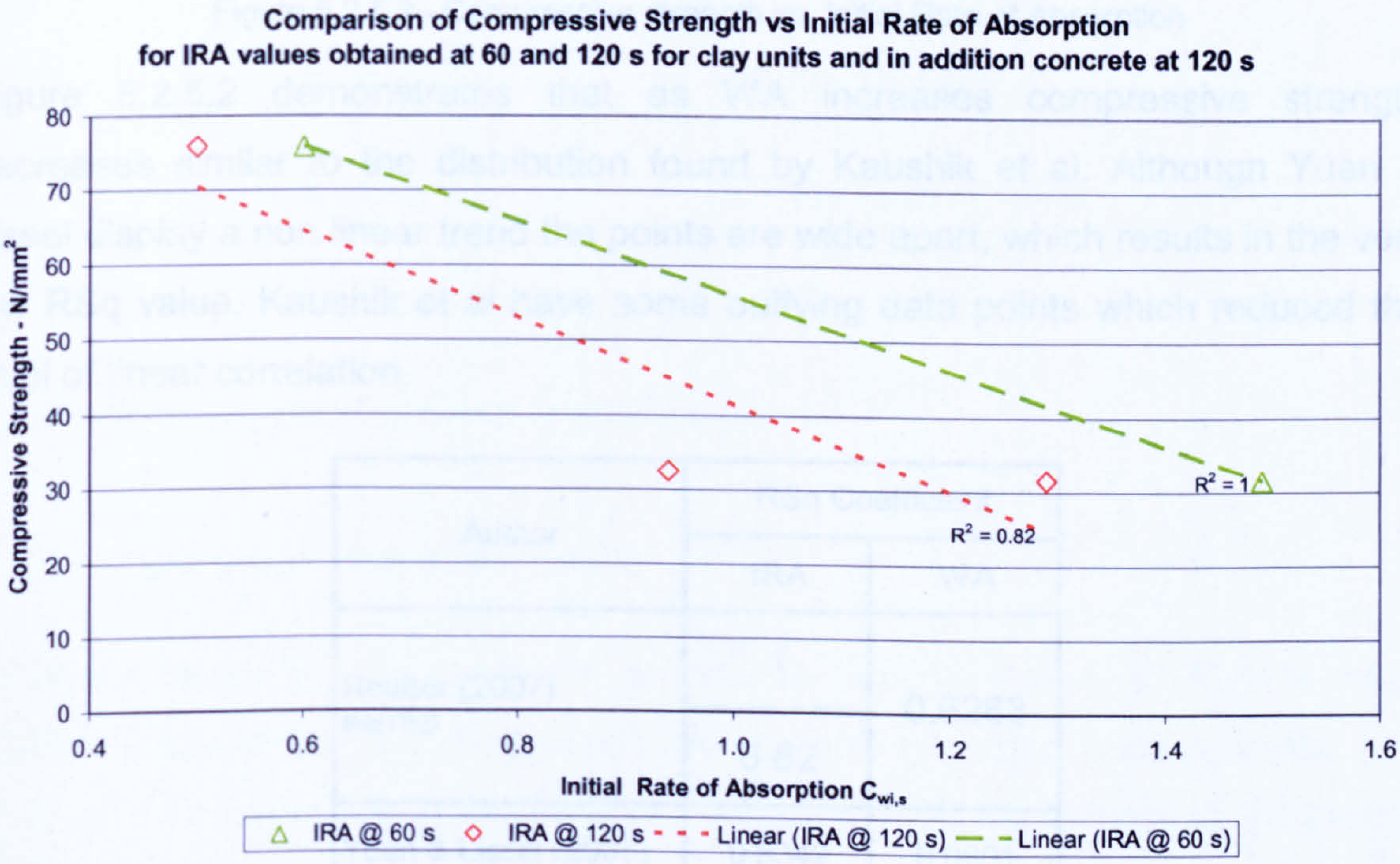


Figure 5.2.5.1 – Compressive strength vs. initial rate of absorption

Figure 5.2.5.1 demonstrates that as IRA increases compressive strength decreases similar to the distribution found by Yuen & Lissel. The linear function for IRA @ 60 seconds is accepted on the basis of comparison with results from other research. Kaushik et al (2007) shows the same but with a greater spread at the higher IRA's. Whereas in general Yuen & Lissel, displayed one more closely correlated to the linear trend.

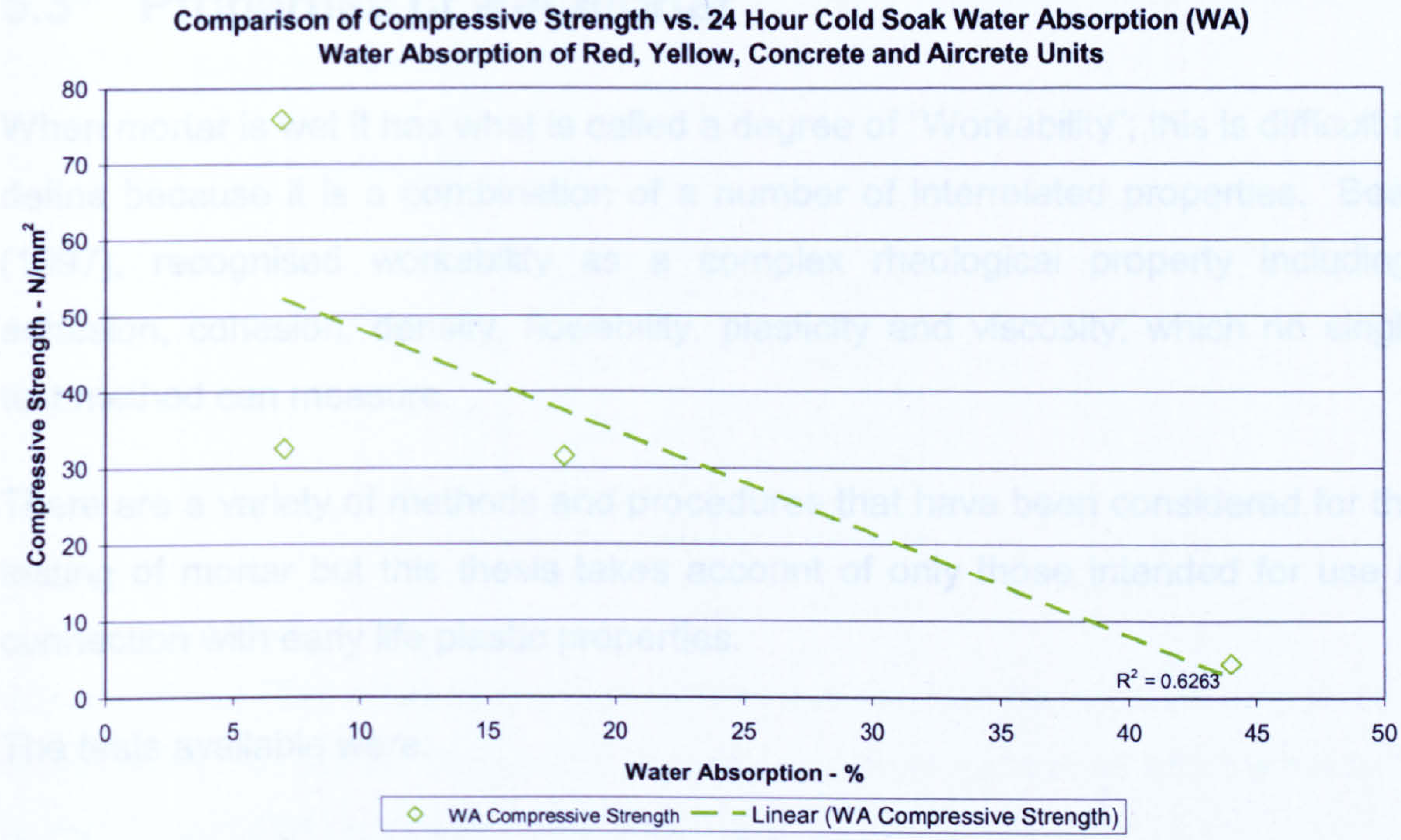


Figure 5.2.5.2– Compressive strength vs. Initial Rate of Absorption

Figure 5.2.5.2 demonstrates that as WA increases compressive strength decreases similar to the distribution found by Kaushik et al. Although Yuen & Lissel display a non linear trend the points are wide apart, which results in the very low RSq value. Kaushik et al have some outlying data points which reduced the level of linear correlation.

<table>
<tr><th rowspan="2">Author</th><th colspan="2">RSq Coefficient</th></tr>
<tr><th>IRA</th><th>WA</th></tr>
<tr><td rowspan="2">Reutter (2007)
this PhD</td><td>1</td><td rowspan="2">0.6263</td></tr>
<tr><td>0.82</td></tr>
<tr><td>Yuen & Lissel (2007)</td><td>0.8342</td><td>0.0601</td></tr>
<tr><td>Kaushik et al (2007)</td><td>0.77</td><td>0.24</td></tr>
</table>

Table 5.2.5 – Units – Linearity Comparison (RSq)

Overall as Table 5.2.5 suggests there is a strong indication that there is a relationship between IRA and compressive strength as concluded by all three research programmes. Water absorption demonstrates a stronger relationship in this research than Kaushik et al and Yuen & Lissel suggest.

5.3 Properties of wet mortar

When mortar is wet it has what is called a degree of "Workability"; this is difficult to define because it is a combination of a number of interrelated properties. Beall (1997), recognised workability as a complex rheological property including: adhesion, cohesion, density, flowability, plasticity and viscosity; which no single test method can measure.

There are a variety of methods and procedures that have been considered for the testing of mortar but this thesis takes account of only those intended for use in connection with early life plastic properties.

The tests available were:

- flow table – BS4551-1:1998
- dropping ball – BS4551-1:1998
- flow table – BS EN 1015-3:1999
- plunger penetration – BSEN 1015-5:1999

The findings are discussed in this section.

5.3.1 Flow table – BS 4551-1:1998

Originally based on the American Standards Testing Materials (ASTM) table, BS4551's use of the flow table was a measure of plasticity. Essentially the flow table gives a quantifiable measurement to what would be instinct to a qualified brick layer. In addition, for those less experienced or for research purposes it provides a good method of quality control and a measure of consistency.

Calculating the old flow table method was using the base internal diameter of 101mm. If the average of the four readings was x mm:

$$Increase\ in\ diameter = x - 101$$

$$Flow = \frac{(x-101)}{101} \times 100\%$$

Table 5.3.1, shows the mean values for the individual mortars across the complete spectrum of testing data.

The trends observed were:

Diameter of Flow	
Mean	**T-N-O**
SD	**T-O-N**
COV	**T-O-N**
Flow %	**T-N-O**

It is noted that TLM attained the highest flow but also had the greatest degree of variability in the results. Conversely NHL was the most consistent with the least variability and OPC had the lowest flow.

FLOW TABLE **BS 4551-1:1998**	Mean	STDEV	COV	% Flow
		NHL		
91 DAY	198	0.82	0.00	96
273 DAY	198	0.82	0.00	96
365 DAY	196	0.50	0.00	94
OVERALL	**197**	0.71	0.00	**95**
		OPC		
273 DAY	188	2.06	0.01	86
365 DAY	176	0.82	0.00	74
OVERALL	**182**	1.44	0.01	**80**
		TLM		
1 DAY	231	8.54	0.04	129
3 DAY	231	8.54	0.04	129
7 DAY	184	6.50	0.04	82
28 DAY	188	0.82	0.00	86
OVERALL	**201**	5.29	0.03	**99**

Table 5.3.1 – Old flow table results

5.3.2 Flow table – BS EN 1015-3:1999

Calculating the new flow table method was using the same method as with the old by taking the base internal diameter of 101mm. If the average of the two readings was x mm:

$$Increase\ in\ diameter = x - 101$$

$$Flow = \frac{(x-101)}{101} \times 100\%$$

Table 5.3.2, shows the mean values for the individual mortars across the complete spectrum of testing data.

Revisions to the design of the flow table, as a result of the European Normalisation process have caused the cam to be reduced in size from 12mm to 10mm. This is the only alteration to the test.

FLOW TABLE BSEN 1015-3:1999	Mean	STDEV	COV	% Flow
	TLM			
1 DAY	211	2.99	0.01	109
3 DAY	212	6.29	0.03	110
7 DAY	214	6.98	0.03	112
28 DAY	200	6.85	0.03	98
OVERALL	**209**	6.71	0.03	**107**

Table 5.3.2 – New flow table results

5.3.3 Dropping ball – BS 4551-1:1998

Resulting in recent conversion the dropping ball test has been eliminated. De Vekey et al (1979) noted that this test can be very inconsistent and insensitive measure of plasticity especially in the hands of unfamiliar operators. However it still provides an indication for people familiar with this test and for this reason as well as its availability in the labs, it was used as a quality control measure.

During the mixing of mortar the result aimed for was a dropping ball reading of 10mm. In the case of NHL, 13 mm was achieved consistently and was used to give the mortar an acceptable pot life; 10mm was found to be inadequate.

OPC had mean value of 11 mm which in terms of the known variability (De Vekey et al, 1979) of this indicative test is completely acceptable.

Since thin layer mortar has not been used greatly no knowledge of dropping ball consistencies was available. The mix was prepared according to manufacturers' specification and it was found to give an average of 11 mm.

DROPPING BALL **BS 4551-1:1998**	Mean	STDEV	COV
	NHL		
91 DAY	13	0.00	0.00
273 DAY	13	0.00	0.00
365 DAY	13	0.58	0.04
OVERALL	**13**	0.19	0.01
	OPC		
273 DAY	13	0.00	0.00
365 DAY	10	0.58	0.06
OVERALL	**11**	0.29	0.03
	TLM		
1 DAY	11	0.46	0.04
3 DAY	10	0.21	0.02
7 DAY	11	0.46	0.04
28 DAY	12	0.58	0.05
OVERALL	**11**	0.41	0.04

Table 5.3.3 – Dropping ball results

The observable trends were:

Mean	N-O-T
SD	T-O-N
COV	T-O-N

Although NHL results in the largest value it is TLM that gives the most consistent result.

5.3.4 Plunger penetration – BSEN 1015-5:1999

Due to the late availability by the manufacturers of this test, the testing program was well advanced by time the equipment was able to be used. A direct replacement for the dropping ball experiment, its ease of use and rigid build produced good results, displayed in Table 5.3.4.

The main advantages when compared to the dropping ball are the level of consistency and the ease of use.

PLUNGER PENETRATION BSEN 1015-5:1999	Mean	STDEV	COV
TLM			
1 DAY	3	0.15	0.06
3 DAY	3	0.15	0.06
7 DAY	3	0.10	0.03
28 DAY	3	0.15	0.05
OVERALL	3	0.14	0.05

Table 5.3.4 – Plunger penetration data

5.4 Properties of hard mortar

Concurrently to the manufacture of the wallettes and couplets, a range of four mortar specimens were cast. Following demoulding a day after they were cast, the specimens were placed into a curing room and cured at 95% relative humidity until the time of testing. When the testing of wallettes and couplets were carried out; the mortar specimens were tested just prior to or following the experiments.

5.4.1 Compressive strength – 100mm cubes – BS 4551-1:1998

Cast in 100mm square metal moulds, three sets of specimens were cast per test. Table 5.4.1, shows the range of compressive strengths for hardened mortar at the specified times. This test gives you the hardest possible strength of mortar as it is cured for the entire time in 95% humidity. As it is not in contact with any porous surface it is stronger than any of the mortar unit specimens.

100mm CUBE BS 4551-1:1998	Mean N/mm^2	STDEV	COV
NHL			
91 DAY	1.23	0.02	0.03
273 DAY	2.11	0.03	0.05
365 DAY	2.30	0.23	0.10
OPC			
273 DAY	3.88	0.12	0.03
365 DAY	4.12	0.08	0.02
TLM			
1 DAY	1.80	0.03	0.12
3 DAY	2.22	0.01	0.03
7 DAY	5.79	0.04	0.04
28 DAY	15.04	0.06	0.04

Table 5.4.1 – Compressive strength 100mm cubes

The observable trends were:

Mean	T-O-N
SD	T-O-N
COV	N-T-O

TLM has the highest compressive strength but the largest standard deviation, as a result of the high mean. However it is NHL which is the least consistent.

5.4.2 Compressive strength – 40mm cubes – BS EN 1015-11:1999

Being the product of the prisms used in the flexural test of mortar, the dimensions of the prism ends are roughly the same; with the variations dependent on the outcome of the flexural test. The advantage is that it is more sustainable because they reduce the number of specimens required, therefore reducing mortar wastage.

The cross section measures 40x40 mm whilst the length can be anything between 70 to 80 mm. During tests the platens were positioned in the middle of the length and flush with the width.

40mm CUBE BS EN 1015-11:1999	Mean N/mm^2	STDEV	COV
NHL			
91 DAY	1.42	0.08	0.05
273 DAY	2.39	0.21	0.09
365 DAY	2.58	0.31	0.12
OPC			
273 DAY	4.55	0.35	0.08
365 DAY	4.68	0.36	0.08
TLM			
1 DAY	3.30	0.25	0.08
3 DAY	4.65	0.35	0.08
7 DAY	7.43	0.42	0.06
28 DAY	15.60	0.75	0.05

Table 5.4.2 – Compressive strength 40mm cubes

Observable trends are:

Mean	T-O-N
SD	T-O-N
COV	N-O-T

TLM is the strongest and the most consistent whereas NHL is the reverse.

5.4.3 Flexural strength – prisms – BS EN 1015-11:1999

Using the automatic jig the prisms were tested using a three point loading method described in chapter 4.

PRISM BS EN 1015-11:1999	Mean N/mm^2	STDEV	COV
NHL			
91 DAY	0.42	0.02	0.03
273 DAY	0.58	0.03	0.05
365 DAY	0.64	0.07	0.11
OPC			
273 DAY	0.69	0.03	0.03
365 DAY	0.78	0.16	0.21
TLM			
1 DAY	0.17	0.03	0.12
3 DAY	0.50	0.01	0.03
7 DAY	0.95	0.04	0.04
28 DAY	1.34	0.06	0.04

Table 5.4.3 – Flexural strength of mortar prisms

From the above table the observable trends are:

Mean	T-O-N
SD	O-N-T
COV	O-T-N

The highest flexural strength is given by TLM and OPC has the greatest variability.

5.4.4 Tensile strength – dog bones

Hardened mortar will never see the light of day in regards to being subjected to pure tensile stresses. Although it is no longer a standard test, due to its availability and the possibility of alternative analyses, tests were conducted. Testing was carried out using as that used for the flexural testing of mortar prisms. Table 5.4.4, shows the mean value achieved at the specified times. NHL displays a steady gradual growth from 91 to 273 days, whilst a rapider strength gains when comparing 273 and 365 days. Although a similar trend is mirrored in OPC it seems somewhat unusual and need to be observed with caution. TLM in a much shorter space of time show signs of gradual strength development.

DOG BONE	Mean N/mm^2	STDEV	COV
NHL			
91 DAY	0.51	0.02	0.03
273 DAY	0.62	0.03	0.05
365 DAY	0.68	0.14	0.20
OPC			
273 DAY	0.76	0.07	0.10
365 DAY	0.85	0.10	0.12
TLM			
1 DAY	0.20	0.03	0.12
3 DAY	0.50	0.01	0.03
7 DAY	1.08	0.04	0.04
28 DAY	1.35	0.11	0.08

Table 5.4.4 – Tensile strength of mortar

Observable trends are:

Mean	T-O-N
SD	N-T-O
COV	N-O-T

TLM is best in tension and has the most consistent results. NHL is the weakest and the most variable.

5.5 Properties of masonry

The sizes of the wallettes, as well as the testing procedure, complied with the recommendations of the British Standards Institution as outlined in BS 5628: Part 1, Appendix A.3, and conformed to BS EN 1052:3.

In the case of laterally loaded masonry walls, the British code BS5628-1:1985 suggests standardised sizes of wallettes to be tested, as shown in Figure 4.4.1. It recommends that in uni-axial flexure tests, the wallettes should be loaded with two line loads (four-point loading), oriented in such a way that the load is not applied directly over the mortar joints that are parallel to the load bearings. The four-point loading subjects the central portion of the panel to constant bending moment and zero shear force. Some researchers, amongst them, have recommended that a horizontal orientation is more efficient if a state of pure bending is desired, especially for tensile loading perpendicular to the bed joints (vertical bending). However, since walls in real buildings have a vertical orientation, the vertical orientation approximates the real conditions in a better way, and has been adopted in the UK and Europe. This arrangement also allows forces and displacements to be measured with ease and accuracy, and deformations and crack propagations to be easily observed.

The aim of the research was to keep the constructional variables to a minimum in the hope that cross mortar comparison could be assessed. The "Bricky" tool was used on all OPC and NHL wallettes and couplets. Each wallette and couplet joint was given an inverted "bucket handle".

5.5.1 P wallettes

For tensile loading parallel to bed joints (horizontal bending), the load bearers (shown in Figure 5.5.1.1 labelled - load) were located as near as practicable midway between the nearest perpend joints. The central region of the wallette is again subjected to constant bending moment and zero shear force. Unlike in the vertical bending tests, the upright orientation of the wallette in horizontal bending has less influence on the bending stresses, as the in-plane stress resulting from the effect of the self-weight is in a direction perpendicular to the bending stress being studied.

For the purpose of this thesis a system was devised to help analyse breakage patterns. This process was found suitable, providing an easy method for identifying and comparing results.

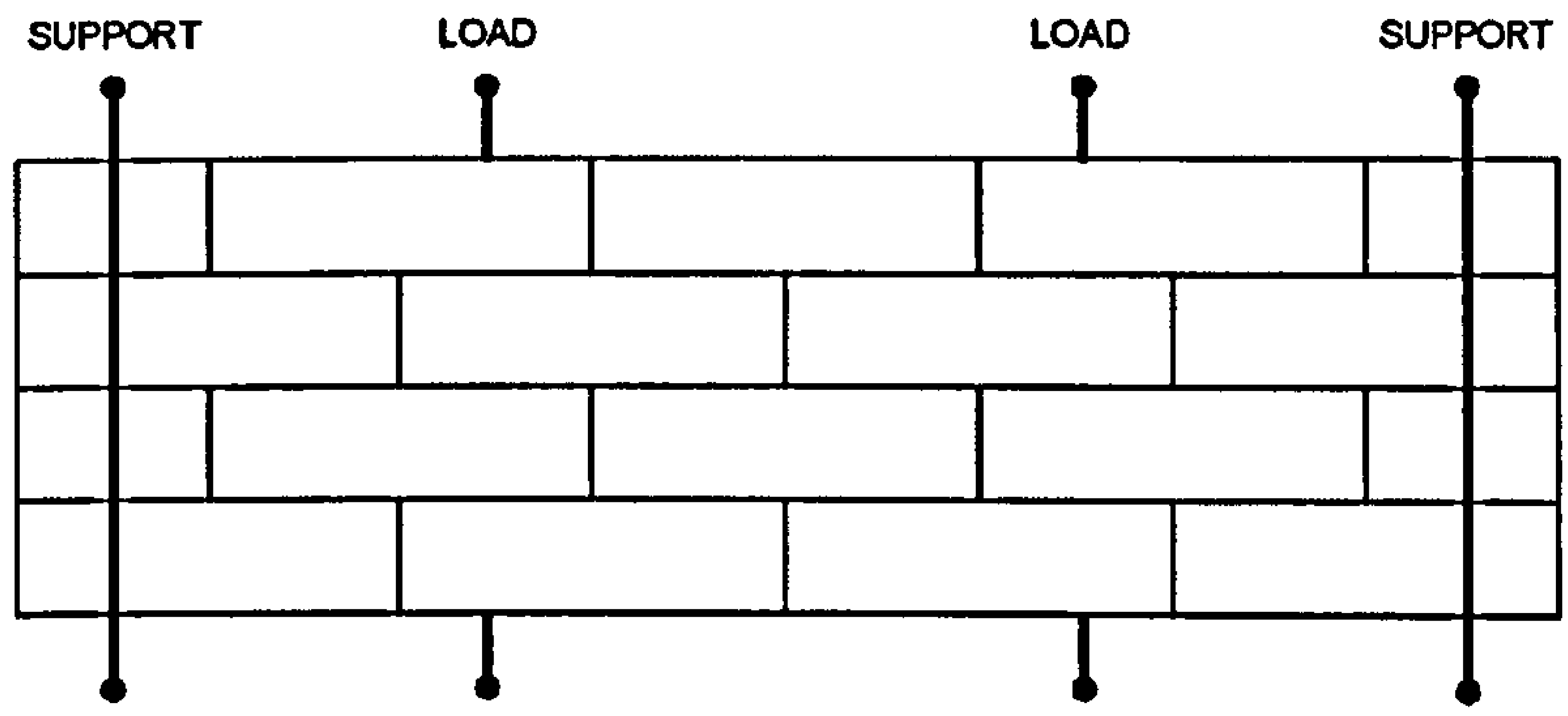


Figure 5.5.1.1 – P wallettes - Identification of support and load bars

The process in which a P wallette is analysed takes the form of grid pattern shown in Figure 5.5.1.2. The red dotted lines were drawn in to indicate the line of breakage, corresponding to the number label at the top. Whilst, letters A to D identify the first to forth row from the top, respectively. The process of using the grid always takes a path starting from the top left, across and then down as shown in Figure 5.5.1.3.

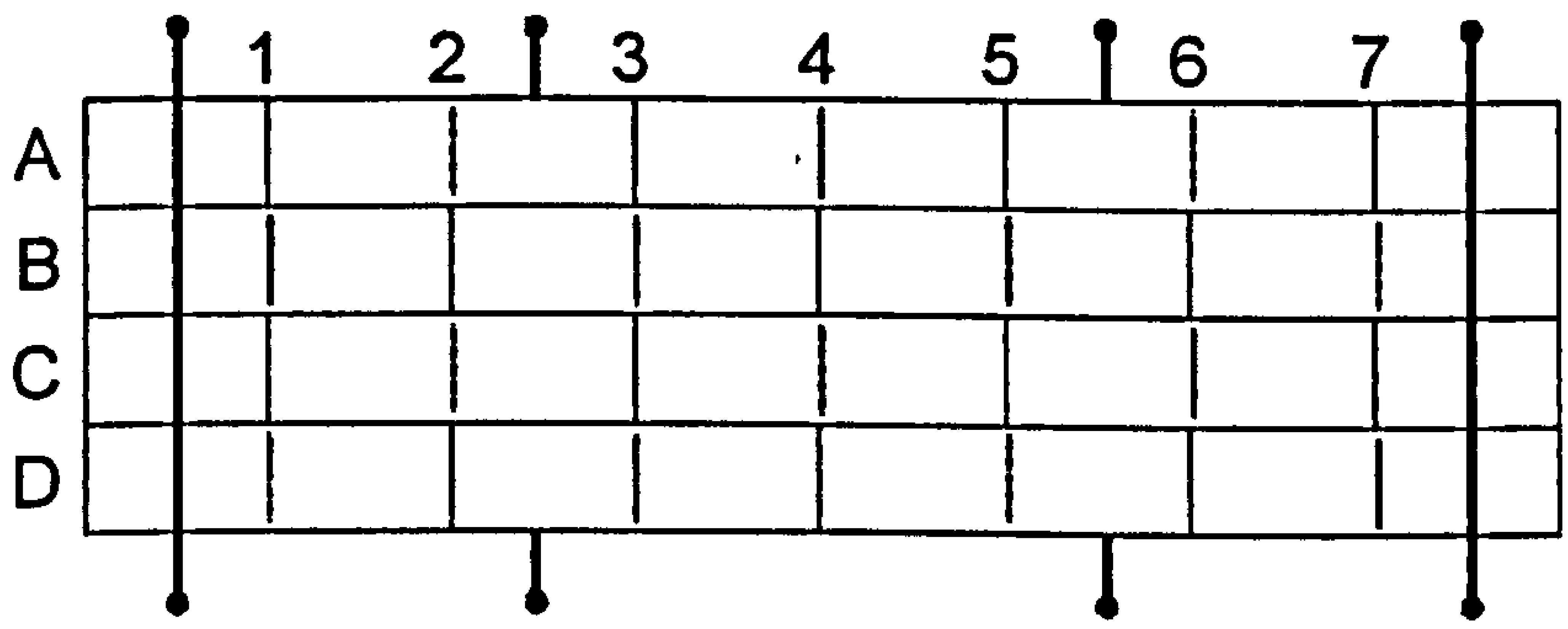


Figure 5.5.1.2 – P wallettes - Grid pattern

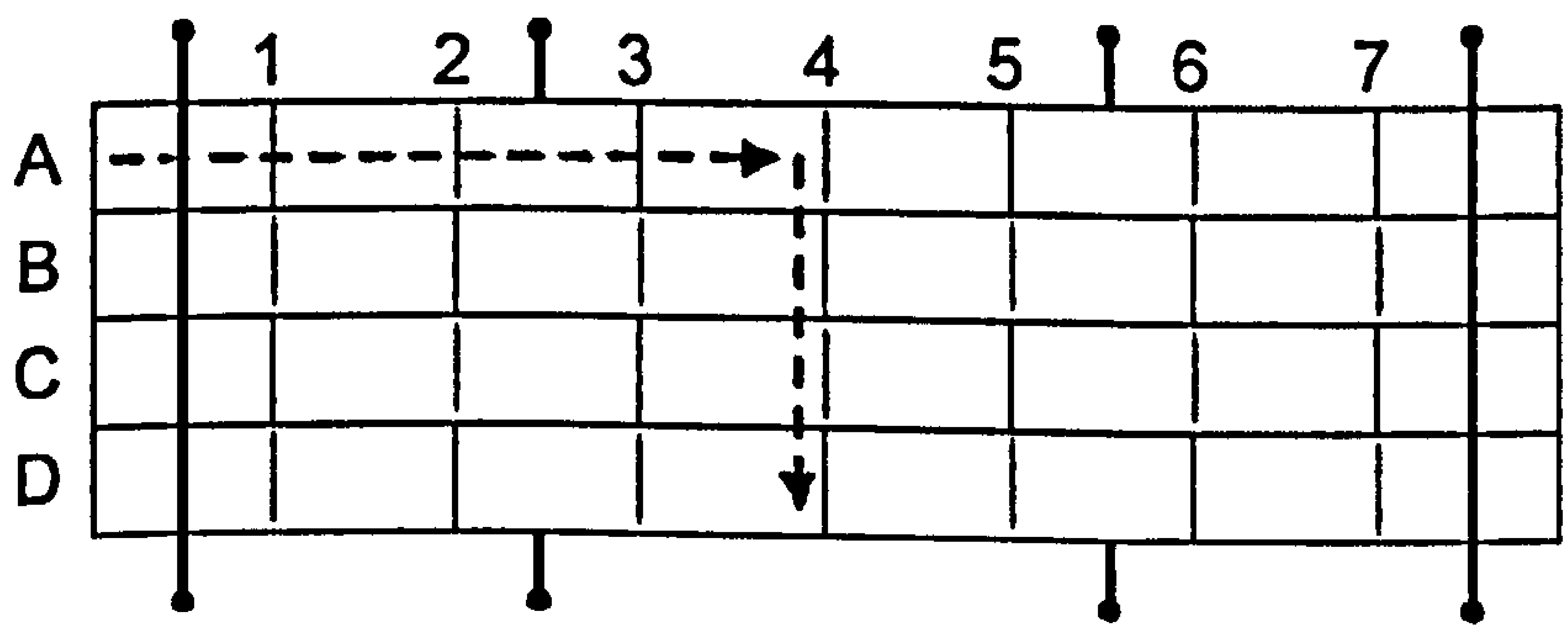


Figure 5.5.1.3 – P wallettes – path taken for reading wallette failure pattern

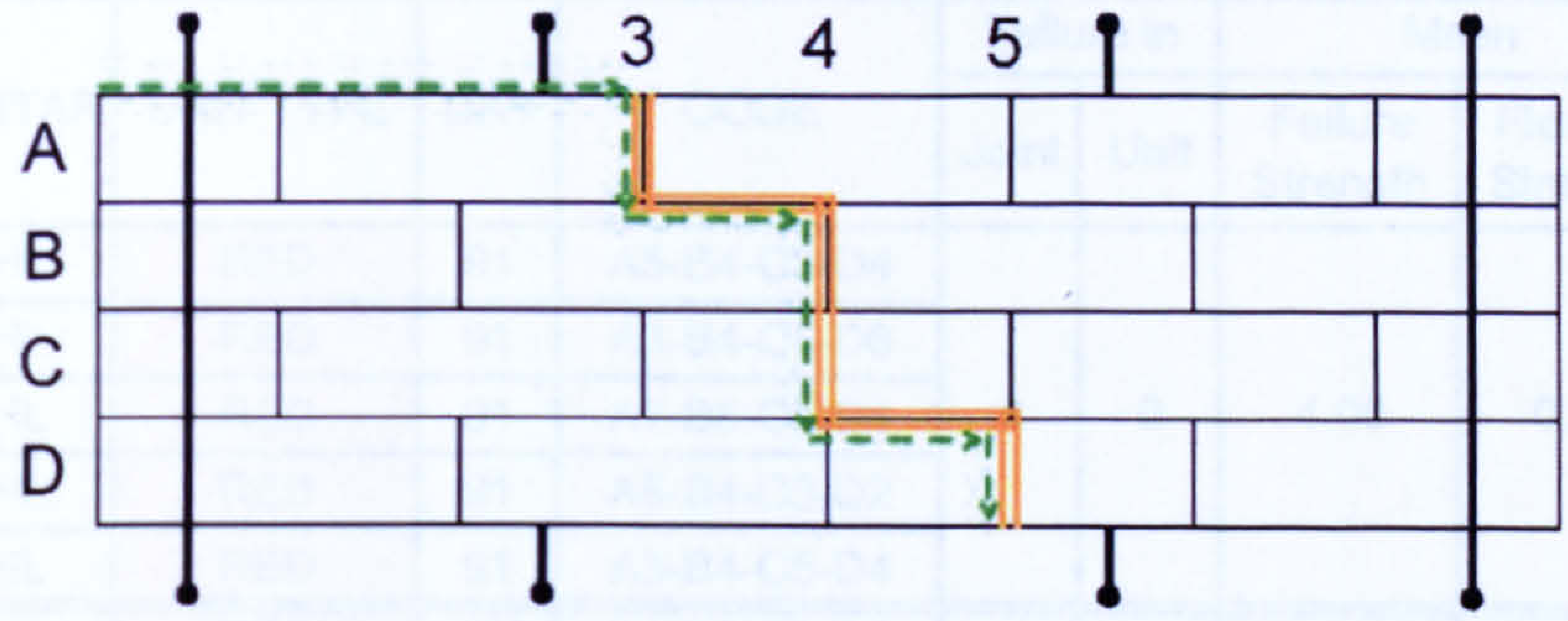


Figure 5.5.1.4 – P wallettes – example wallette failure pattern

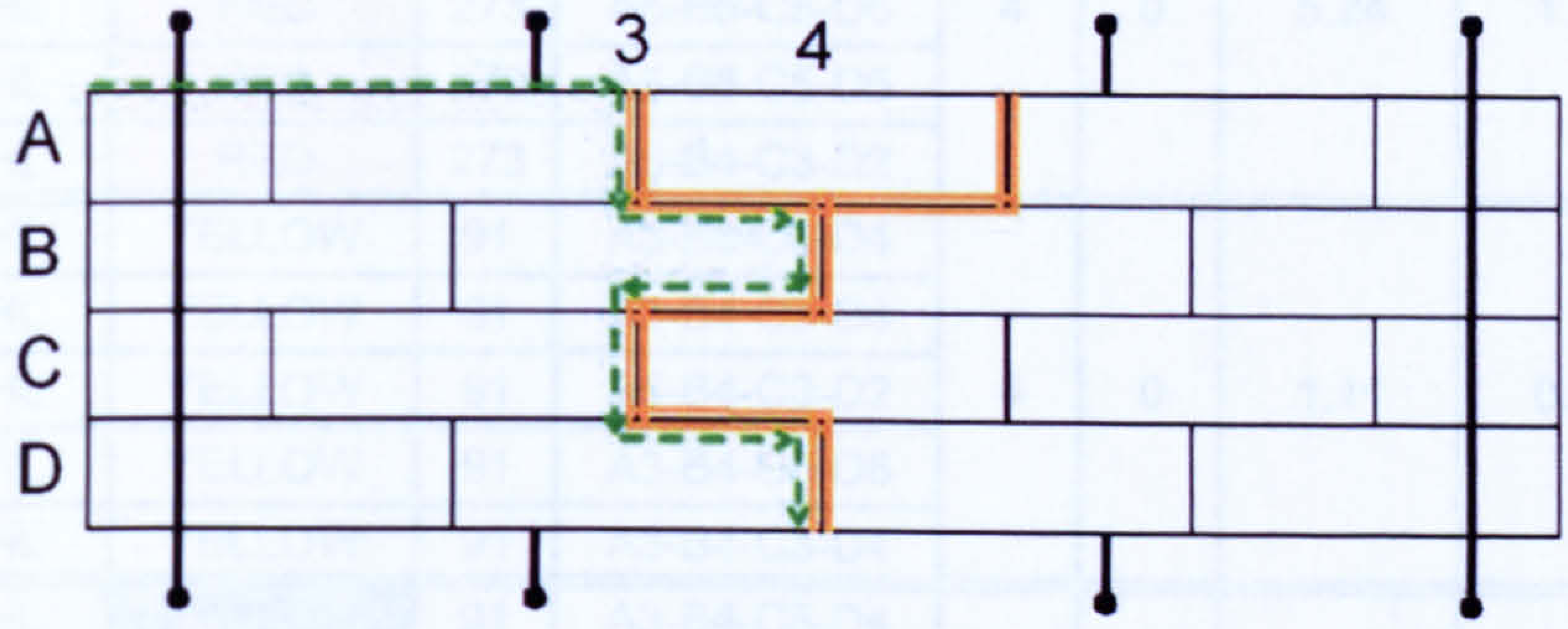


Figure 5.5.1.5 – P wallettes – special case example wallette failure pattern

Figure 5.5.1.4, shows an example failure pattern. Starting from the top left it will translate to A3 – B4 – C4 – D5. Since this test is only interested in the form of perpend failure, in particular whether breakage occurs in the mortar joint or in the unit; the horizontal path is not taken into account other than the unit row. In the rare occurrence when a failure is propagated in the horizontal bed into adjacent units in the shape of a fork as seen in Figure 5.5.1.5 the pattern furthest to the left is taken into consideration. These types of patterns were noted in eleven out of eighty tests, of which six occurred with NHL mortar. Table 5.5.1.1 gives a quick reference guide to codes and types of perpend failures.

Breakage in Joint	Breakage in Unit
A1, A3, A5, A7	A2, A4, A6
B2, B4, B6	B1, B3, B5, B7
C1, C3, C5, C7	C2, C4, C6
D2, D4, D6	D1, D3, D5, D7

Table 5.5.1.1 – P wallette – reference table for failure codes

An amalgamated table 5.5.1.2, shows the failure code pattern with how many joint and unit failures occurred and at what failure strength. Red event at 273 days had no unit failures, in comparison to Aircrete at 91 days where the mean failure was through 2 units and 2 joints.

MORTAR	UNIT TYPE	DAY	CODE	Failure in		Mean	
				Joint	Unit	Failure Strength	Flexural Strength
NHL	RED	91	A5-B4-C3-D4	4	0	4.06	0.93
NHL	RED	91	A3-B4-C5-D6				
NHL	RED	91	A7-B6-C5-D4				
NHL	RED	91	A5-B4-C3-D2				
NHL	RED	91	A3-B4-C5-D4				
NHL	RED	273	A4-B4-C3-D2	4	0	5.24	1.20
NHL	RED	273	A3-B4-C5-D6				
NHL	RED	273	A5-B5-C5-D6				
NHL	RED	273	A5-B6-C5-D5				
NHL	RED	273	A5-B4-C3-D2				
NHL	YELLOW	91	A5-B6-C5-D4	4	0	1.11	0.25
NHL	YELLOW	91	A3-B4-C3-D4				
NHL	YELLOW	91	A5-B4-C3-D2				
NHL	YELLOW	91	A3-B4-C5-D6				
NHL	YELLOW	91	A3-B4-C3-D4				
NHL	CONCRETE	91	A3-B4-C5-D4	4	0	5.04	1.16
NHL	CONCRETE	91	A4-B4-C4-D4				
NHL	CONCRETE	91	A5-B4-C5-D4				
NHL	CONCRETE	91	A5-B4-C5-D4				
NHL	CONCRETE	91	A5-B4-C3-D2				
NHL	AIRCRETE	91	A5-B5-C5-D5	2	2	7.33	1.86
NHL	AIRCRETE	91	A4-B4-C4-D4				
NHL	AIRCRETE	91	A3-B3-C3-D4				
NHL	AIRCRETE	91	A5-B5-C5-D5				
NHL	AIRCRETE	91	A3-B3-C3-D3				

Table 5.5.1.2 – NHL - P wallette – failure codes and mean data

OPC has an unusually weak trend where all wallettes broke through the mortar joint and only 1 through a unit. As all the units were dry during building to maintain equilibrium for comparison between the three mortar types, this could result in lower bond strength due to osmotic effects disturbing the process of hydration which OPC utilizes to increase in strength.

MORTAR	UNIT TYPE	DAY	CODE	Failure in		Mean	
				Joint	Unit	Failure Strength	Flexural Strength
OPC	RED	3	A3-B4-C5-D6	4	0	2.92	0.66
OPC	RED	3	A5-B4-C5-D6				
OPC	RED	3	A3-B4-C3-D4				
OPC	RED	3	A3-B4-C5-D4				
OPC	RED	3	A3-B4-C3-D4				
OPC	RED	7	A3-B4-C3-D2	4	0	3.32	0.75
OPC	RED	7	A5-B6-C5-D4				
OPC	RED	7	A5-B6-C5-D6				
OPC	RED	7	A1-B2-C3-D2				
OPC	RED	7	A5-B4-C3-D2				
OPC	RED	28	A5-B4-C5-D5	4	0	3.69	0.84
OPC	RED	28	A5-B4-C3-D4				
OPC	RED	28	A3-B4-C3-D4				
OPC	RED	28	A3-B4-C5-D6				
OPC	RED	28	A5-B4-C5-D6				
OPC	YELLOW	28	A5-B6-C5-D4	4	0	2.08	0.47
OPC	YELLOW	28	A3-B4-C3-D4				
OPC	YELLOW	28	A5-B4-C3-D2				
OPC	YELLOW	28	A3-B4-C5-D6				
OPC	YELLOW	28	A3-B4-C3-D4				
OPC	CONCRETE	28	A5-B4-C5-D4	4	0	3.30	0.75
OPC	CONCRETE	28	A5-B4-C3-D4				
OPC	CONCRETE	28	A3-B4-C3-D4				
OPC	CONCRETE	28	A3-B4-C5-D6				
OPC	CONCRETE	28	A3-B4-C3-D4				
OPC	AIRCRETE	28	A3-B4-C5-D6	3	1	1.79	0.40
OPC	AIRCRETE	28	A3-B4-C3-D4				
OPC	AIRCRETE	28	A4-B4-C4-D4				
OPC	AIRCRETE	28	A5-B4-C3-D2				
OPC	AIRCRETE	28	A4-B4-C4-D4				

Table 5.5.1.3 – OPC - P wallette – failure codes and mean data

MORTAR	UNIT TYPE	DAY	CODE	Failure in		Mean	
				Joint	Unit	Failure Strength	Flexural Strength
TLM	RED	1	A3-B4-C5-D6	4	0	4.07	1.02
TLM	RED	1	A3-B4-C3-D4				
TLM	RED	1	A5-B4-C5-D6				
TLM	RED	1	A3-B4-C5-D6				
TLM	RED	1	A5-B4-C3-D2				
TLM	RED	7	A4-B4-C4-D4	2	2	10.96	2.75
TLM	RED	7	A3-B3-C3-D4				
TLM	RED	7	A4-B3-C3-D4				
TLM	RED	7	A4-B4-C4-D4				
TLM	RED	7	A6-B5-C3-D3				
TLM	YELLOW	7	A3-B4-C4-D5	2	2	8.45	2.12
TLM	YELLOW	7	A4-B5-C4-D5				
TLM	YELLOW	7	A4-B3-C3-D3				
TLM	YELLOW	7	A4-B4-C4-D4				
TLM	YELLOW	7	A5-B4-C3-D2				
TLM	CONCRETE	7	A3-B3-C3-D3	3	1	13.59	3.41
TLM	CONCRETE	7	A4-B4-C3-D2				
TLM	CONCRETE	7	A5-B4-C3-D2				
TLM	CONCRETE	7	A4-B4-C4-D4				
TLM	CONCRETE	7	A5-B5-C5-D5				
TLM	AIRCRETE	7	A5-B5-C5-D5	2	2	2.89	0.73
TLM	AIRCRETE	7	A4-B4-C4-D4				
TLM	AIRCRETE	7	A4-B4-C4-D4				
TLM	AIRCRETE	7	A3-B3-C3-D3				
TLM	AIRCRETE	7	A4-B4-C4-D4				

Table 5.5.1.4 – TLM - P wallette – failure codes and mean data

5.5.2 B wallettes

The test results are summarised in Tables 5.5.2.2, 5.5.2.3 & 5.5.2.4, which present mean failure loads and flexural strength for all the seventy five B wallettes tested. Counting from the first joint below the top unit, Table 5.5.2.1, shows the pattern of joint failures for each set of wall tests. Each day of testing and unit type has five repetitions. Overall just fewer than 50% of all B wallettes tested broke along the middle joint (No 5). Over 90% of all test wallettes broke along one of the three middle joints, fourth, fifth or sixth from the top.

Mortar - Day - Unit	Joint Number								
	1	2	3	4	5	6	7	8	9
NHL - 91 DAY - RED	0	0	0	0	3	2	0	0	0
NHL - 91 DAY - YELLOW	0	0	0	3	1	1	0	0	0
NHL - 91 DAY - CONCRETE	0	0	0	0	3	2	0	0	0
NHL - 91 DAY - AIRCRETE	0	0	0	2	2	1	0	0	0
OPC - 3 DAY - RED	0	0	1	1	2	1	0	0	0
OPC - 7 DAY - RED	0	0	1	1	2	0	1	0	0
OPC - 28 DAY - RED	0	0	0	2	3	0	0	0	0
OPC - 28 DAY - YELLOW	0	0	0	2	2	1	0	0	0
OPC - 28 DAY - CONCRETE	0	0	0	1	3	1	0	0	0
OPC - 28 DAY - AIRCRETE	0	0	0	2	2	1	0	0	0
TLM - 1 DAY - RED	0	1	0	2	2	0	0	0	0
TLM - 7 DAY - RED	0	0	1	2	2	0	0	0	0
TLM - 7 DAY - YELLOW	0	0	0	1	2	1	1	0	0
TLM - 7 DAY - CONCRETE	0	0	0	0	4	1	0	0	0
TLM - 7 DAY - AIRCRETE	0	0	1	2	2	0	0	0	0

Table 5.5.2.1 – B wallette – Frequency of joint failures

NHL				
B	MEAN FAILURE STRENGTH		MEAN FLEXURAL STRENGTH	
Unit \ Day	91	273	91	273
RED	0.96	2.25	0.10	0.23
YELLOW	0.48	-	0.05	-
CONCRETE	10.98	-	1.13	-
AIRCRETE	0.45	-	0.46	-

Table 5.5.2.2 – NHL - B wallette – Mean failure and flexural strengths

OPC						
B	MEAN FAILURE STRENGTH			MEAN FLEXURAL STRENGTH		
Unit \ Day	3	7	28	3	7	28
RED	1.05	1.48	1.74	0.11	0.15	0.18
YELLOW	-	-	1.61	-	-	0.17
CONCRETE	-	-	2.48	-	-	0.26
AIRCRETE	-	-	1.31	-	-	0.14

Table 5.5.2.3 – OPC - B wallette – Mean failure and flexural strengths

TLM				
B	MEAN FAILURE STRENGTH		MEAN FLEXURAL STRENGTH	
Unit \ Day	1	7	1	7
RED	4.96	10.46	0.57	1.21
YELLOW	-	6.30	-	0.73
CONCRETE	-	12.32	-	1.42
AIRCRETE	-	2.65	-	0.31

Table 5.5.2.4 – TLM - B wallette – Mean failure and flexural strengths

5.5.3 Couplets

The test results are summarised in Tables 5.5.3.1, 5.5.3.2 & 5.5.3.3, which present mean failure loads and bond strength for all three hundred and sixty couplets tested.

The percentage mean of the modes of failure across all mortars and specimens is shown in Figure 5.5.3.1. The corresponding graphical representation of the modes is shown in Figure 4.5.3. The frequency of all failures for TLM is shown in Figure 5.5.3.2 and NHL in Figure 5.5.3.3, where each day of testing and unit type has 10 repetitions.

NHL			
COUPLETS	MEAN FAILURE STRENGTH		
Unit \ Day	91	273	365
RED	229.0	280.5	374.0
YELLOW	125.5	147.5	141.5
CONCRETE	59.0	77.5	85.5
AIRCRETE	42.0	71.0	59.5
COUPLETS	MEAN INDIVIDUAL BOND STRENGTH		
Unit \ Day	91	273	365
RED	0.58	0.71	0.95
YELLOW	0.32	0.37	0.36
CONCRETE	0.15	0.17	0.21
AIRCRETE	0.10	0.18	0.15

Table 5.5.3.1 – NHL – Couplets – Mean failure and flexural strengths

OPC		
COUPLETS	MEAN FAILURE STRENGTH	MEAN INDIVIDUAL BOND STRENGTH
Unit \ Day	7	7
RED	239.00	0.48
YELLOW	69.00	0.14
CONCRETE	109.50	0.22
AIRCRETE	45.50	0.09

Table 5.5.3.2 – OPC – Couplets – Mean failure and flexural strengths

TLM					
COUPLETS	MEAN FAILURE STRENGTH				
Unit \ Day	1	3	7	28	56
RED	85.50	291.50	415.50	325.00	429.17
YELLOW	79.50	157.50	286.50	330.00	399.50
CONCRETE	239.40	350.50	319.50	479.58	517.00
AIRCRETE	117.50	154.50	159.00	163.00	174.50
COUPLETS	MEAN INDIVIDUAL BOND STRENGTH				
Unit \ Day	1	3	7	28	56
RED	0.26	0.91	1.13	1.03	1.36
YELLOW	0.26	0.49	0.84	0.96	1.15
CONCRETE	0.70	1.08	1.01	1.26	1.43
AIRCRETE	0.35	0.42	0.32	0.33	0.33

Table 5.5.3.3 – TLM – Couplets – Mean failure and flexural strengths

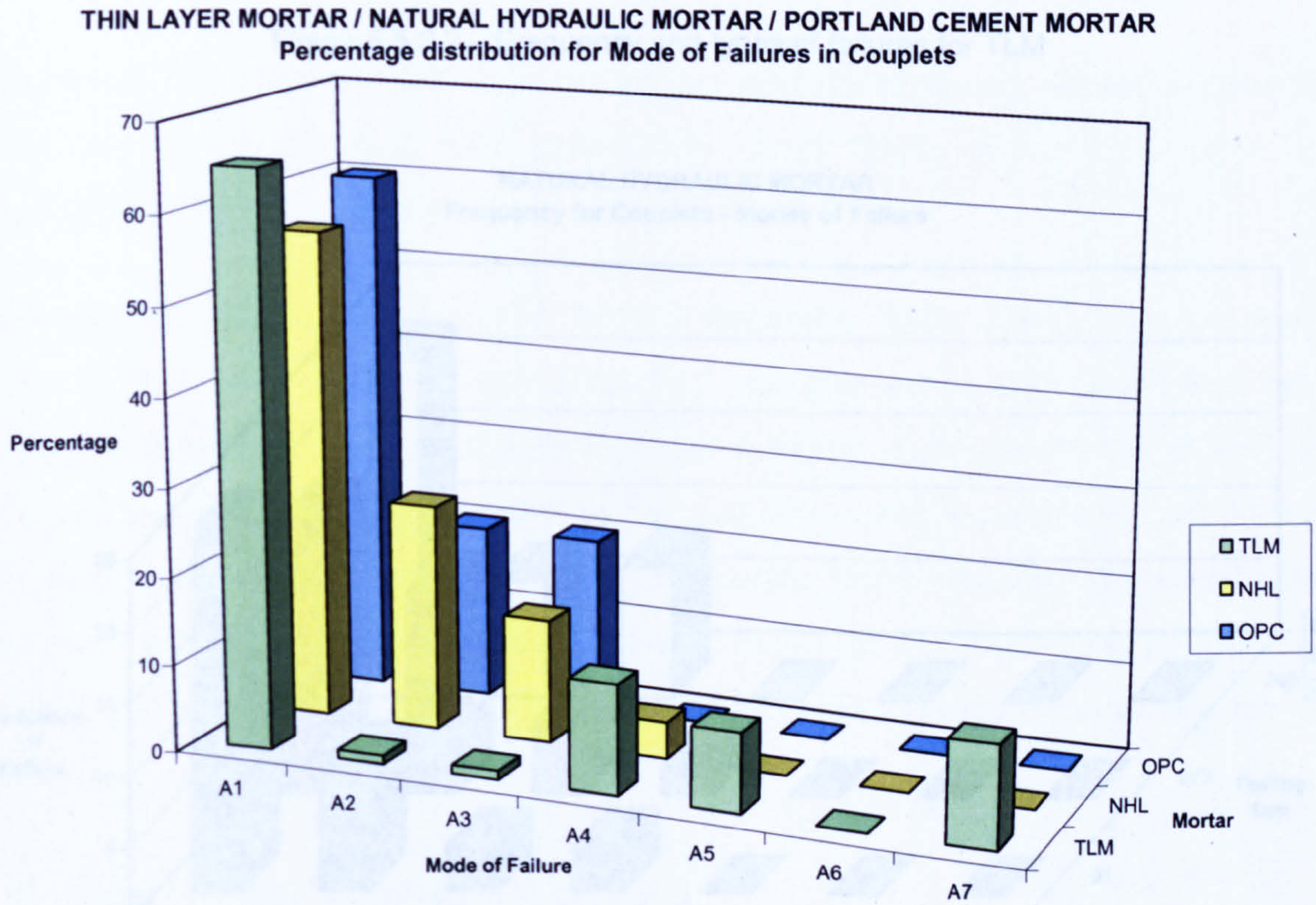


Figure 5.5.3.1 – Couplets % Mean modes of failure across all 360 specimens

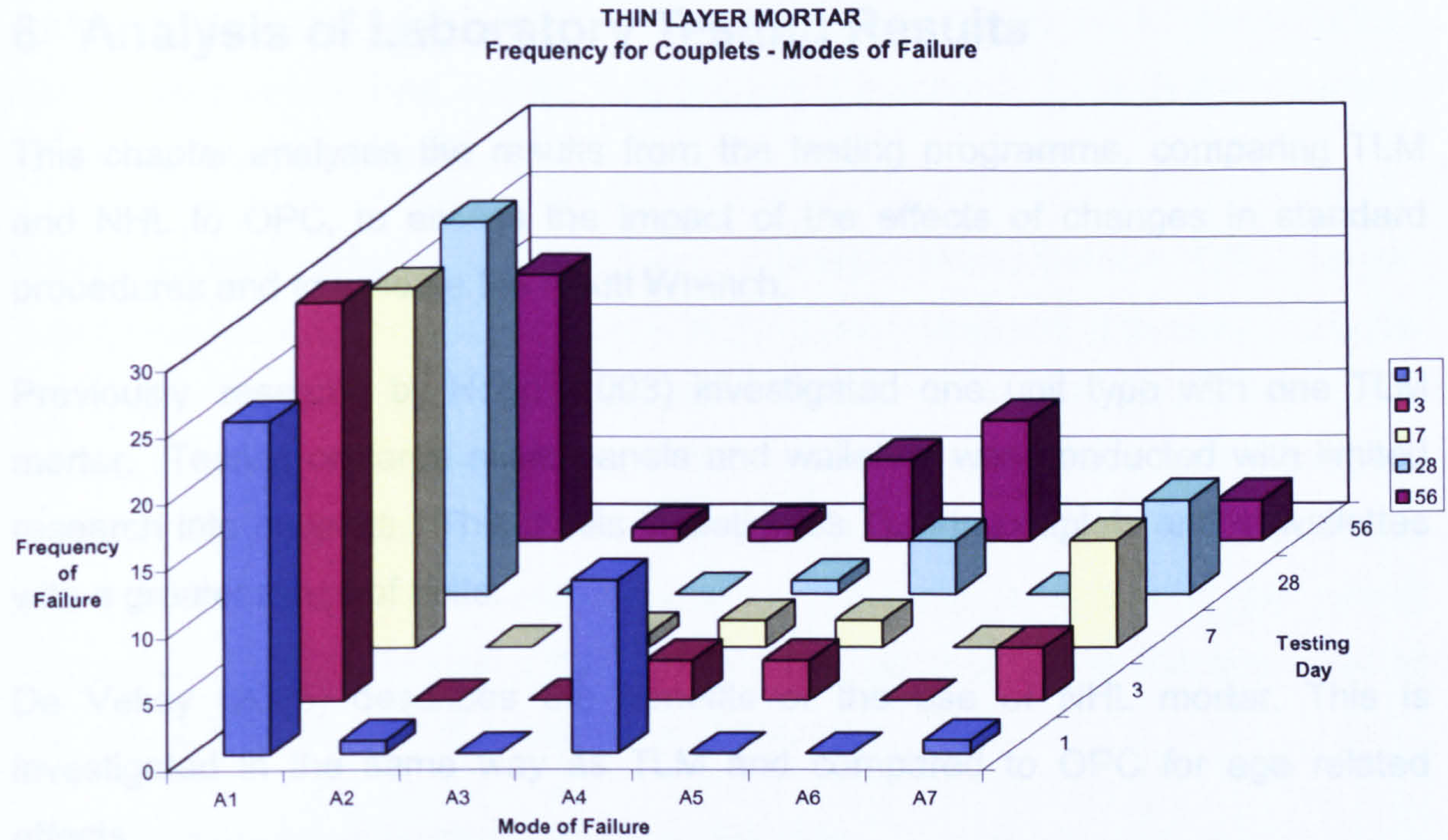


Figure 5.5.3.2 – Frequency and types of failures for TLM

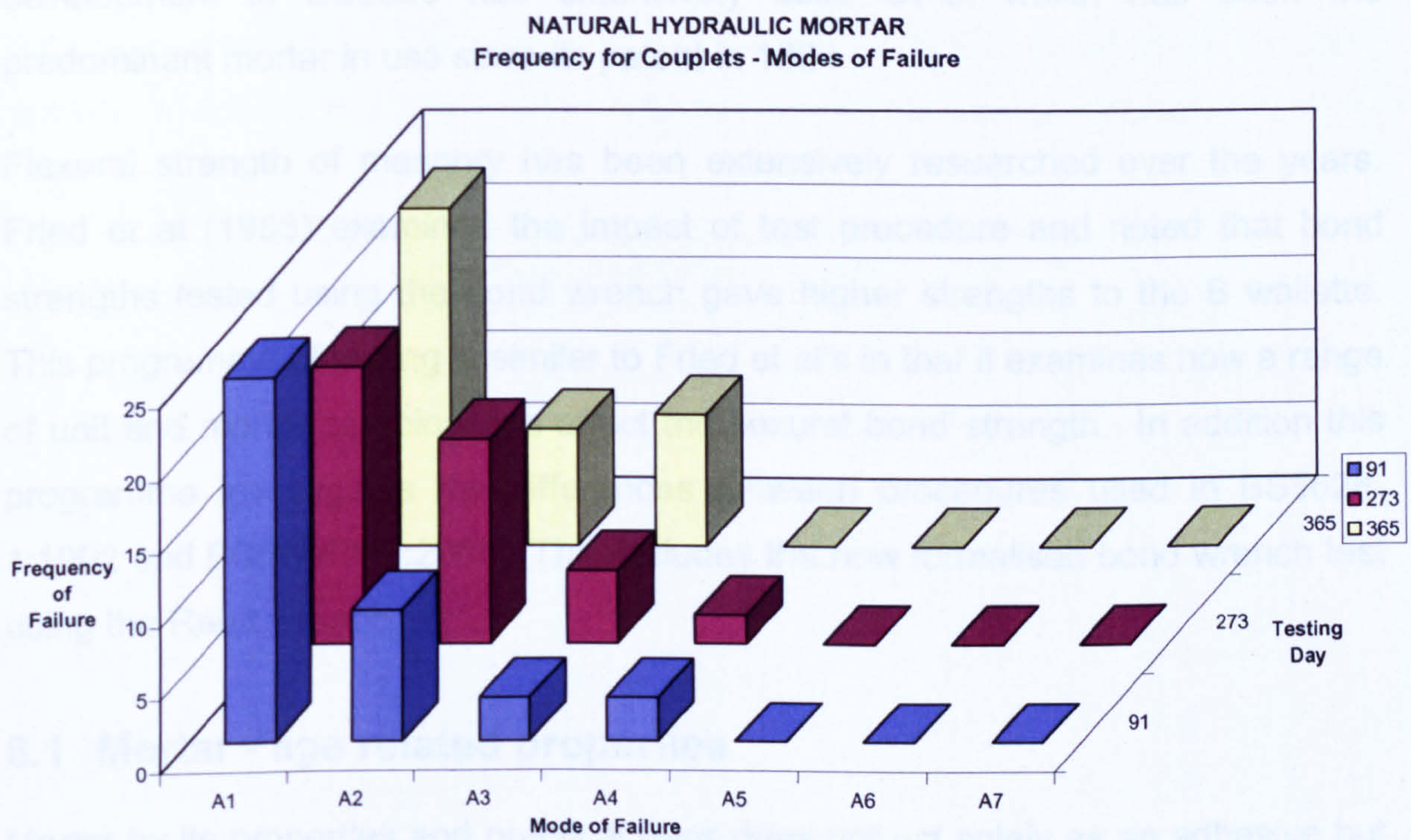


Figure 5.5.3.3 – Frequency and types of failures for NHL

6 Analysis of Laboratory Testing Results

This chapter analyses the results from the testing programme, comparing TLM and NHL to OPC, to assess the impact of the effects of changes in standard procedures and to validate the Reutt Wrench.

Previously, research by Hogg (2003) investigated one unit type with one TLM mortar. Testing on large scale panels and wallettes was conducted with limited research into couplets. This thesis investigates TLM in couplets and in wallettes with a greater range of units.

De Vekey (2005) describes the benefits of the use of NHL mortar. This is investigated in the same way as TLM and compared to OPC for age related effects.

Properties and uses of OPC are well known and documented. Research into the development of BS5628 has extensively used OPC, which has been the predominant mortar in use since its patent in 1824.

Flexural strength of masonry has been extensively researched over the years. Fried et al (1988) examined the impact of test procedure and noted that bond strengths tested using the bond wrench gave higher strengths to the B wallette. This programme of testing is similar to Fried et al's in that it examines how a range of unit and mortar combinations affect the flexural bond strength. In addition this programme investigates the differences between procedures used in BS5628-1:1992 and BSEN 1015:2005. This includes the now formalised bond wrench test using the Reutt wrench.

6.1 Mortar - age related properties

Mortar by its properties and practical uses does not act solely as an adhesive but mainly as a spacer; the reason being that not all units are identical. An important parameter for mortar to act in this way is its compressive strength. Historically, practitioners and researchers have concluded that OPC has 80% of its compressive strength at 28 days (Johnson – pers.com July 2005).

Age related testing is necessary to ascertain the rate at which the mortars compressive strength is developed. Furthermore, testing of mortar in tension and flexure at the same time as compression gives a wider scope for investigation. For this reason test methods are detailed in the standards to verify the quality of the mortar and its rate of curing.

Unlike Natural Hydraulic Lime (NHL) and Ordinary Portland Cement (OPC) mortar, Thin Layer Mortar (TLM) has a very sticky nature. Moulding difficulties occurred due to this sticky property, requiring the use of more mould release lubricating mineral oil to be used, ensuring a uniformly smooth and bubble less specimen. The mould release oil has an indeterminate effect on the edges of the joint area and it is though that it is sufficiently large not have an effect on the overall properties. During the testing it was noted that none of the specimens failed to test and all showed correct explosive patterns.

6.1.1 Compressive strength – cube – 100mm

Figure 6.1.1.1, shows how the mean compressive strength of mortar specimens determined using 100mm cubes varies with age when tested in accordance with BS 4551 – 1: 1998. The graph examines the performance of three mortars, namely TLM, OPC and NHL mortar. The testing of TLM was undertaken at 1, 3, 7,

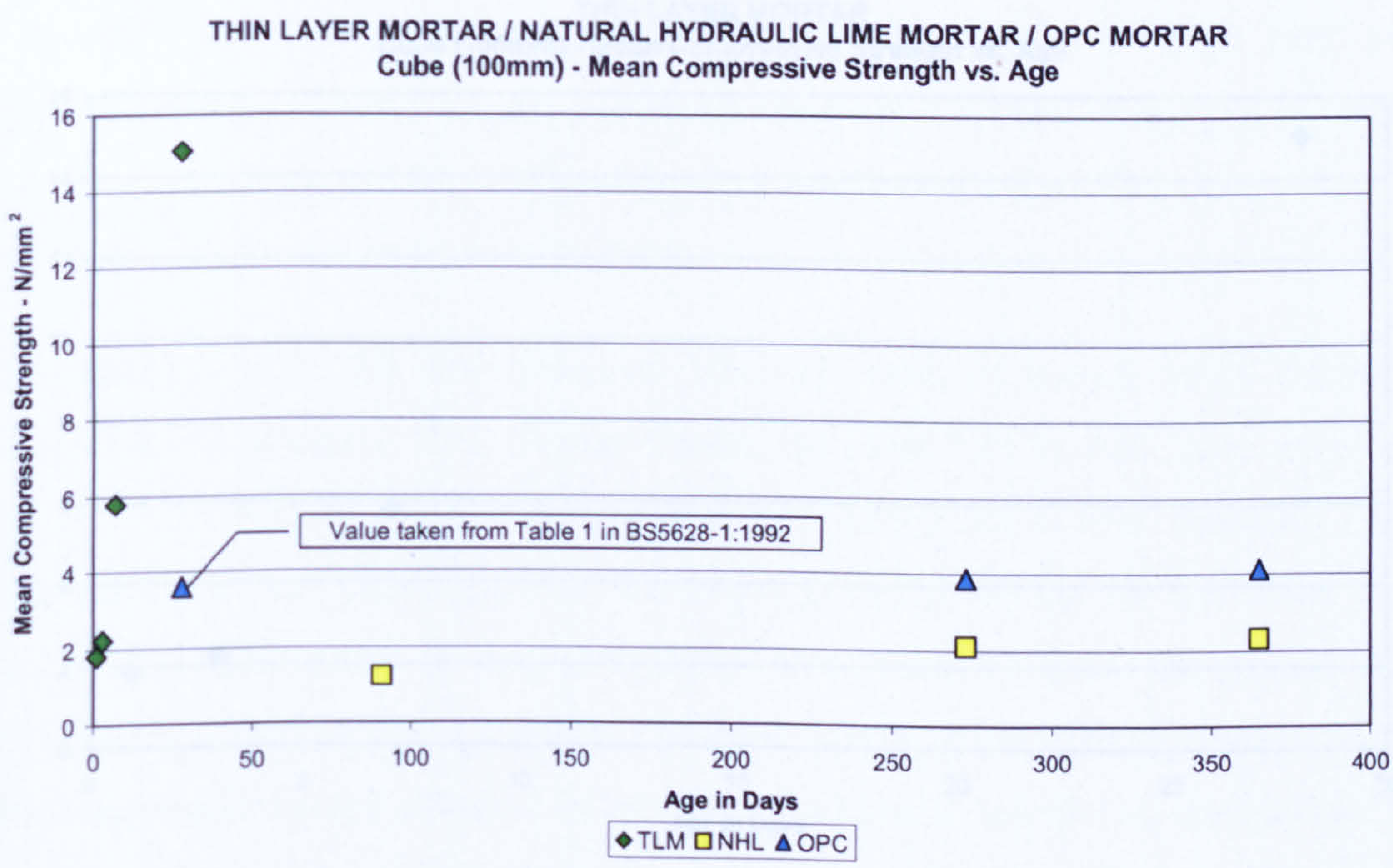


Figure 6.1.1.1 - Cube (100mm) - mean compressive strength vs. age for TLM, NHL and OPC mortar

and 28 days; NHL mortar was tested at 91, 273 and 365 days whilst OPC mortar was tested at 273 and 365 days. In addition a value for OPC at 28 days was taken from the BS5628-1:1992 standard. The reason for the testing of higher age of OPC mortar was to enable comparisons with NHL mortar at these ages.

The maximum compressive strength of the TLM at 28 days was 3.7 times the strength of the OPC at 365 days, and 6.5 times the strength of NHL at 365 days. It was noted that the strength gain of TLM to 28 days was nearly linear, as indicated in Figure 6.1.1.2. In comparison NHL mortar increased in strength at a gradual rate with age then levelled off. OPC behaved in a similar way to NHL but increased in strength at a faster rate with age to a higher resultant compressive strength. As a direct comparison at 28 days, a value for OPC was taken from BS 5628 – 1:1992, this is approximately 20% of the strength of TLM at the same age. However at 365 days it is double the strength of NHL.

TLM is notably stronger and has a quicker strength to age ratio than the other two mortars. The implications of these findings are that TLM is good to use in situations where high compressive strength is required rather than flexibility of movement. NHL on the other hand is not good for compressive strength but is more forgiving to creep.

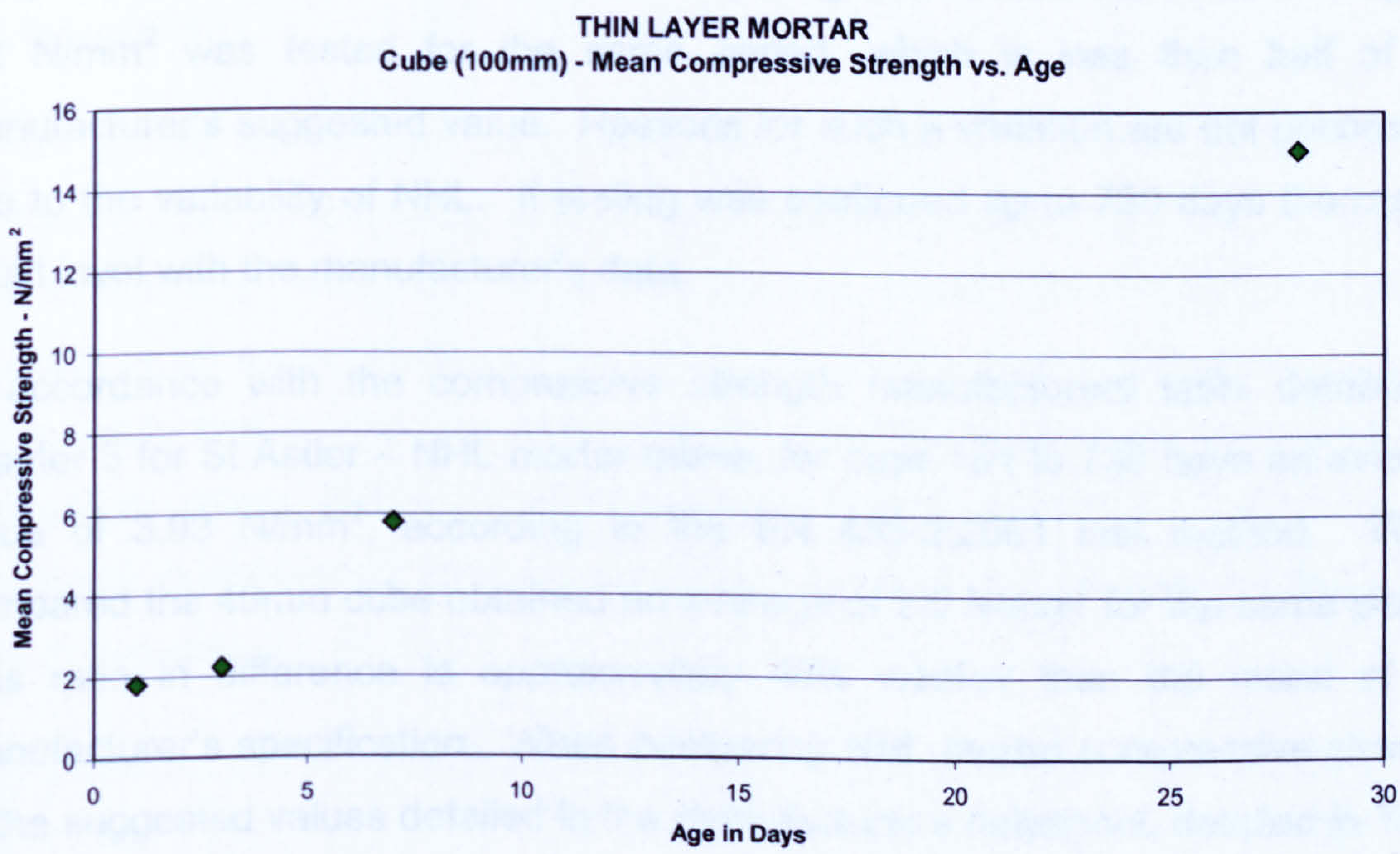


Figure 6.1.1.2 – Cube (100mm) - mean compressive strength vs. age for TLM

6.1.2 Compressive strength – cube – 40mm

Figure 6.1.2.1, examines how the strength of mortar is related to age and tested in accordance with BS EN 1015-11:1999. Using a product of the flexure test detailed in section 6.1.3; where prisms of dimensions 40 x 40 x 160mm (width x height x length) were split in two. Variations in the resulting length of the cubes were between 70 to 80 mm. The physical properties gave rise to the colloquial term "Prism Ends".

The graph examines the performance of the three mortars at various ages. The testing of TLM was undertaken at 1, 3, 7 and 28 days; NHL mortar was tested at 91, 273 and 365 days whilst for the purpose of comparison with NHL, OPC mortar was tested at 273 and 365 days. In addition a value for OPC at 28 days was taken from the BS EN 1015-11:1999 standard. This complies with the comparison of the standards value for the 28 day tests.

St Astier manufactured the NHL used in this testing program. In the data tables provided, 3.93 N/mm^2 is given as a suggested typical compressive strength characteristic for days ranging from 181 to 730. The test data does not specify the sample size or method used. When comparing the 100mm cubes an average of 2.2 N/mm^2 was tested for the same period, which is less than half of the manufacturer's suggested value. Reasons for such a variation are not uncommon due to the variability of NHL. If testing was continued up to 730 days the means could level with the manufacturer's data.

In accordance with the compressive strength manufacturers table detailed in chapter 5 for St Astier – NHL mortar mixes, for days 181 to 730 have an average value of 3.93 N/mm^2, according to the EN 459-2:2001 test method. When compared the 40mm cube obtained an average of 2.5 N/mm^2 for the same period. This ratio in difference is approximately 40% weaker than the mean of the manufacturer's specification. When comparing NHL mortar compressive strength to the suggested values detailed in the manufacturer's datasheet, detailed in Table 5.2.5, the observed trend was that 40 mm cubes reduce the difference in means.

In Figure 6.1.2.1 TLM clearly exhibits a higher rate of strength gain with age than NHL or OPC. TLM at 28 days is 3.5 times the strength of OPC at 365 days and 8 times the strength of NHL at the same age. Using the value from EN 998 – 2: 2003 for OPC at 28 days gives a strength that is 25% of TLM at the same age.

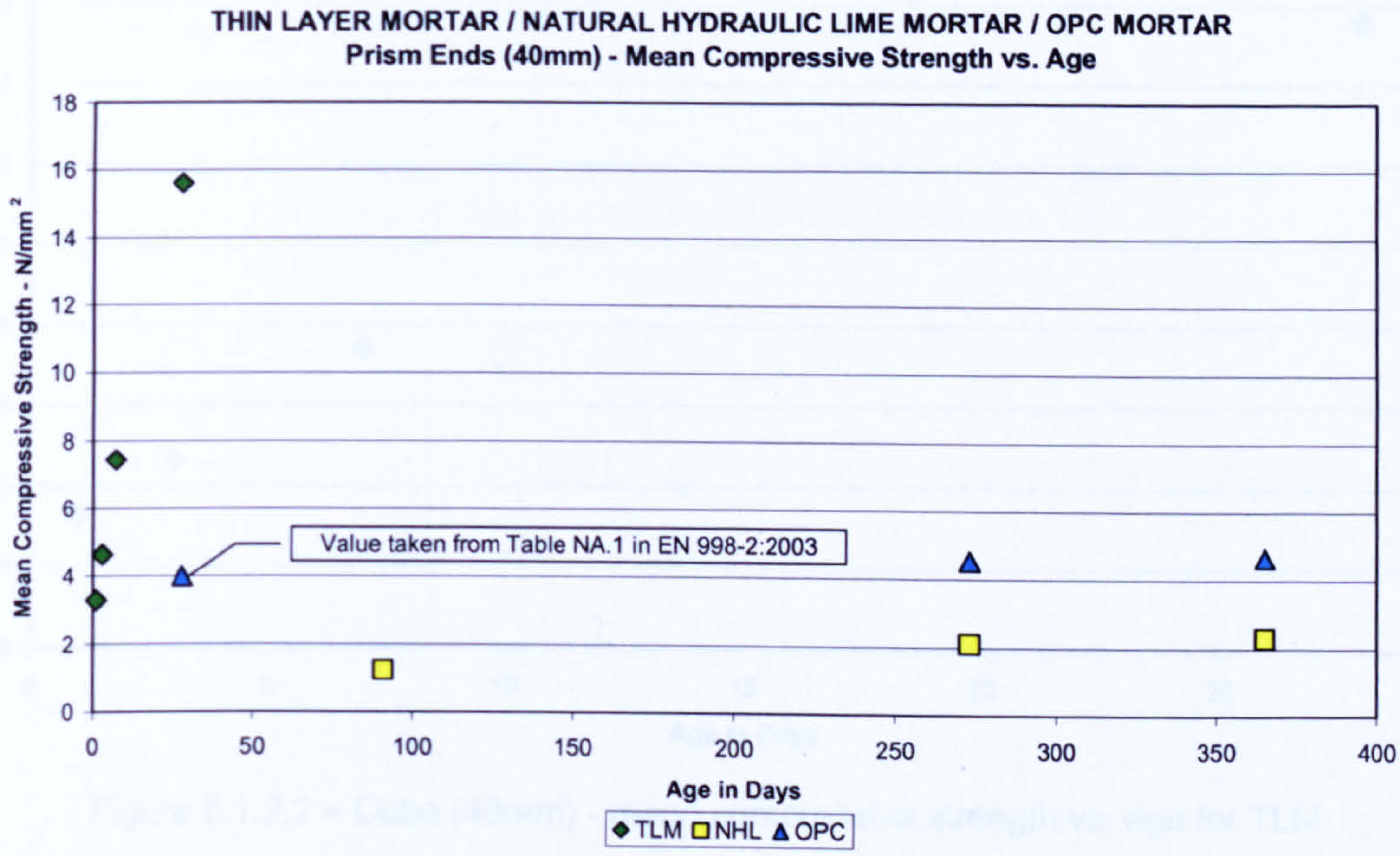
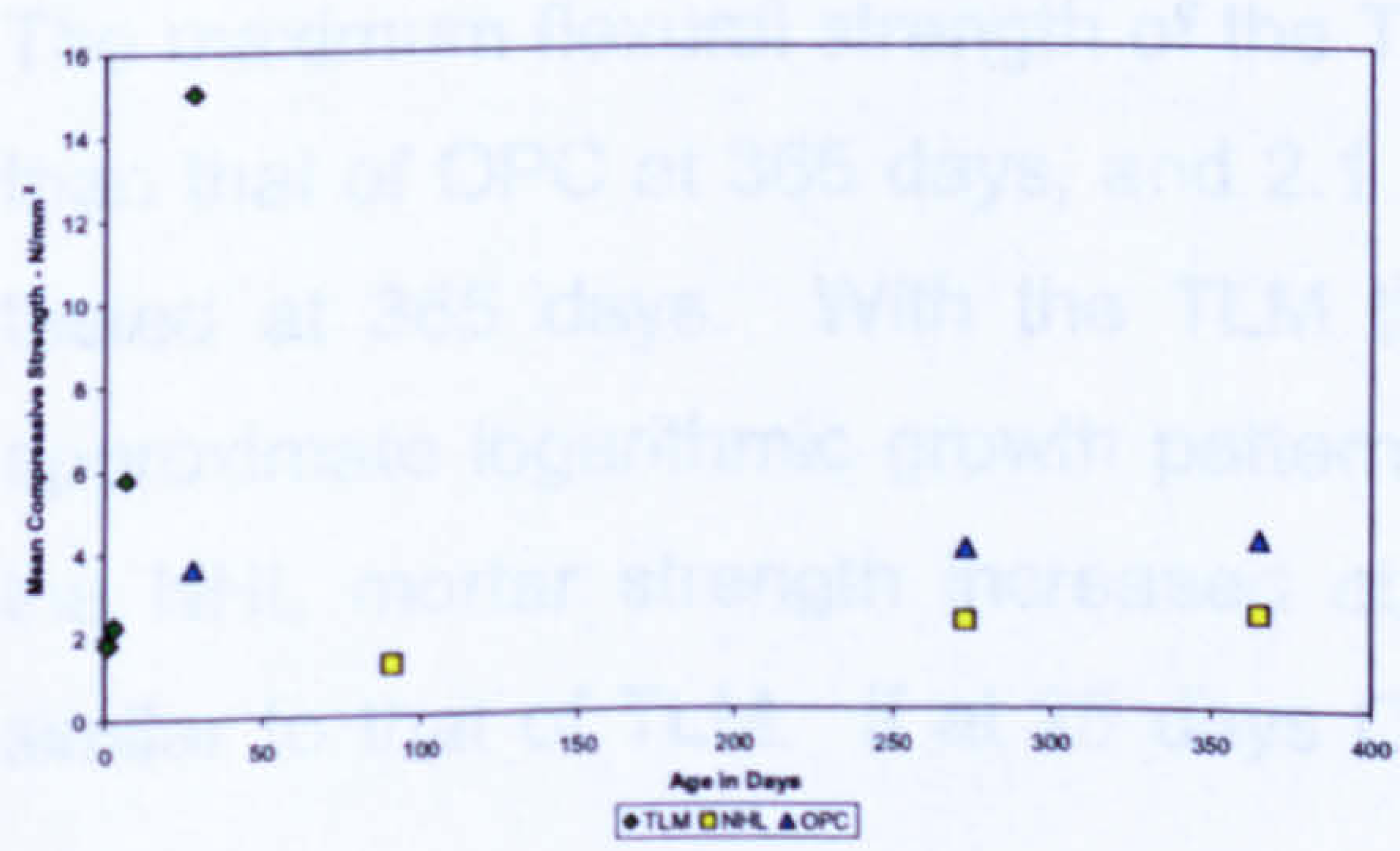
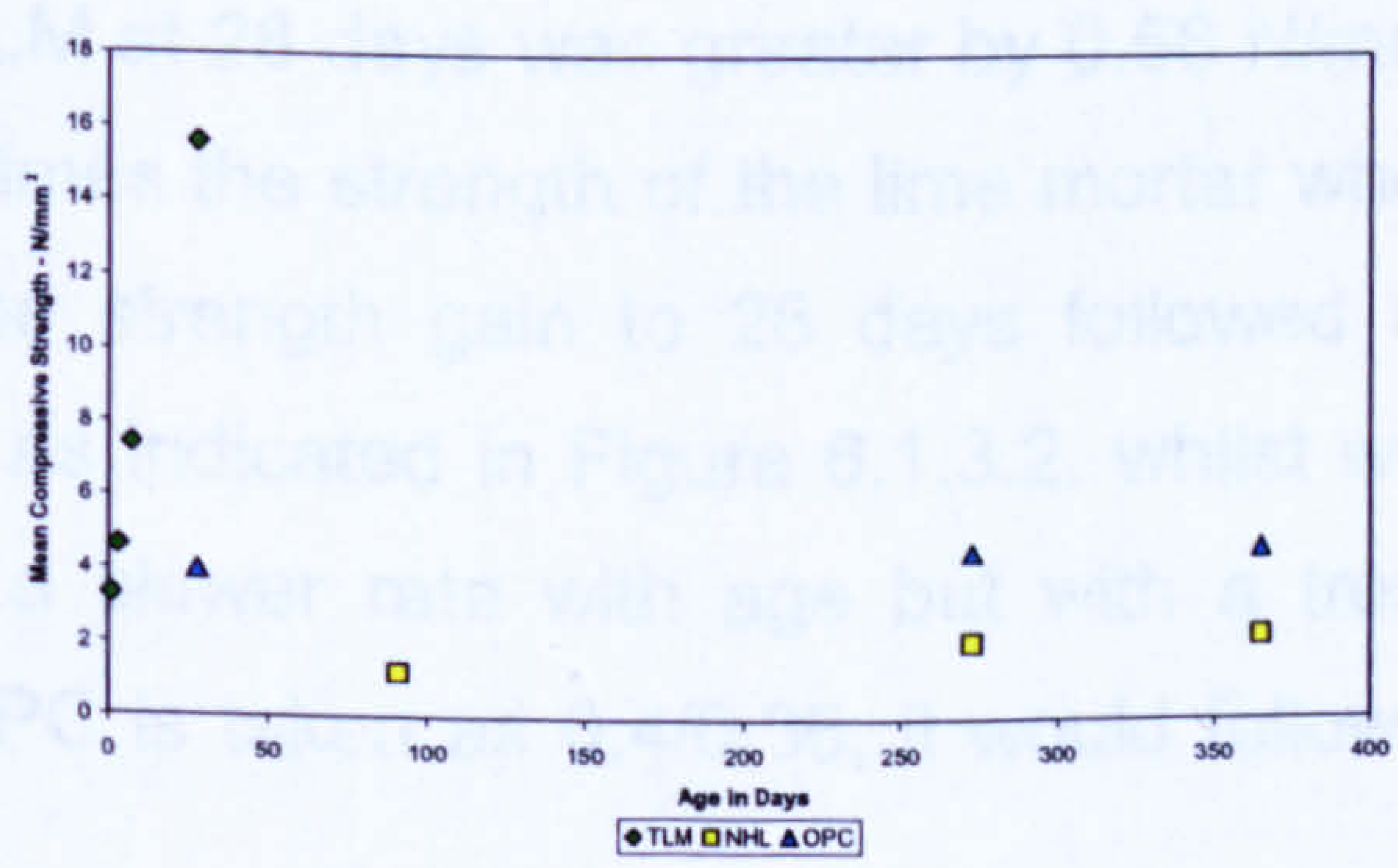


Figure 6.1.2.1 – Cube (40mm) - mean compressive strength vs. age for TLM, NHL & OPC

Figure 6.1.2.2 examines the strength of TLM again determined using 40 mm cubes (prism ends). On close inspection the graph follows a second order polynomial trend.

Similar trends are as seen to those in Figure 6.1.1.1, with the strength of the 40mm cube specimens being stronger in all cases. Neville (1995) indicates there, is a size and an overhang effect with respect to the compressive strength of concrete prism ends, which is likely to be mirrored in mortar specimens. Neville further adds that as the specimen size for concrete specimens is reduced, the strength increases slightly. This observation is also relevant to mortar and the hypothesis is confirmed, by comparing 6.1.1.1, with 6.1.2.1 shown for illustration purposes below:





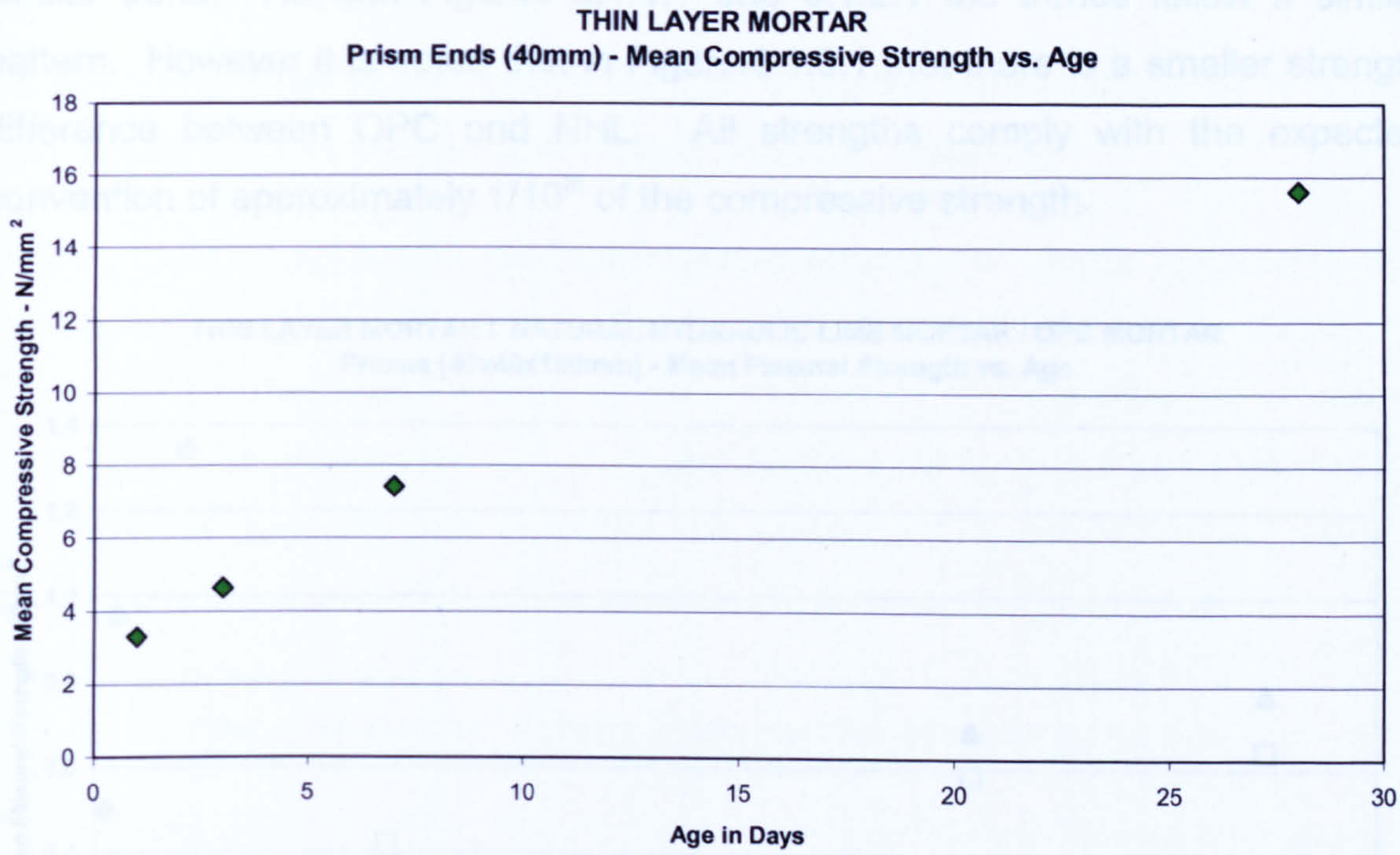


Figure 6.1.2.2 – Cube (40mm) - mean compressive strength vs. age for TLM

6.1.3 Flexural strength – prisms

Since the machine used is an automatic testing rig the testing procedures were consistent. Using the three point loading gave approximate breakage within 10% of the middle. The end products are the prism ends which are then used for the compressive strength tests.

Figure 6.1.3.1, shows how the mean flexural strength of mortar specimens was determined using prism of dimensions 40 x 40 x 160mm (w x d x l). Similar to Figure 6.1.1.1, the graph examines the performance of three mortars. Specifically the testing of TLM was undertaken at 1, 3, 7 and 28 days; NHL mortar was tested at 91, 273 and 365 days whilst OPC mortar was tested at 273 and 365 days. As discussed previously the reason for the higher age of cement mortar to usual was to enable comparisons with NHL mortar at these ages.

The maximum flexural strength of the TLM at 28 days was greater by 0.56 N/mm^2 than that of OPC at 365 days, and 2.1 times the strength of the lime mortar when tested at 365 days. With the TLM the strength gain to 28 days followed an approximate logarithmic growth pattern as indicated in Figure 6.1.3.2, whilst with the NHL mortar strength increased at a slower rate with age but with a trend similar to that of TLM. If at 28 days OPC is taken as 0.4/0.36, it would follow a similar trend. As with Figures 6.1.1.1 and 6.1.2.1 the trends follow a similar pattern. However it is noted that in Figure.6.1.3.1 that there is a smaller strength difference between OPC and NHL. All strengths comply with the expected convention of approximately 1/10th of the compressive strength.

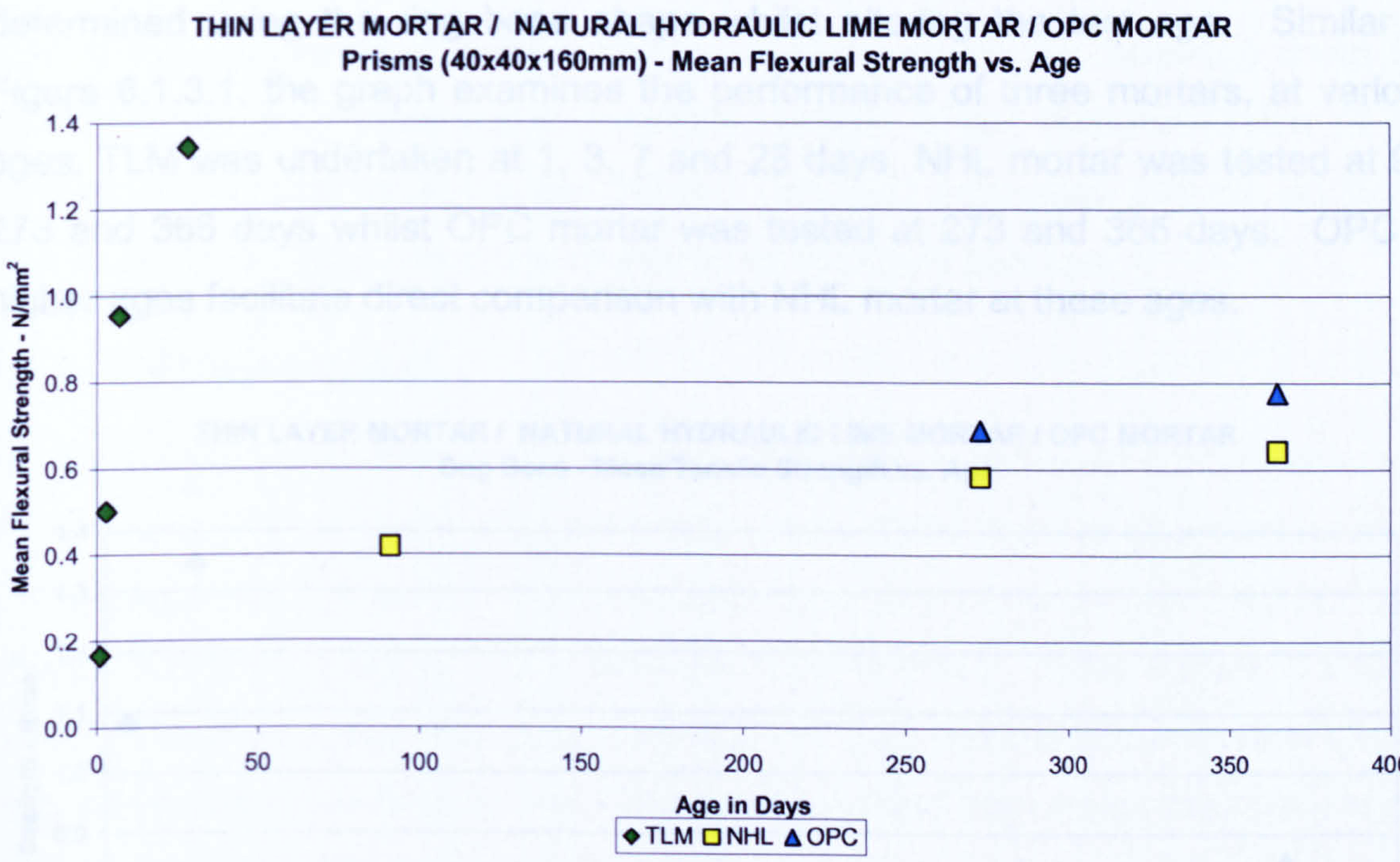


Figure 6.1.3.1 – Prisms (40x40x160mm) - mean flexural strength vs. age for TLM, NHL and OPC mortar

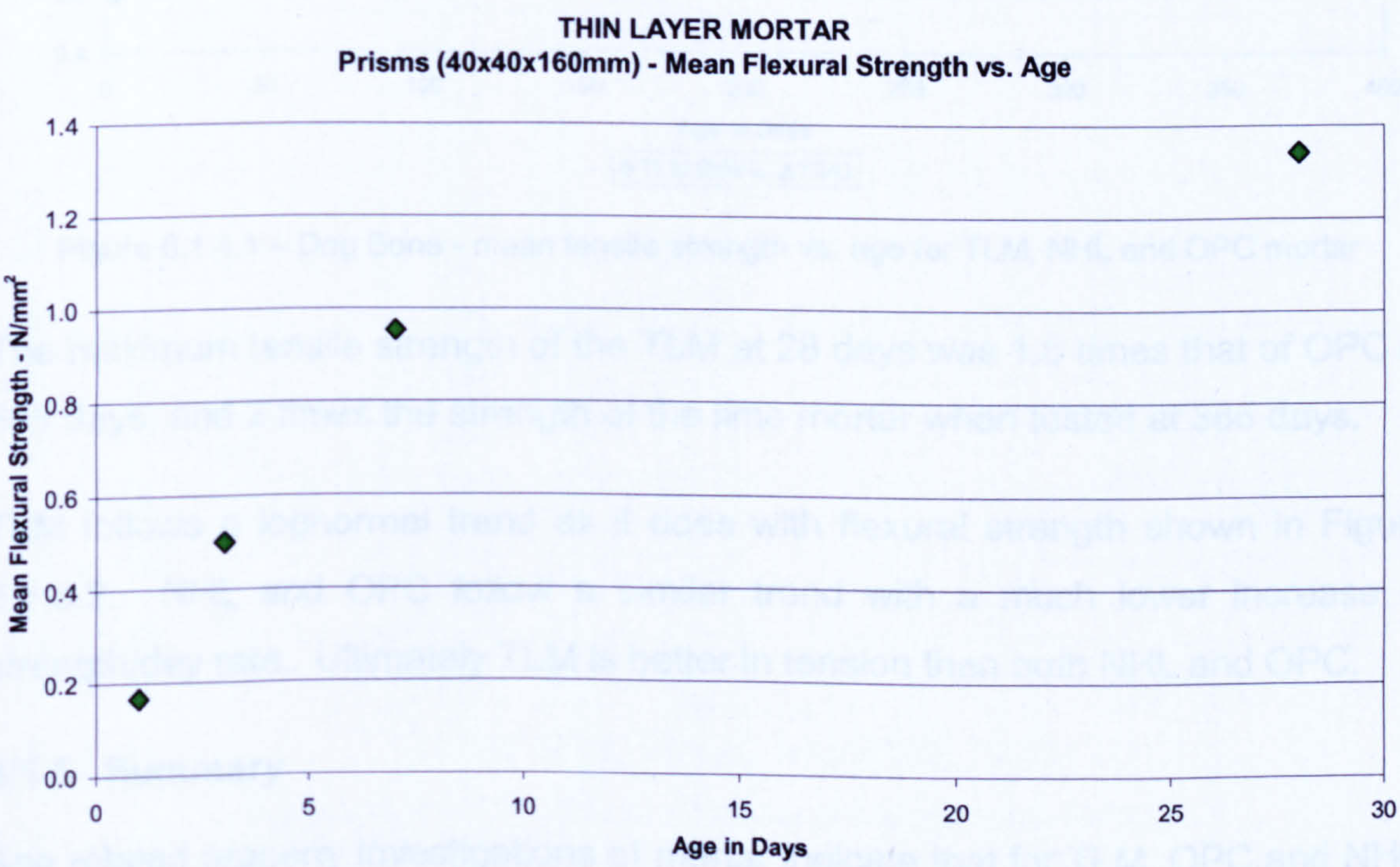


Figure 6.1.3.2 – Prisms (40x40x160mm) - mean flexural strength vs. age for TLM

6.1.4 Tensile strength – dog bones

As when investigating the flexural strength of mortar, the same test rig was used with attachments for the specimen shape shown in chapter 4.

Figure 6.1.4.1 shows how the mean tensile strength of mortar specimens was determined using the dog bone shape whilst altering the test age. Similar to Figure 6.1.3.1, the graph examines the performance of three mortars, at various ages, TLM was undertaken at 1, 3, 7 and 28 days, NHL mortar was tested at 91, 273 and 365 days whilst OPC mortar was tested at 273 and 365 days. OPC at higher ages facilitate direct comparison with NHL mortar at these ages.

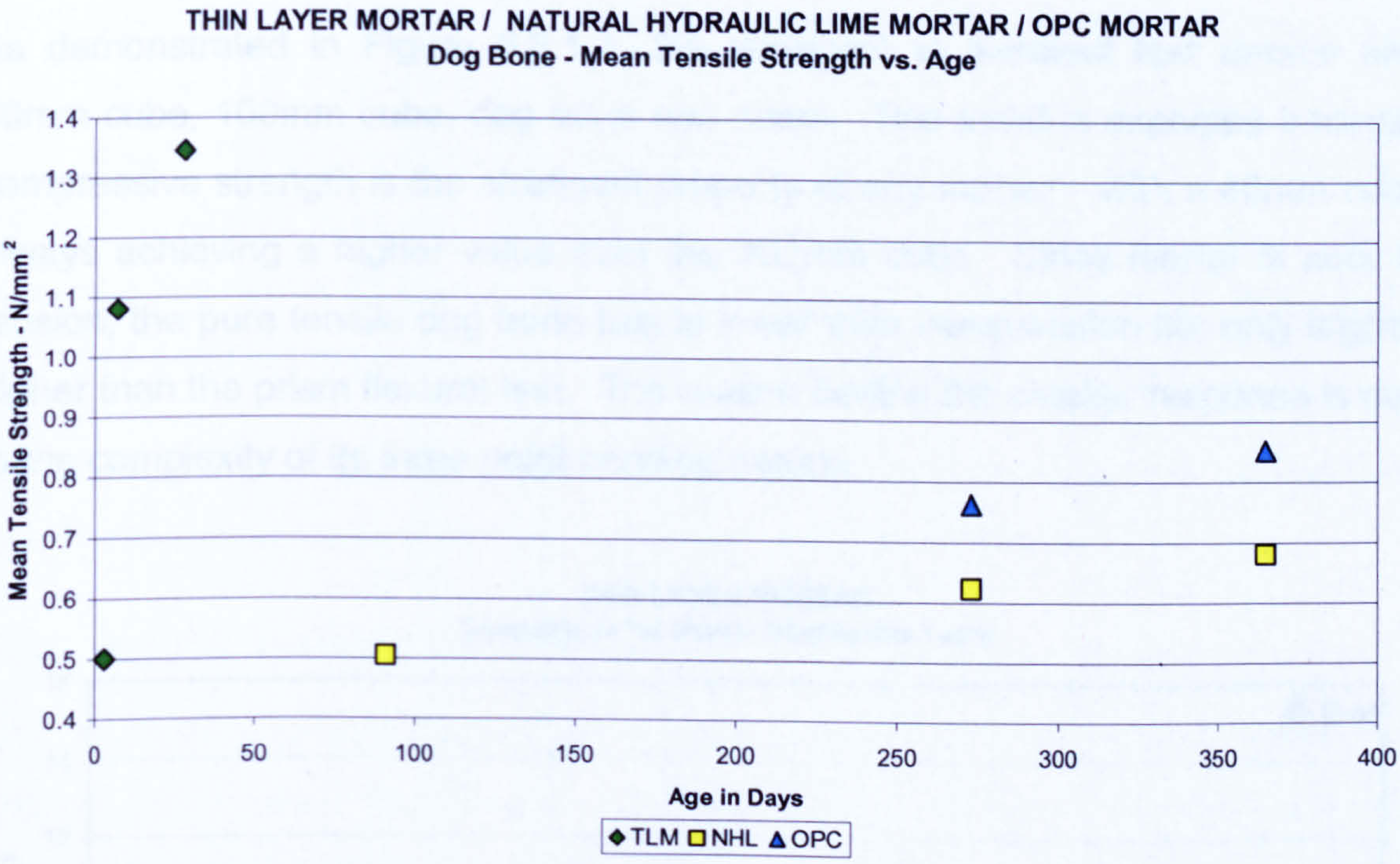


Figure 6.1.4.1 – Dog Bone - mean tensile strength vs. age for TLM, NHL and OPC mortar

The maximum tensile strength of the TLM at 28 days was 1.6 times that of OPC at 365 days, and 2 times the strength of the lime mortar when tested at 365 days.

TLM follows a lognormal trend as it does with flexural strength shown in Figure 6.1.3.2. NHL and OPC follow a similar trend with a much lower increase in strength/day rate. Ultimately TLM is better in tension than both NHL and OPC.

6.1.5 Summary

Age related property investigations of mortar indicate that for TLM, OPC and NHL; all increase in strength with age but at different rates and do not achieve the same flexural strengths. TLM attains the highest strengths and has the fastest rate of curing. OPC attains a lower failure strength than TLM but higher than NHL. NHL has the lowest rate of curing which in turn levels off to approximately 80% of OPC.

6.2 Mortar – comparisons of properties

Due to the complexity of understanding masonry structures, breaking down the elements into their constituent materials, enable better comprehension of the situation. By cross analysis the different physical properties give an all round picture and indication to how the mortar in its own right behaves.

6.2.1 Thin layer mortar

As demonstrated in Figure 6.2.1.1, the strongest to weakest test means are: 40mm cube, 100mm cube, dog bone and prism. This trend is expected because compressive strength is the strongest property of any mortar – with a 40mm cube always achieving a higher value than the 100mm cube. Since mortar is poor in tension, the pure tensile dog bone test is lower than compression but only slightly higher than the prism flexural test. The reason behind the weaker response is due to the complexity of its three point bending nature.

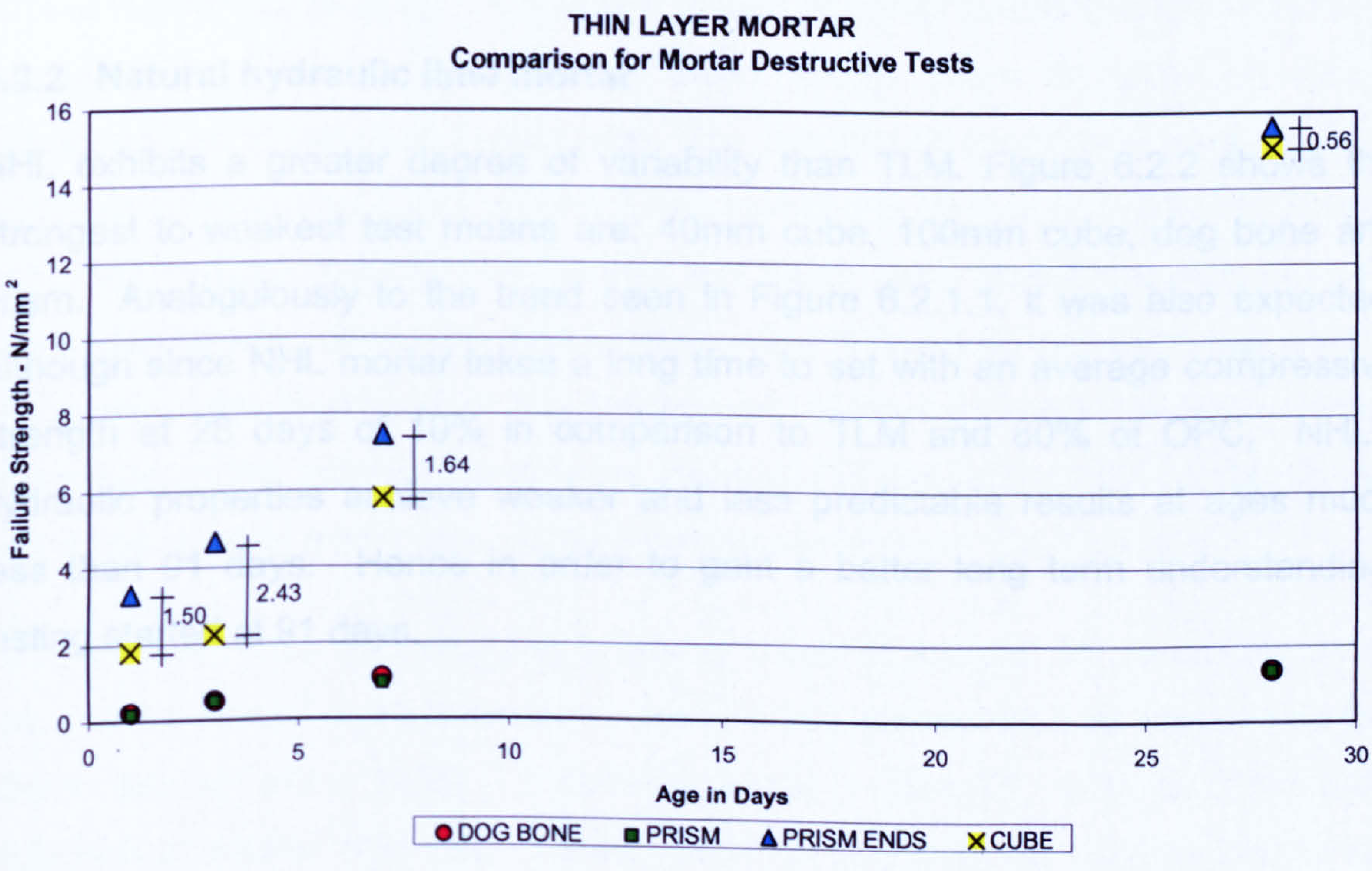


Figure 6.2.1.1 – Comparison of mortar destructive tests for TLM

Unlike the pure tensile dog bone test it is a combination of compression and tension, shown in the diagram below. The red oval line shows the direction of the tensile forces originating from the yellow shaded area.

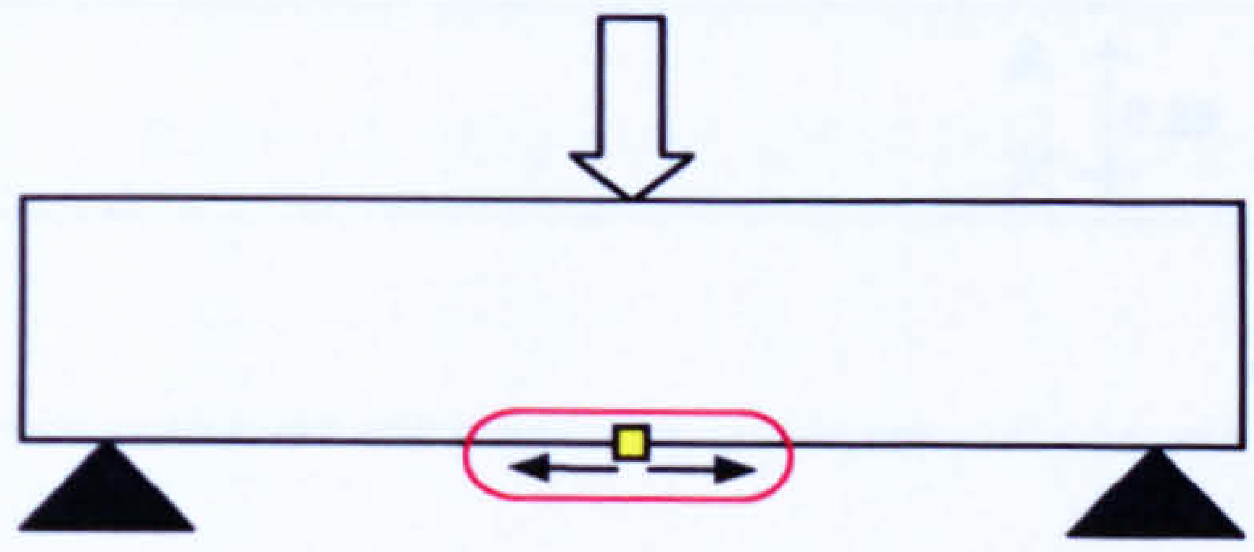


Figure 6.2.1.2 – Flexural prism with compressive and tensile forces represented

The compressive strength of the 40mm cube (prism ends) is greater than that for the 100mm cube. For the 1, 3, 7 & 28 day tests the difference in values is: 1.50, 2.40, 1.64 & 0.56 respectively. What is noted through these results is that at the early stages the predictability is low whilst at 28 days the difference is minimal. From the limited experimental results, it could be drawn that these trends prescribe the use of 100mm cubes for early age compressive strength testing and for longer term testing the 40 mm cubes would give a more conservative result.

The flexural and tensile tests follow a pattern with little resemblance between the results other than the dog bone always being fractionally higher.

6.2.2 Natural hydraulic lime mortar

NHL exhibits a greater degree of variability than TLM. Figure 6.2.2 shows the strongest to weakest test means are: 40mm cube, 100mm cube, dog bone and prism. Analogulously to the trend seen in Figure 6.2.1.1, it was also expected. Although since NHL mortar takes a long time to set with an average compressive strength at 28 days of 10% in comparison to TLM and 80% of OPC. NHL's hydraulic properties achieve weaker and less predictable results at ages much less than 91 days. Hence in order to gain a better long term understanding, testing started at 91 days.

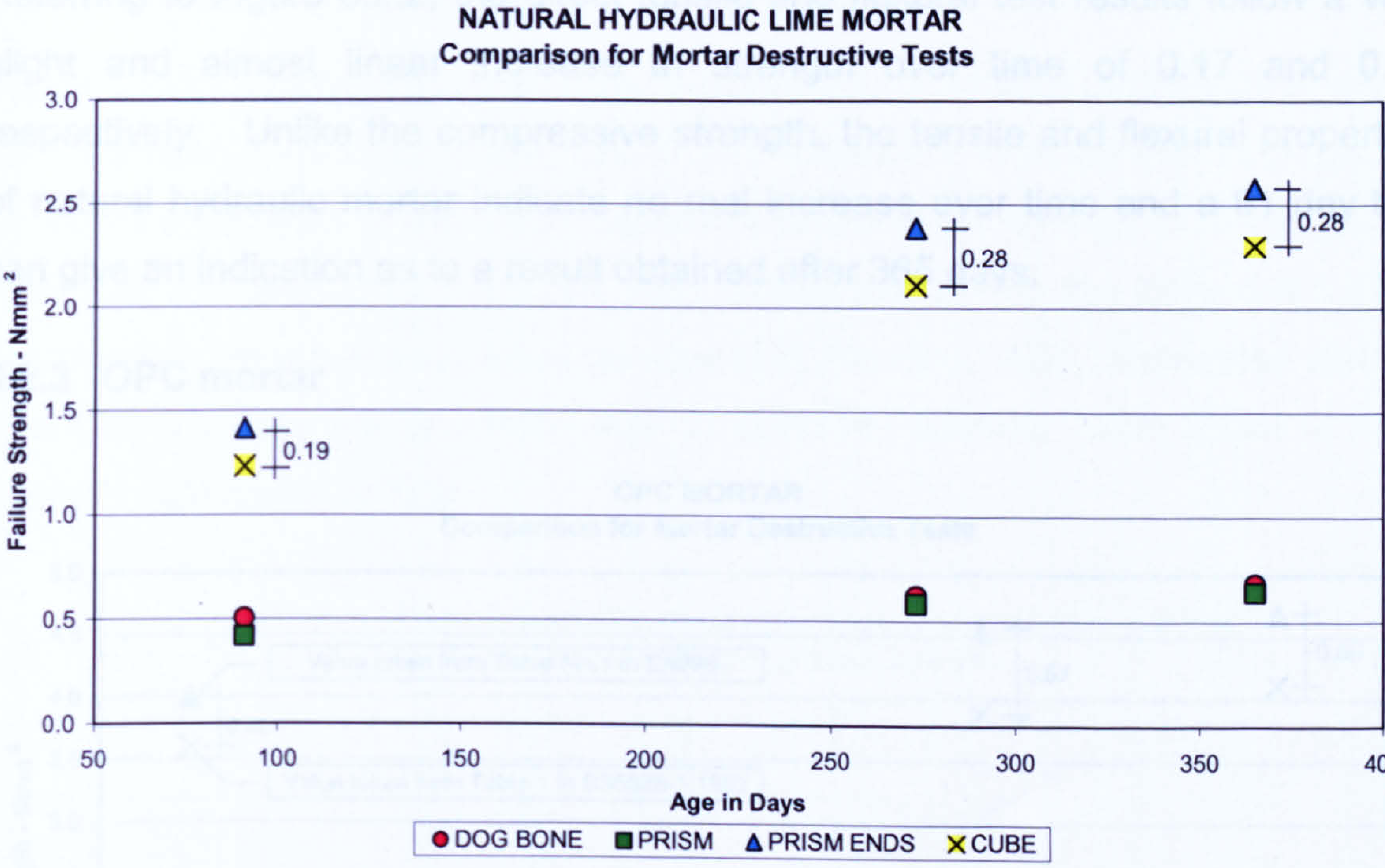


Figure 6.2.2 – Comparison of mortar destructive tests for NHL mortar

Following Figure 6.2.2, the compressive strength of the 40mm cube (prism ends) is greater than that for the 100mm cube. For 91, 273 & 365 day tests the difference in values is: 0.19, 0.28 & 0.20 respectively. What is noted through these results is that unlike TLM the difference between the compressive tests is almost uniform for all ages. A steady increase in compressive strength is evident. Owing to its relative unpredictability these results seem to follow an almost predictable trend between themselves. The batches of specimens were moulded at the same time and cured within close proximity in the same humid conditions. This may indicate that the NHL mortar mix batch gives consistent properties for that particular mix. Since the mixes only contain 1 part lime to 3 parts well graded sharp sand the likelihood of the mortar not being well mixed is less. When comparing to the process used when mixing OPC designation (iii) mortar, it was noted that ease of mixing depended on the water content of the sand.

Although the manufacturers give a typical value of around 3.9 N/mm^2, a mean value of 2.5 N/mm^2 was achieved. Everett (1994); states that both coarse and fine sands require more water to achieve equal workability, with a consequent reduction in mortar strength. Taking this into account one explanation for the consistent lower value for compressive strength is due to the mix having a higher water content.

Referring to Figure 6.2.2, the direct tensile and flexural test results follow a very slight and almost linear increase in strength over time of 0.17 and 0.22 respectively. Unlike the compressive strength, the tensile and flexural properties of natural hydraulic mortar indicate no real increase over time and a 91 day test can give an indication as to a result obtained after 365 days.

6.2.3 OPC mortar

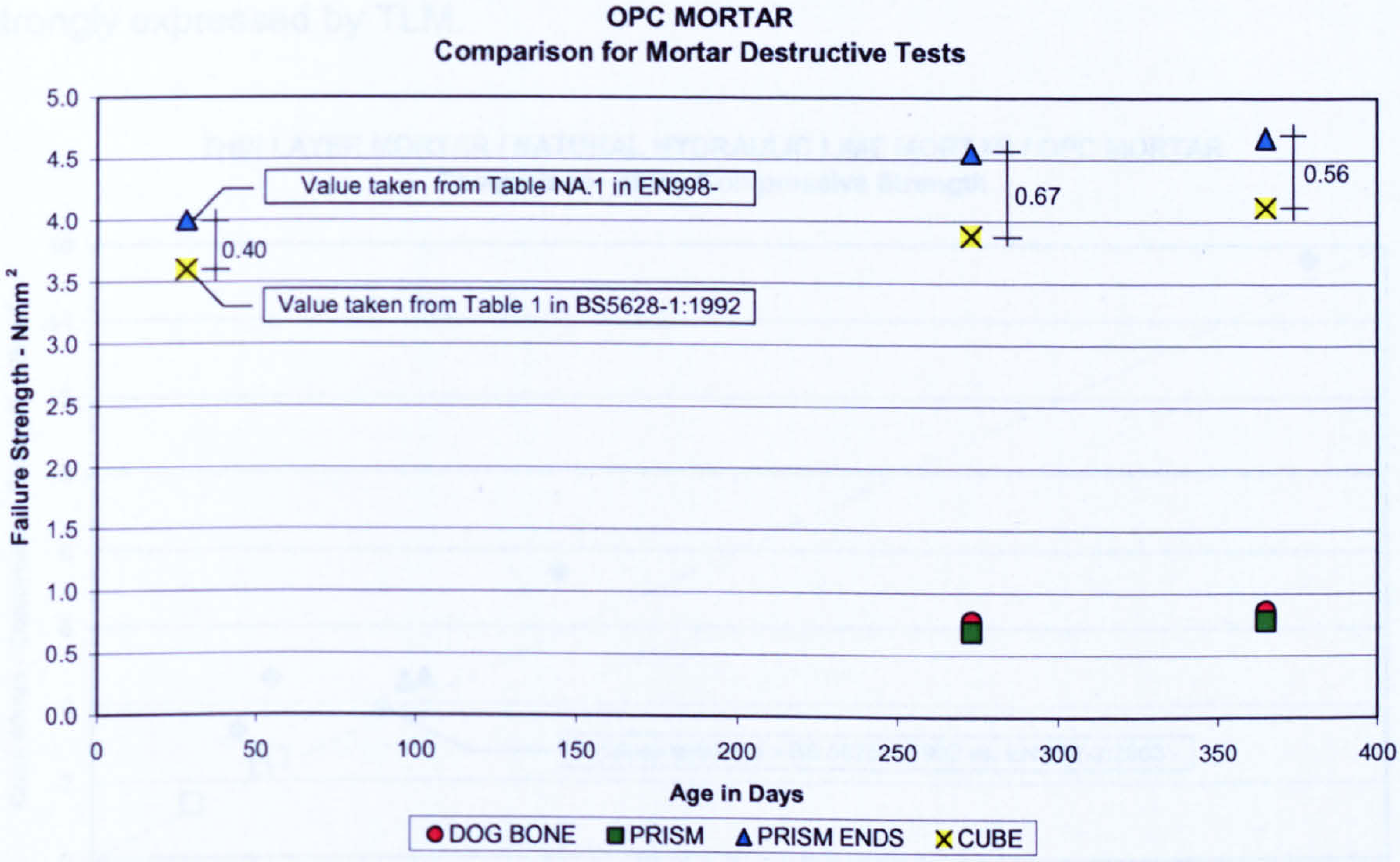


Figure 6.2.3 – Comparison of mortar destructive tests for OPC mortar

Following Figure 6.2.3, the compressive strength of the 40mm cube (prism ends) is greater than that for the 100mm cube. For 91, 273 & 365 day tests the difference in values is: 0.19, 0.28 & 0.20 respectively. What is noted through these results is that unlike TLM the difference between the compressive tests is almost uniform for all ages. A steady increase in compressive strength is evident. Owing to its relative unpredictability these results seem to follow an almost predictable trend between themselves. The batches of specimens were moulded at the same and cured within close proximity in the same humid conditions.

Similar to the trend in Lime shown in Figure 6.2.2 the cube compressive strength is greater than the prism ends at 273 and 365 days. Analogously the flexural and tensile strength are of similar values.

6.2.4 Strength comparisons

Figure 6.2.4, displays a trend showing that prism ends tend to obtain higher values than the cube compressive strength. In this situation it is noted that TLM has the strongest replication of this trend especially at the lower strengths. Furthermore, NHL has a more borderline state, with values just above the unity line. OPC conforms to the prism ends trend as expected. Neville (1995) commented that the effect of reducing the specimen size in concrete sample. This effect is most strongly expressed by TLM.

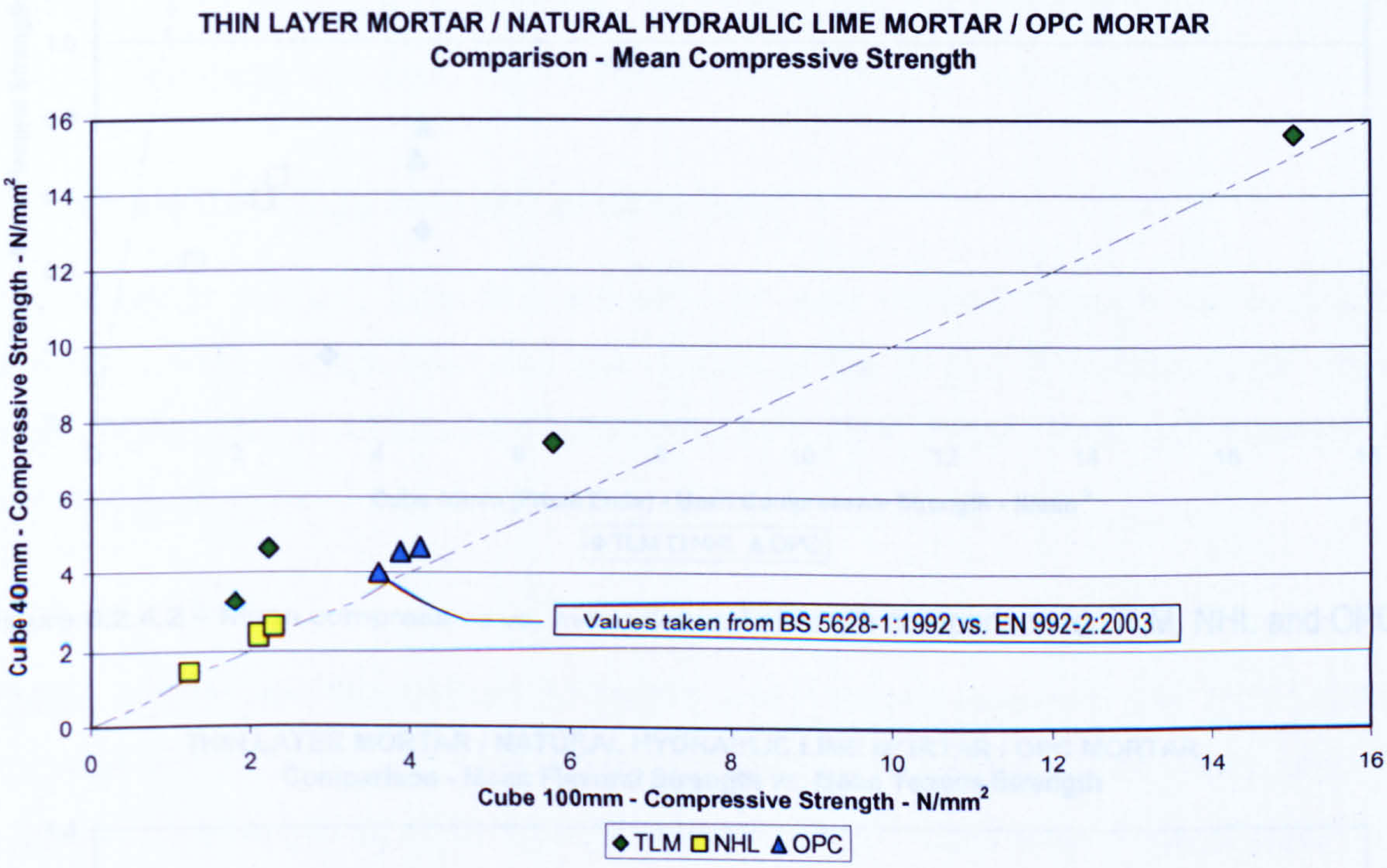


Figure 6.2.4.1 – Mean compressive strength comparison for TLM, NHL and OPC

Figure 6.2.4.2, clearly shows that the mean compressive strength is far greater in relation to the flexural strength. Despite both NHL and OPC displaying a linear progression in strength, TLM has a logarithmic trend comparable to cement. Although all specimens are stronger in compression that flexure, NHL exhibits the least difference in strength whereas TLM shows the greatest. All conform to the expectation that compressive strength is stronger than flexure. However not all exactly replicate the 1/10th rule.

Figure 6.2.4.3, clearly shows that direct tensile strength is stronger than flexural strength on all occasions for all mortars. Similarly to Figure 6.2.4.2 TLM is the nearest to the unity line and therefore had the strongest trend towards flexure and NHL overall had the strongest trend towards tension.

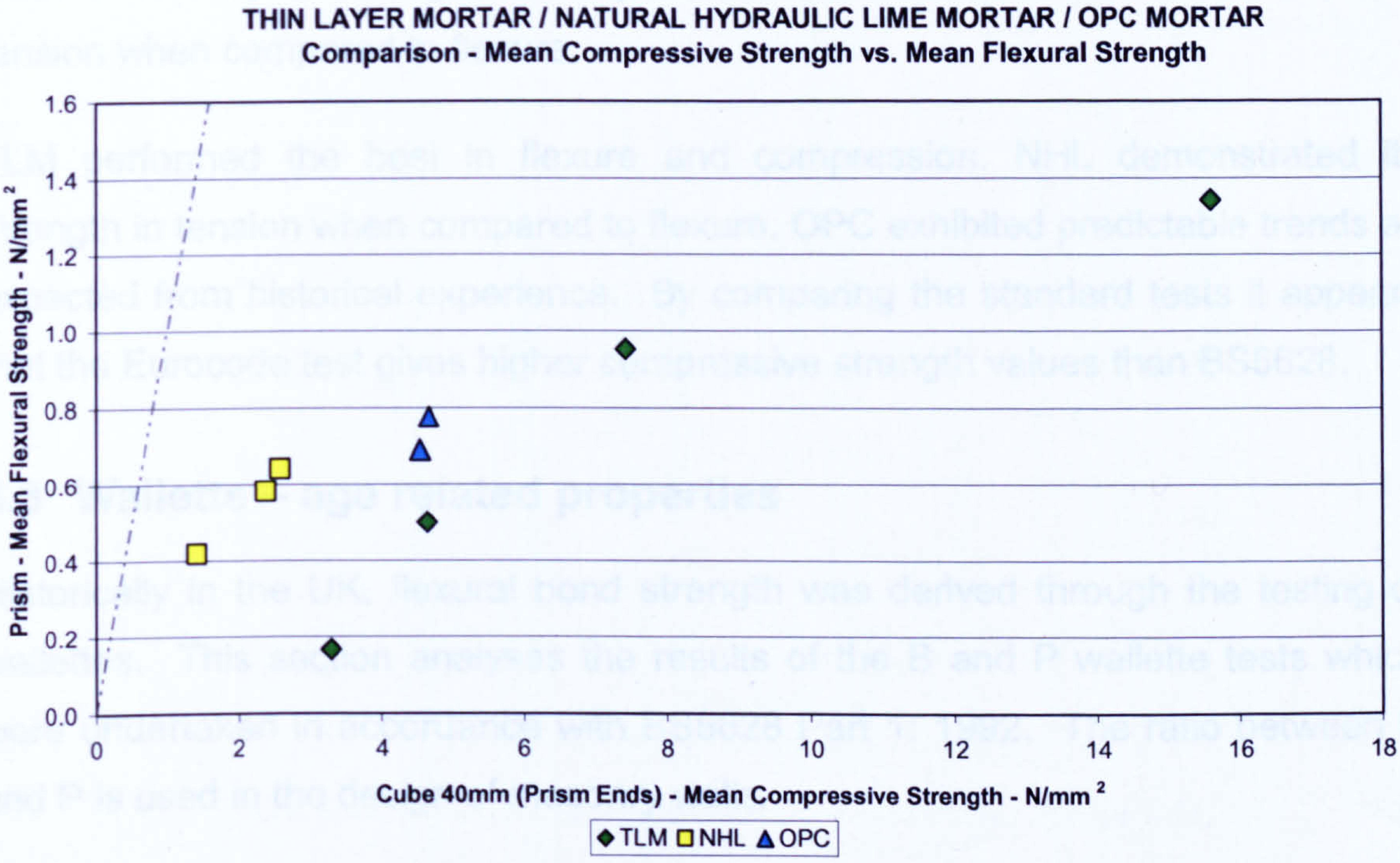


Figure 6.2.4.2 – Mean compressive vs. mean flexural strength comparison for TLM, NHL and OPC

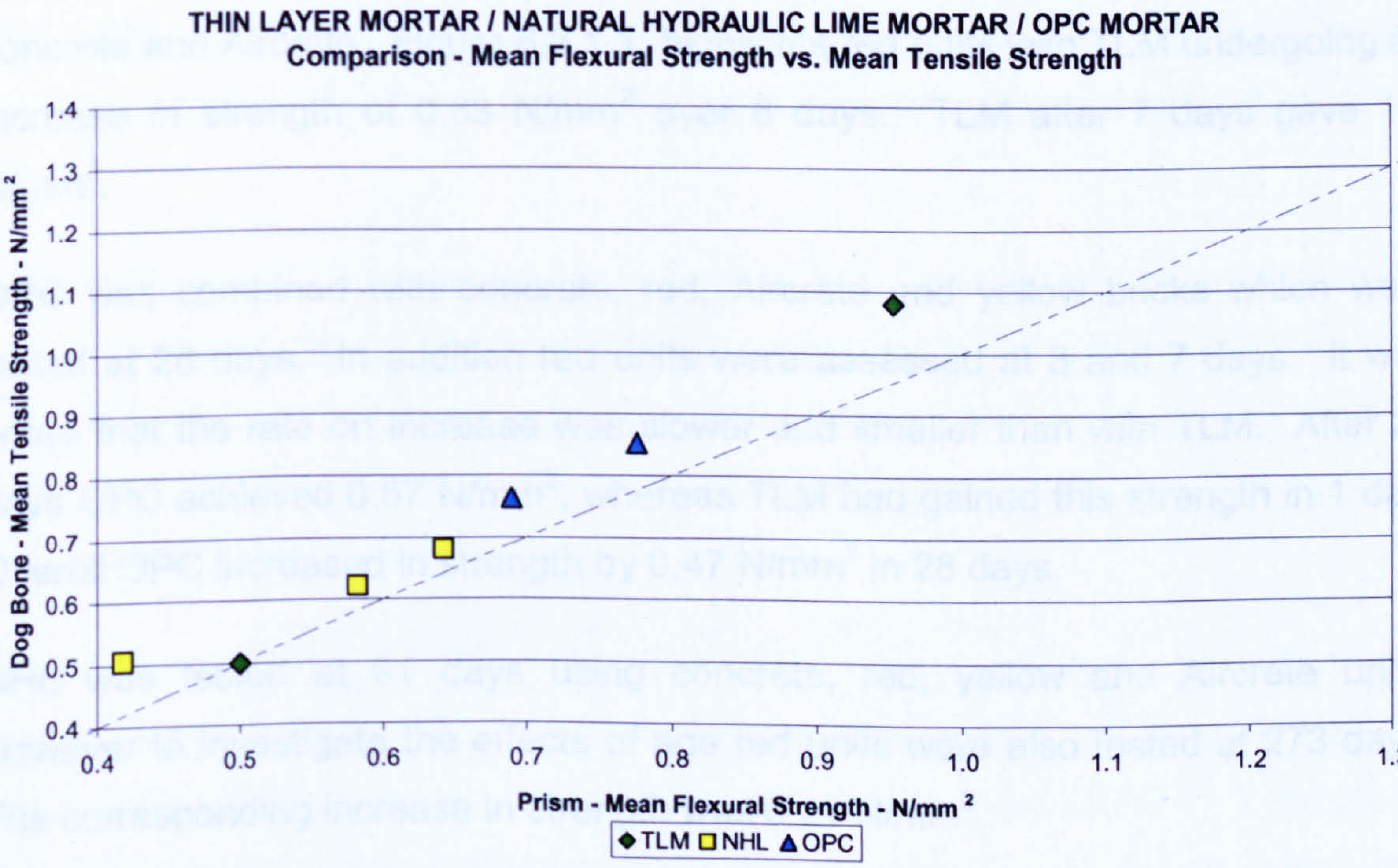


Figure 6.2.4.3 – Mean flexural strength vs. mean tensile strength comparison for TLM, NHL and OPC mortar

6.2.5 Summary

All the three mortars conformed to the expectation that the compressive strength was higher than the tensile and flexural strength. Flexural strength is a measure of how much load can be applied before failure occurs and as explained in section 6.1.3 is a complex strength. As expected the mortars also performed better in tension when compared to flexure.

TLM performed the best in flexure and compression. NHL demonstrated its strength in tension when compared to flexure. OPC exhibited predictable trends as expected from historical experience. By comparing the standard tests it appears that the Eurocode test gives higher compressive strength values than BS5628.

6.3 Wallette – age related properties

Historically in the UK, flexural bond strength was derived through the testing of wallettes. This section analyses the results of the B and P wallette tests which were undertaken in accordance with BS5628 Part 1: 1992. The ratio between B and P is used in the design of masonry walls.

6.3.1 B wallette

Tests on TLM were undertaken on days 1 and 7 for red units and day 7 for yellow, concrete and Aircrete. Figure 6.3.1.1, highlights red units with TLM undergoing an increase in strength of 0.63 N/mm^2 over 6 days. TLM after 7 days gave 1.2 N/mm^2.

OPC was combined with concrete, red, Aircrete and yellow bricks which were tested at 28 days. In addition red units were assessed at 3 and 7 days. It was noted that the rate on increase was slower and smaller than with TLM. After 28 days OPC achieved 0.57 N/mm^2, whereas TLM had gained this strength in 1 day. Overall OPC increased in strength by 0.47 N/mm^2 in 28 days.

NHL was tested at 91 days using concrete, red, yellow and Aircrete units. However to investigate the effects of age red units were also tested at 273 days. The corresponding increase in strength was 0.21 N/mm^2.

Figures 6.3.1.1 to 6.3.1.3 demonstrate the age related effects on B wallettes using red units with TLM, OPC and NHL respectively. To investigate the effects of unit type yellow, concrete and Aircrete were also tested at one age only.

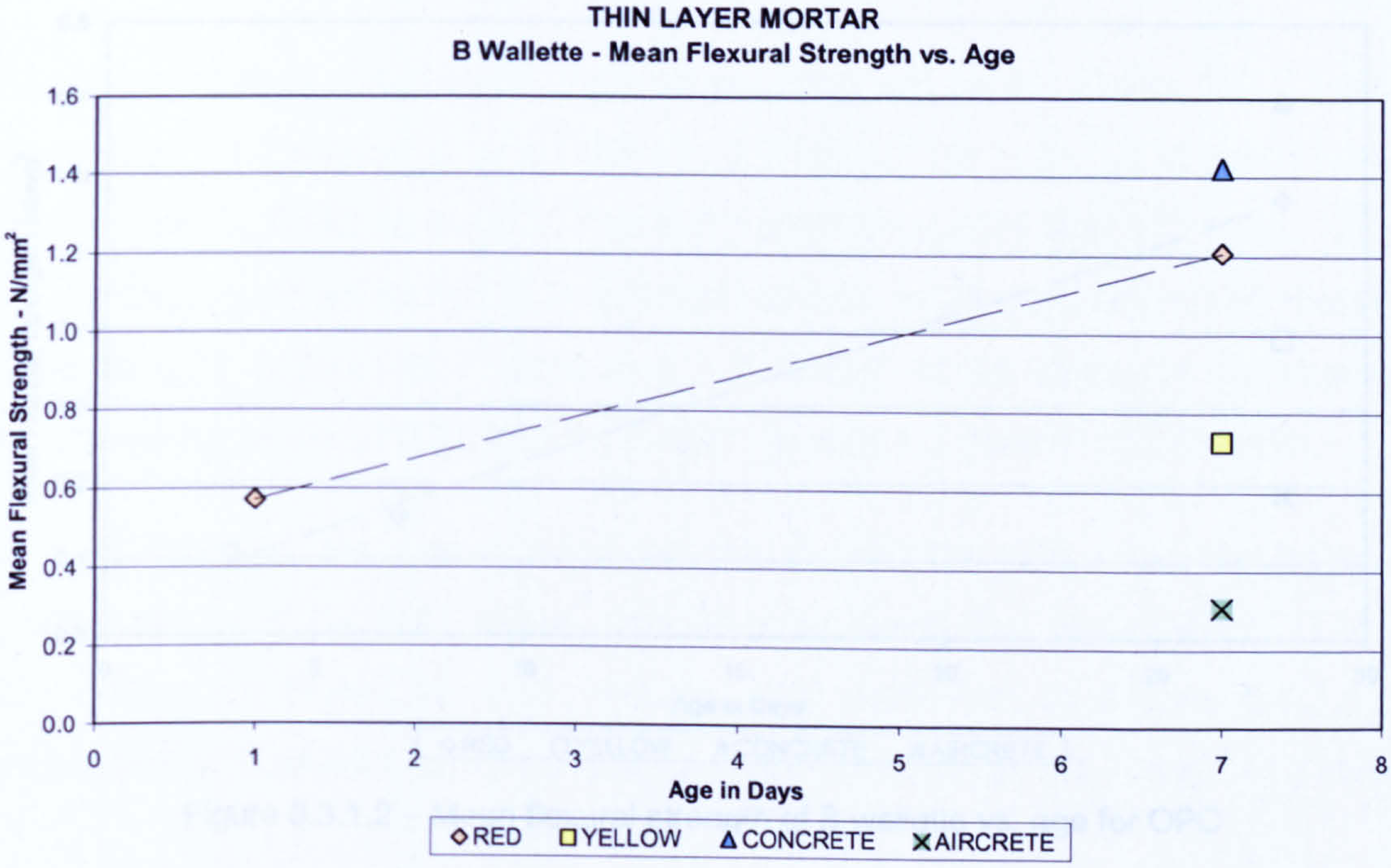


Figure 6.3.1.1 – Mean flexural strength of B wallette vs. age for TLM

Figures 6.3.1.1 and 6.3.1.2 display similar trends for the effects of unit type. TLM attains the highest strength of 1.4 N/mm^2 with concrete units. Red units are about 85% of the strength and yellow approximately 50%. Aircrete is displayed as the weakest with 0.3 N/mm^2, but there was a considerable degree of unit failure during testing.

OPC in Figures 6.3.1.2 was similar to TLM in that concrete was the strongest with a maximum strength of 0.7 N/mm^2. However the distribution seen across the units was notably more evenly spread. Red units were 1.2 N/mm^2 and yellow was 0.3 N/mm^2 weaker than the concrete units. Similar to the effects with TLM concrete failed at 0.2 N/mm^2.

Analogous to TLM and OPC, NHL attained the highest strength with concrete as seen in figure 6.3.1.3. The rest of the unit types achieved half the strength with red at 0.28 N/mm^2, Aircrete at 0.24 N/mm^2 and yellow at 0.18 N/mm^2. It should be noted that Aircrete gave a stronger bond in comparison to yellow units which is in reverse to the other mortars. This may possibly be attributed to the contact area of Aircrete being much greater coupled with the water absorption on the yellow unit affecting the bonding process.

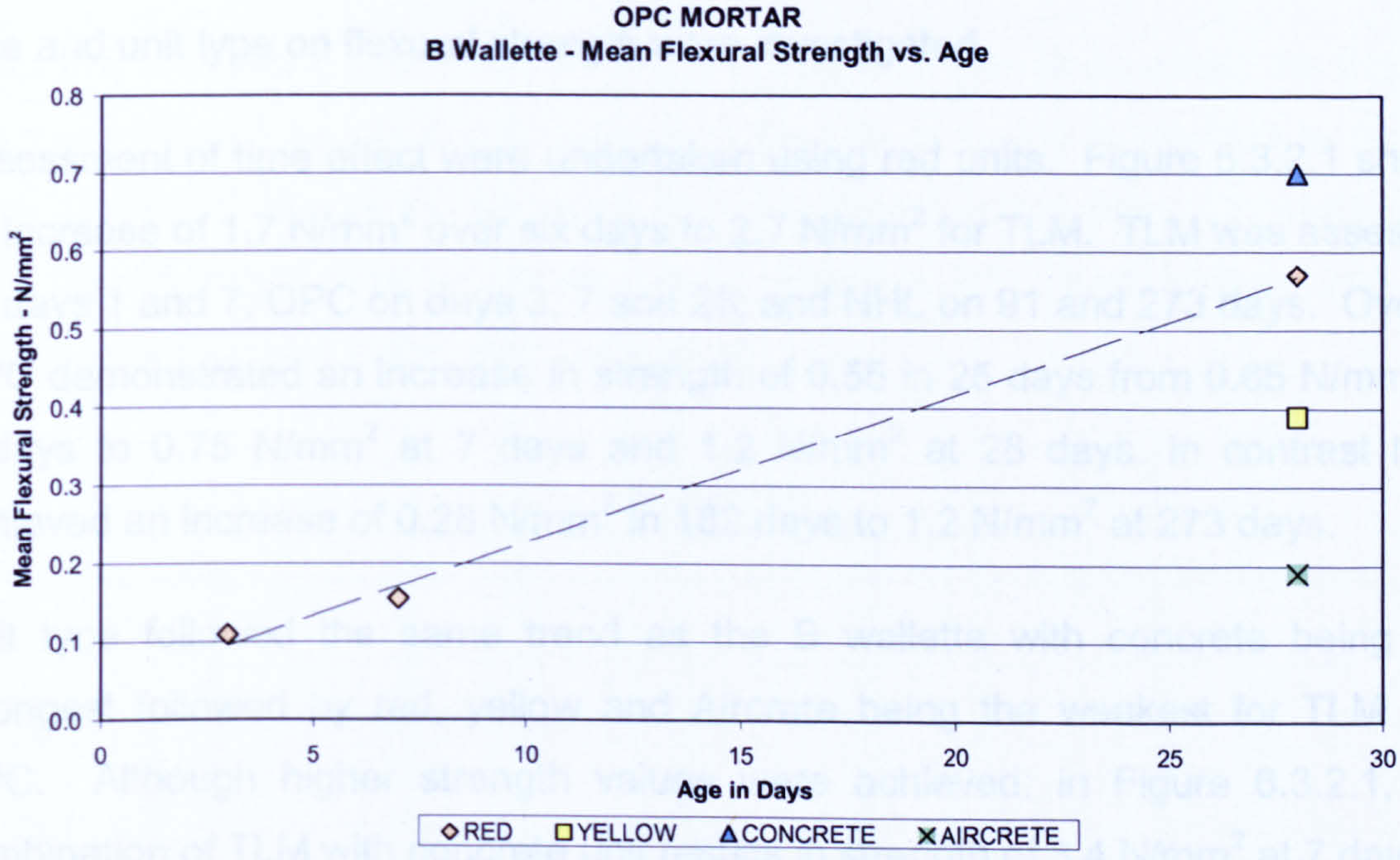


Figure 6.3.1.2 – Mean flexural strength of B wallette vs. age for OPC

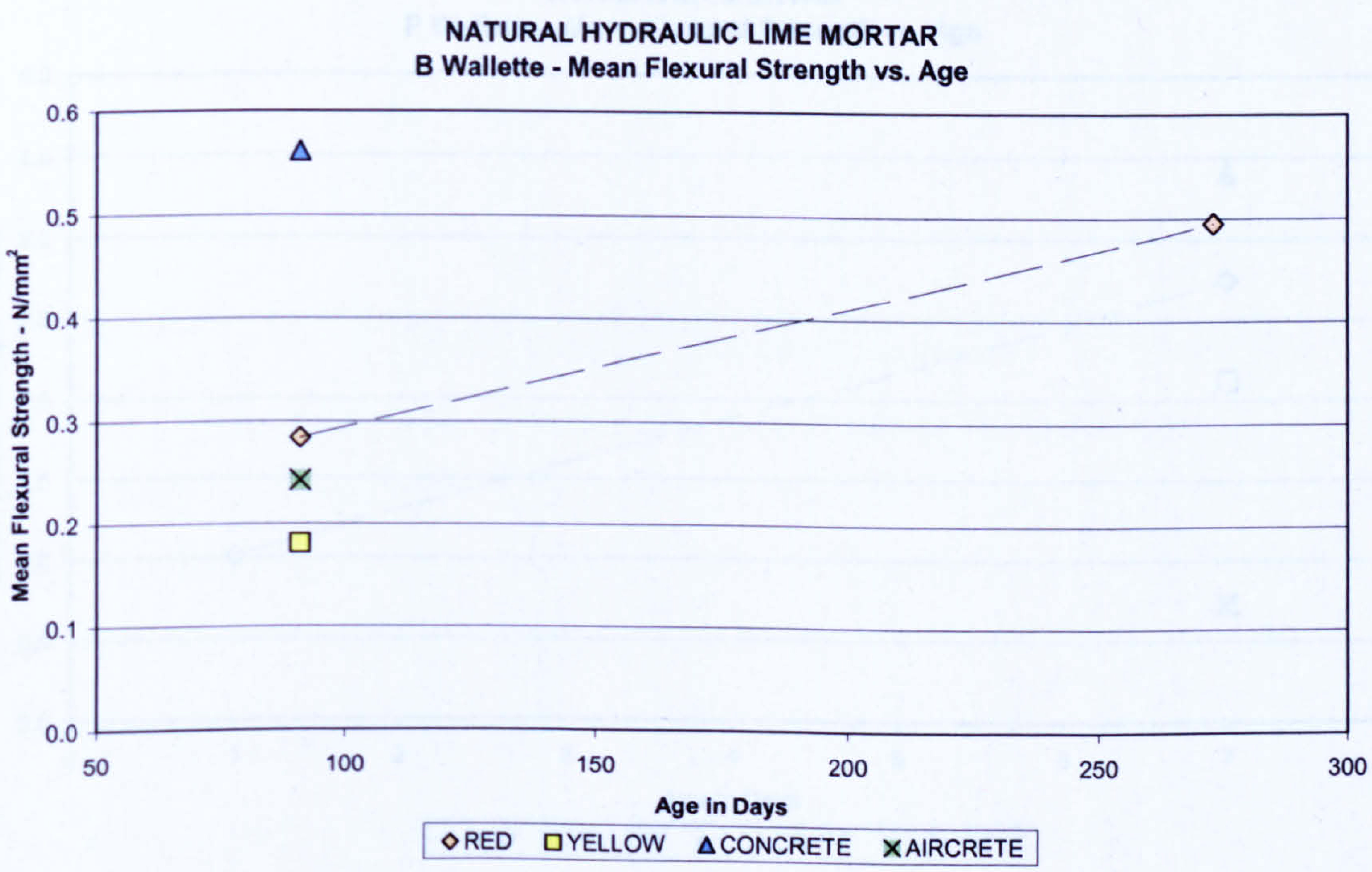


Figure 6.3.1.3 – Mean flexural strength of B wallette vs. age for NHL

6.3.2 P wallette

P wallettes were constructed to assess the effect on the perpendicular mortar joint. In accordance with BS5628 – Part 1:1992. Using the three mortars the effects of time and unit type on flexural strength were investigated.

Assessment of time effect were undertaken using red units. Figure 6.3.2.1 shows an increase of 1.7 N/mm^2 over six days to 2.7 N/mm^2 for TLM. TLM was assessed on days 1 and 7, OPC on days 3, 7 and 28; and NHL on 91 and 273 days. Overall OPC demonstrated an increase in strength of 0.55 in 25 days from 0.65 N/mm^2 at 3 days to 0.75 N/mm^2 at 7 days and 1.2 N/mm^2 at 28 days. In contrast NHL achieved an increase of 0.28 N/mm^2 in 182 days to 1.2 N/mm^2 at 273 days.

Unit type followed the same trend as the B wallette with concrete being the strongest followed by red, yellow and Aircrete being the weakest for TLM and OPC. Although higher strength values were achieved; in Figure 6.3.2.1, the combination of TLM with concrete unit results in strength of 3.4 N/mm^2 at 7 days.

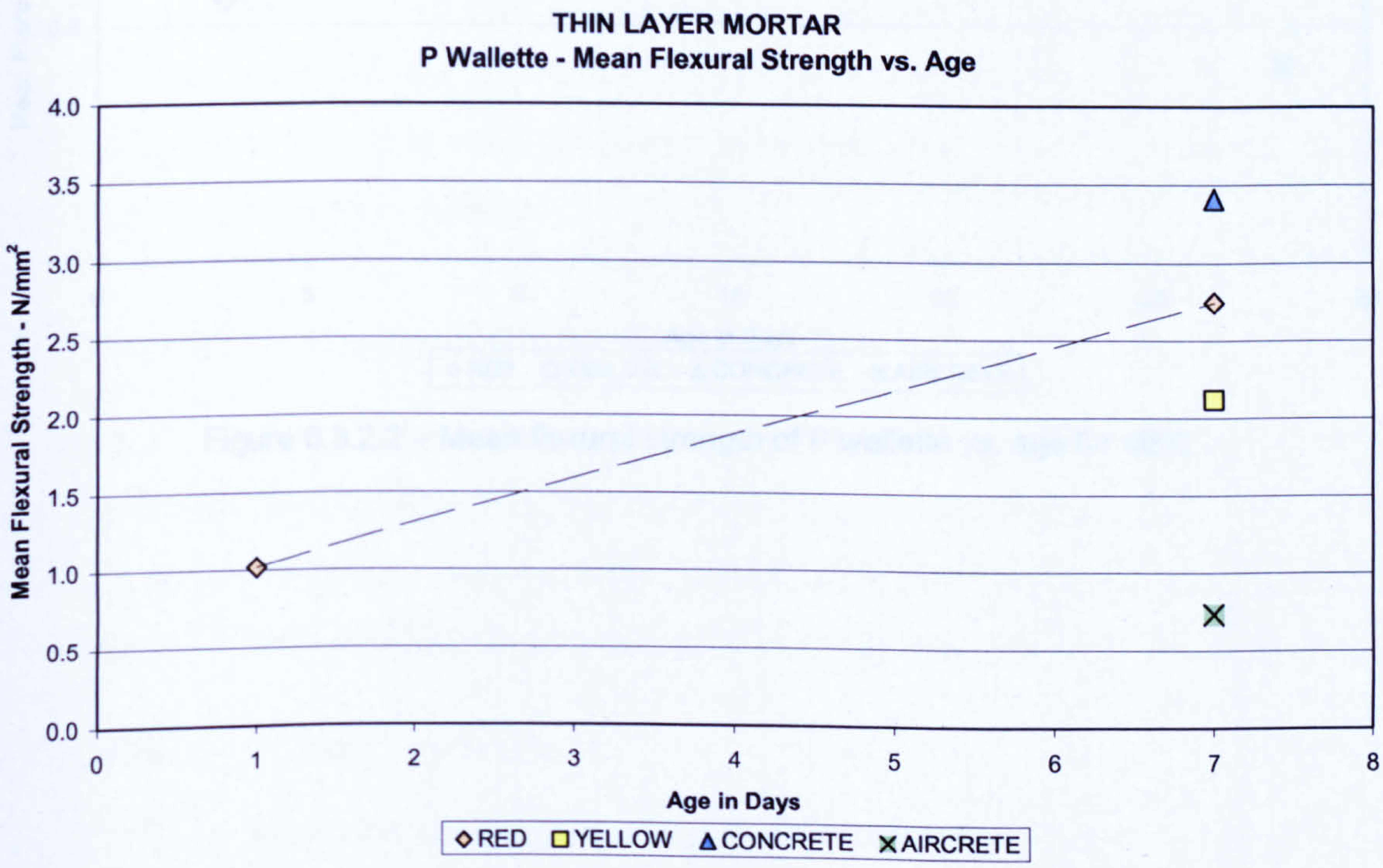


Figure 6.3.2.1 – Mean flexural strength of P wallette vs. age for TLM

Red units follow with 2.7 N/mm^2 with yellow at 2.1 N/mm^2 and Aircrete being the weakest at 0.7 N/mm^2. Figure 6.3.2.2 shows a similar trend, concrete attains the highest flexural strength with 1.4 N/mm^2, red units 1.2 N/mm^2; yellow 1.0 N/mm^2 but again the weakest being Aircrete with 0.5 N/mm^2.

NHL shown in Figure 6.3.2.3 displays a different trend. Concrete is again the strongest with 1.22 N/mm^2 but the second strongest is Aircrete with 1.11 N/mm^2. Red units attain only 0.92 N/mm^2 and the weakest if yellow with 0.65 N/mm^2.

From this analysis it is possible to suggest that unit type does affect the flexural strength in the perpendicular direction and the rate of curing is affected by mortar type. Overall TLM was the strongest with the fastest curing rate. Concrete units were the strongest with all mortar types; whereas OPC and Aircrete had the weakest combination in this mode of testing

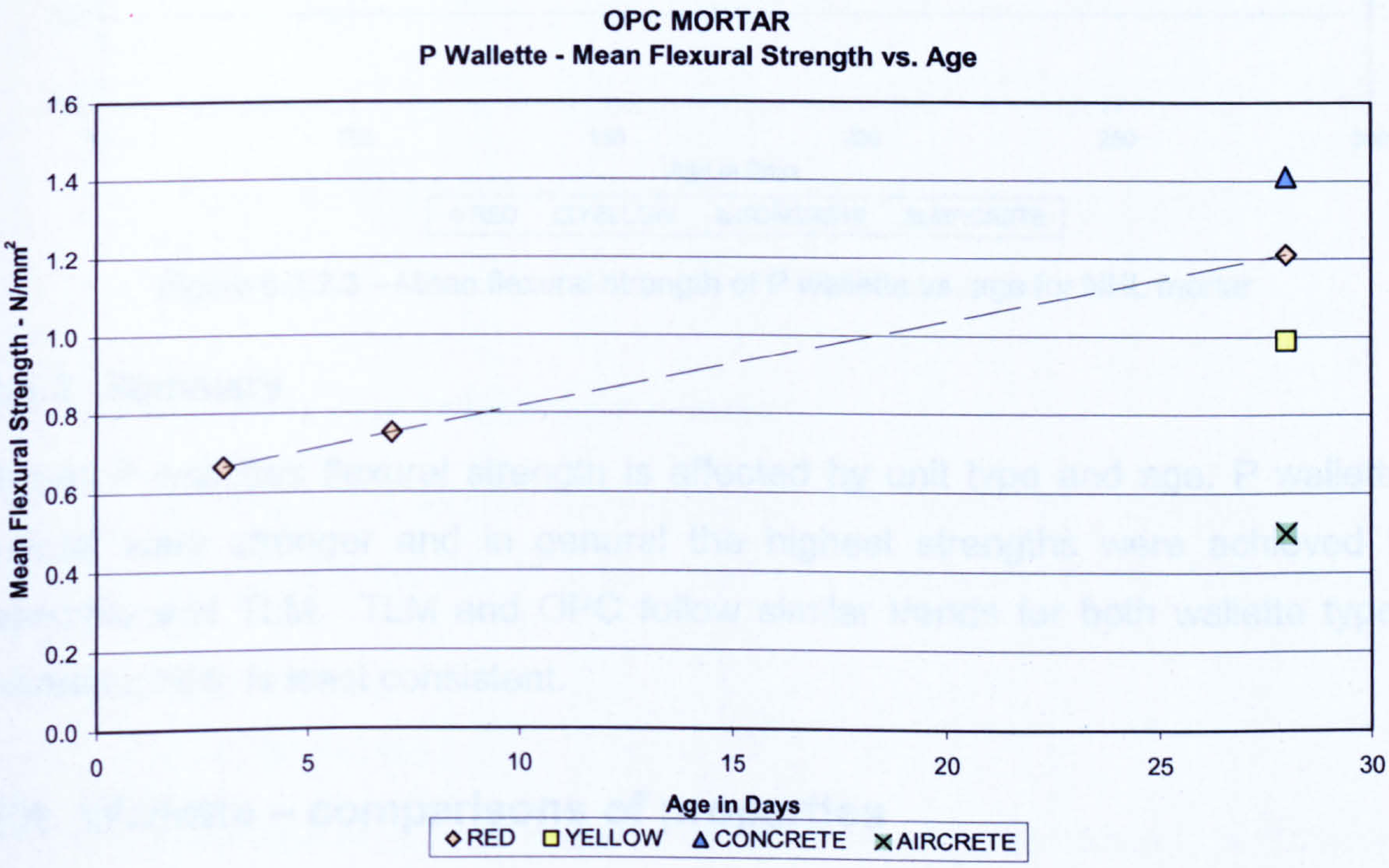


Figure 6.3.2.2 – Mean flexural strength of P wallette vs. age for OPC

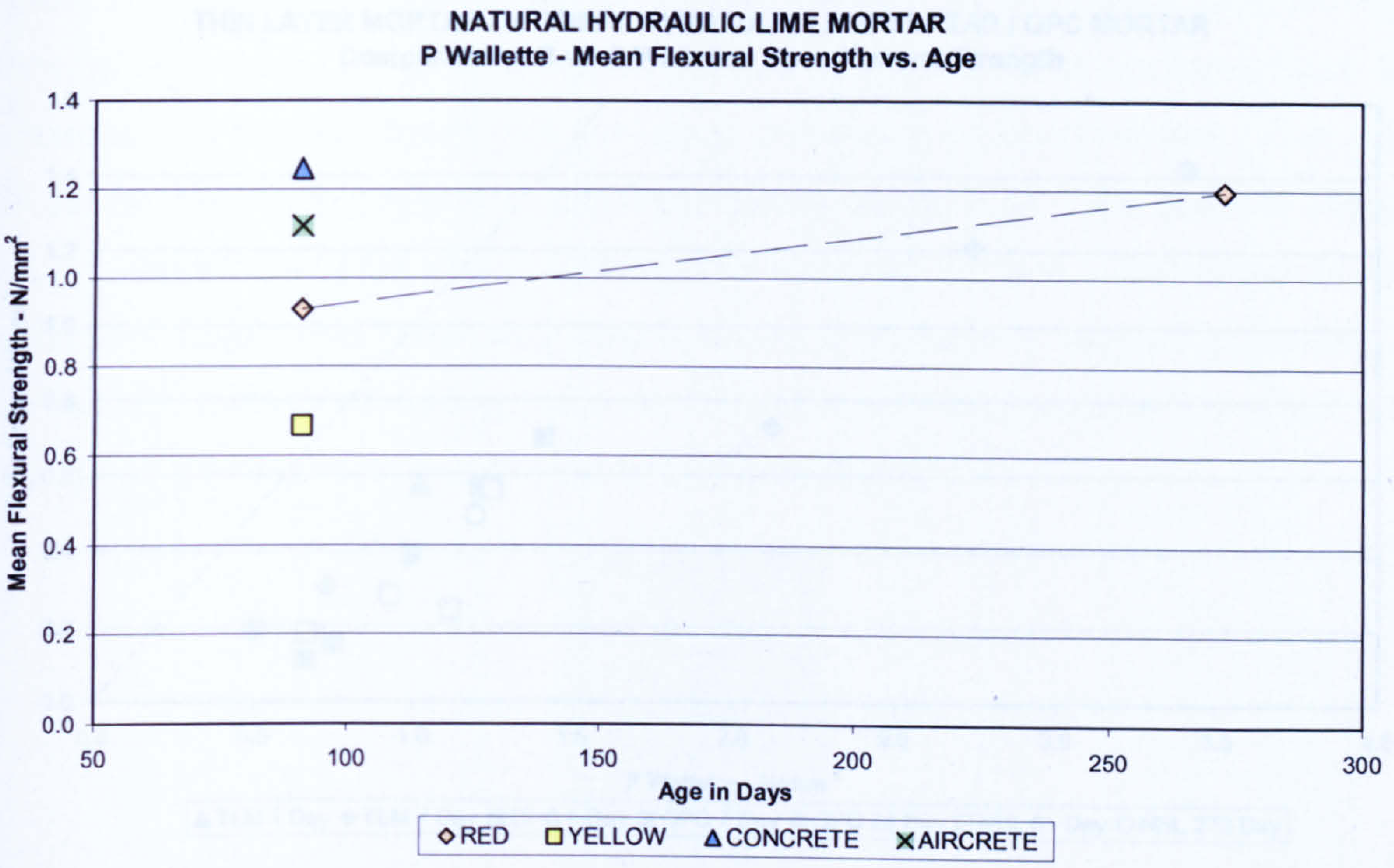


Figure 6.3.2.3 – Mean flexural strength of P wallette vs. age for NHL mortar

6.3.3 Summary

B and P wallettes flexural strength is affected by unit type and age. P wallettes overall were stronger and in general the highest strengths were achieved by concrete and TLM. TLM and OPC follow similar trends for both wallette types; whereas, NHL is least consistent.

6.4 Wallette – comparisons of properties

Comparing wallette data enables the characteristics of the bending that the wallette would be subjected to be ascertained. In addition to past experience there is a presumption that wallette failure strength would be weaker in the horizontal bed joint direction in comparison to the vertical perpend direction.

6.4.1 B wallette vs. P wallette

With the unity line - dividing down the middle, both tests display that no matter which test, material or age the P wallette is stronger than the B wallette test. This trend is most apparent in the TLM 7 day tests and is least evident in the NHL 91 day. TLM achieves the highest strength at 7 days with 3.4 N/mm^2; whereas OPC at 28 days was the weakest. In general TLM shows higher strengths whereas OPC and NHL appear to attain similar longer term values.

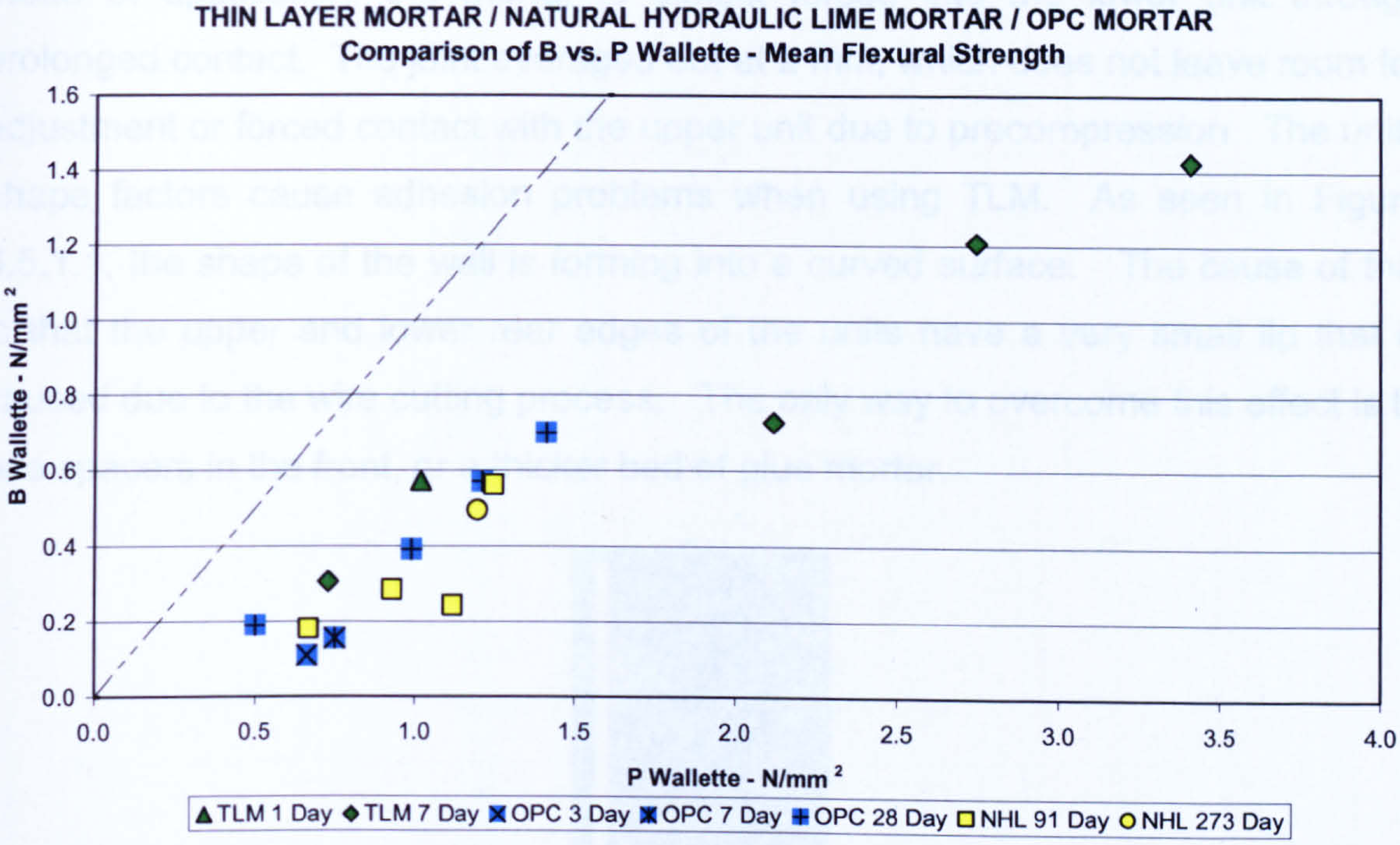


Figure 6.4.1 – Comparison of B vs. P wallettes – mean flexural strength

6.5 Couplets – age related properties

All the couplets were easily manufactured and cured by covering under a polythene sheet until the day of testing and precompressed under three layers of bricks.

6.5.1 Thin layer mortar

The red and yellow units have a similar steep gradient. The concrete units have a smaller gradient than both the red and the yellow. The Aircrete would have had the steepest gradient but at 7, 28 & 56 days the units failed under test and forfeited an actual value. Judging by the value for 1 & 3 days, if a line was to be drawn, the gradient would be far greater than other units.

Analysing the modes of failure has brought to light an interesting occurrence within the unit and mortar interface. Table 6.5.1, gives chances for a particular mode of failure with TLM; scoring 65% for an A1 mode of failure, 13% for A4 and 12% for A7. These modes of failure indicate the type of bond formed between the unit and mortar. Starting with the mode of application for the mortar, the scoop method gives the lower unit preference of initial contact before the top unit has formed contact with the mortar. The scoop containing mortar is dragged along the unit, positioning the mortar into place with a metal comb. As a consequence for the mode of application, the mortar is almost forced into the lower unit through prolonged contact. The joint averaged out at 2 mm, which does not leave room for adjustment or forced contact with the upper unit due to precompression. The units shape factors cause adhesion problems when using TLM. As seen in Figure 6.5.1.1, the shape of the wall is forming into a curved surface. The cause of this is that the upper and lower rear edges of the units have a very small lip that is caused due to the wire cutting process. The only way to overcome this effect is to use spacers in the front, or a thicker bed of glue mortar.

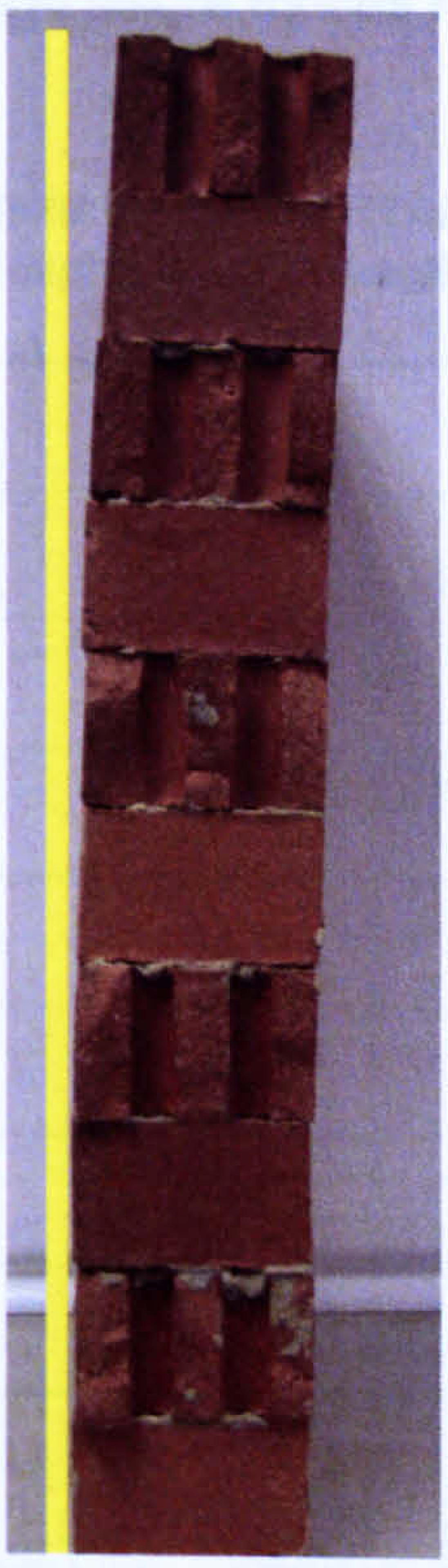


Figure 6.5.1.1 – Banana effect in walls

Since the application method was using a scoop the mortar had a better bond with the lower unit. Overall just fewer than 65% of TLM couplets tested failed in A1 mode, with 56% for NHL and 60% for OPC. The top three modes of failure for each of the mortars are shown in the table below:

TLM	A1 65%	A4 13%	A7 12%
NHL	A1 56%	A2 26%	A3 14%
OPC	A1 60%	A2 20%	A3 20%

Table 6.5.1 – Percentage failure modes for TLM, NHL and OPC

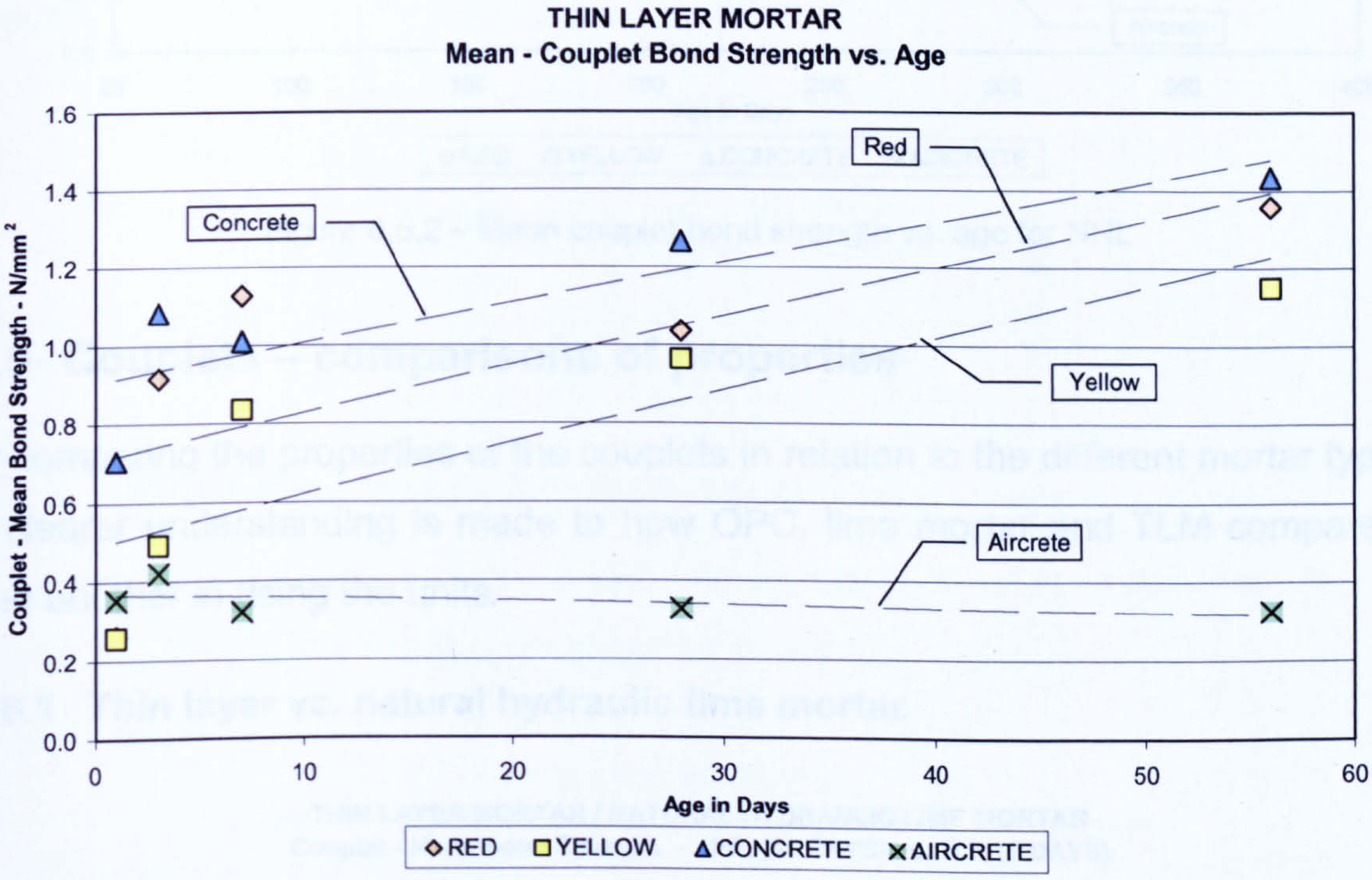


Figure 6.5.1.2 – Mean couplet bond strength vs. age for TLM

6.5.2 Natural hydraulic lime mortar

Figure 6.5.2, shows little sign of change for yellow, concrete and Aircrete over time whilst red shows a steady increase. Lime follows a similar trend set by Portland cement.

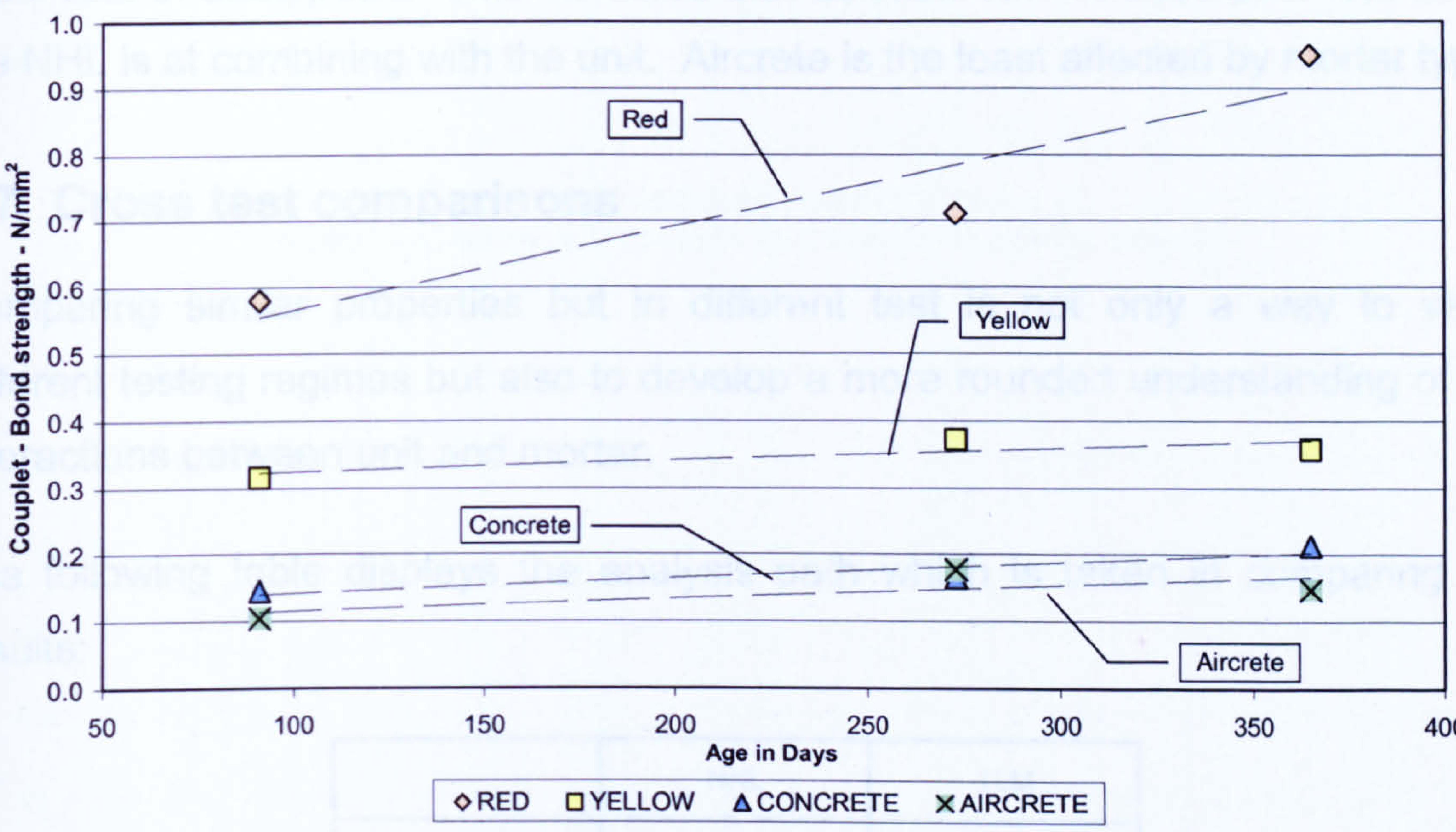


Figure 6.5.2 – Mean couplet bond strength vs. age for NHL

6.6 Couplets – comparisons of properties

In comparing the properties of the couplets in relation to the different mortar types, a clearer understanding is made to how OPC, lime mortar and TLM compare to one another in using the units.

6.6.1 Thin layer vs. natural hydraulic lime mortar

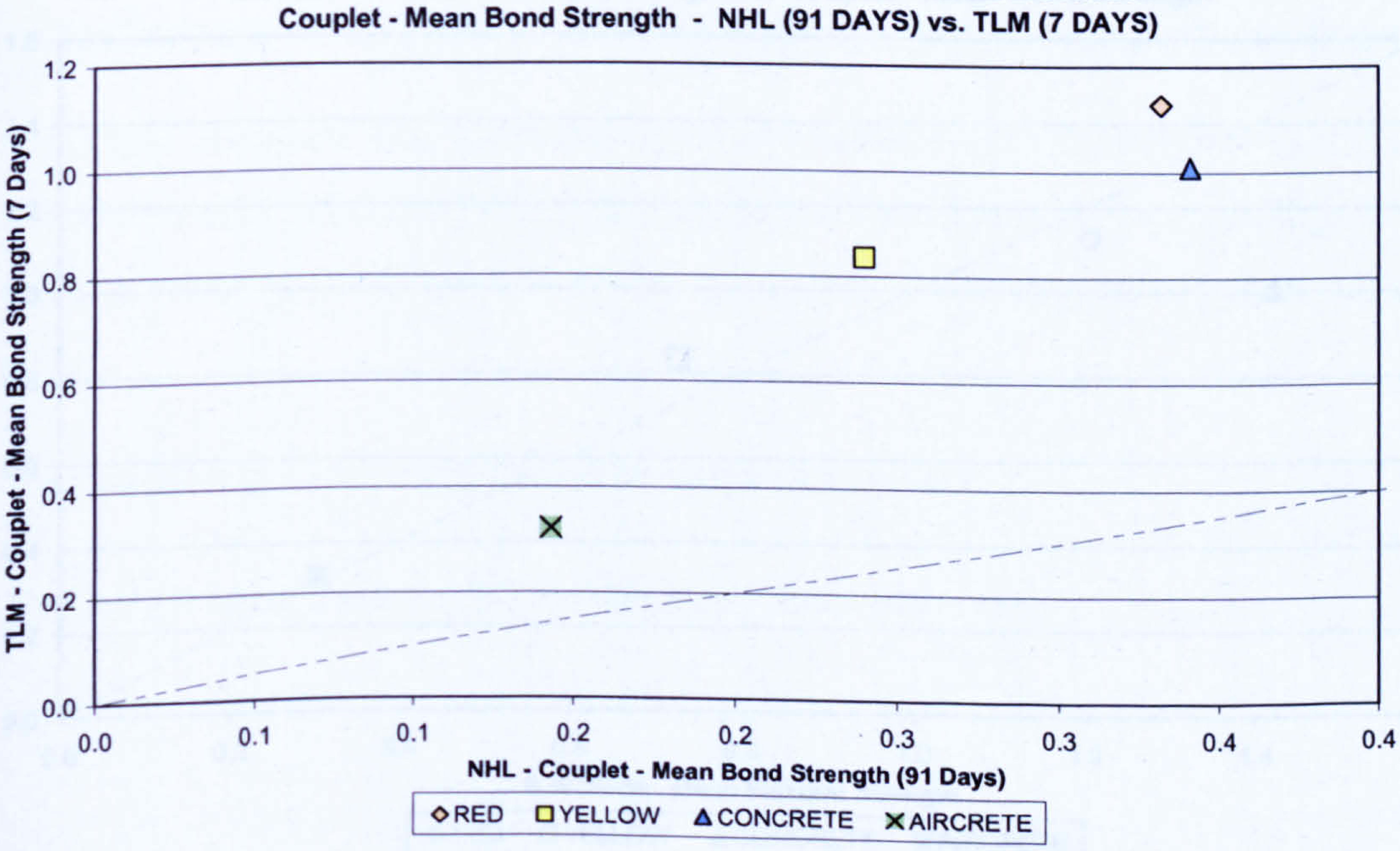


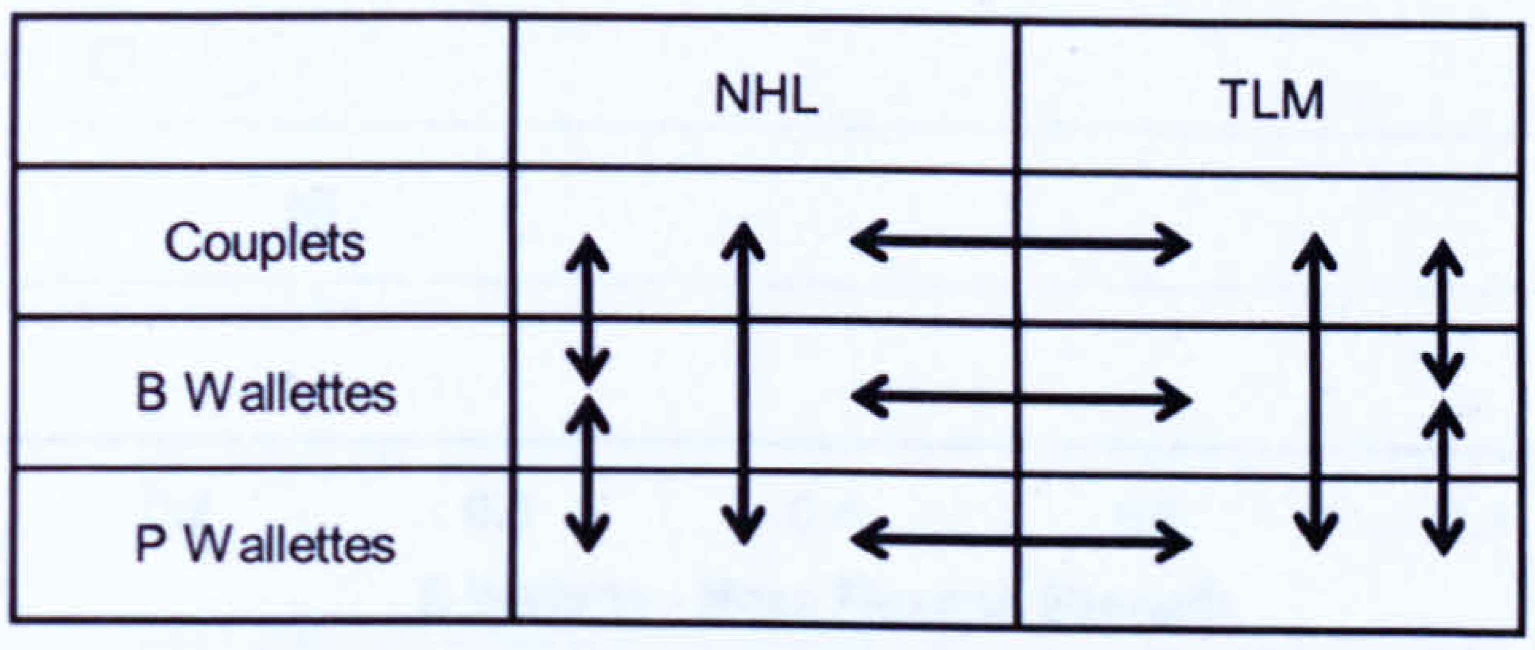
Figure 6.6.1 – Comparison of mean couplet bond strength for NHL vs. TLM

All the TLM are stronger than NHL and follow the same trends is absorption and initial rate of absorption. This indicated that as initial rate of absorption the better the NHL is at combining with the unit. Aircrete is the least affected by mortar type.

6.7 Cross test comparisons

Comparing similar properties but in different test is not only a way to verify different testing regimes but also to develop a more rounded understanding of the interactions between unit and mortar.

The following table displays the analysis path which is taken in comparing the results:



6.7.1 Comparison between B wallette vs. couplets

This set of comparisons is the most interesting in relation to the new test for measuring the bond strength using the Reutt wrench.

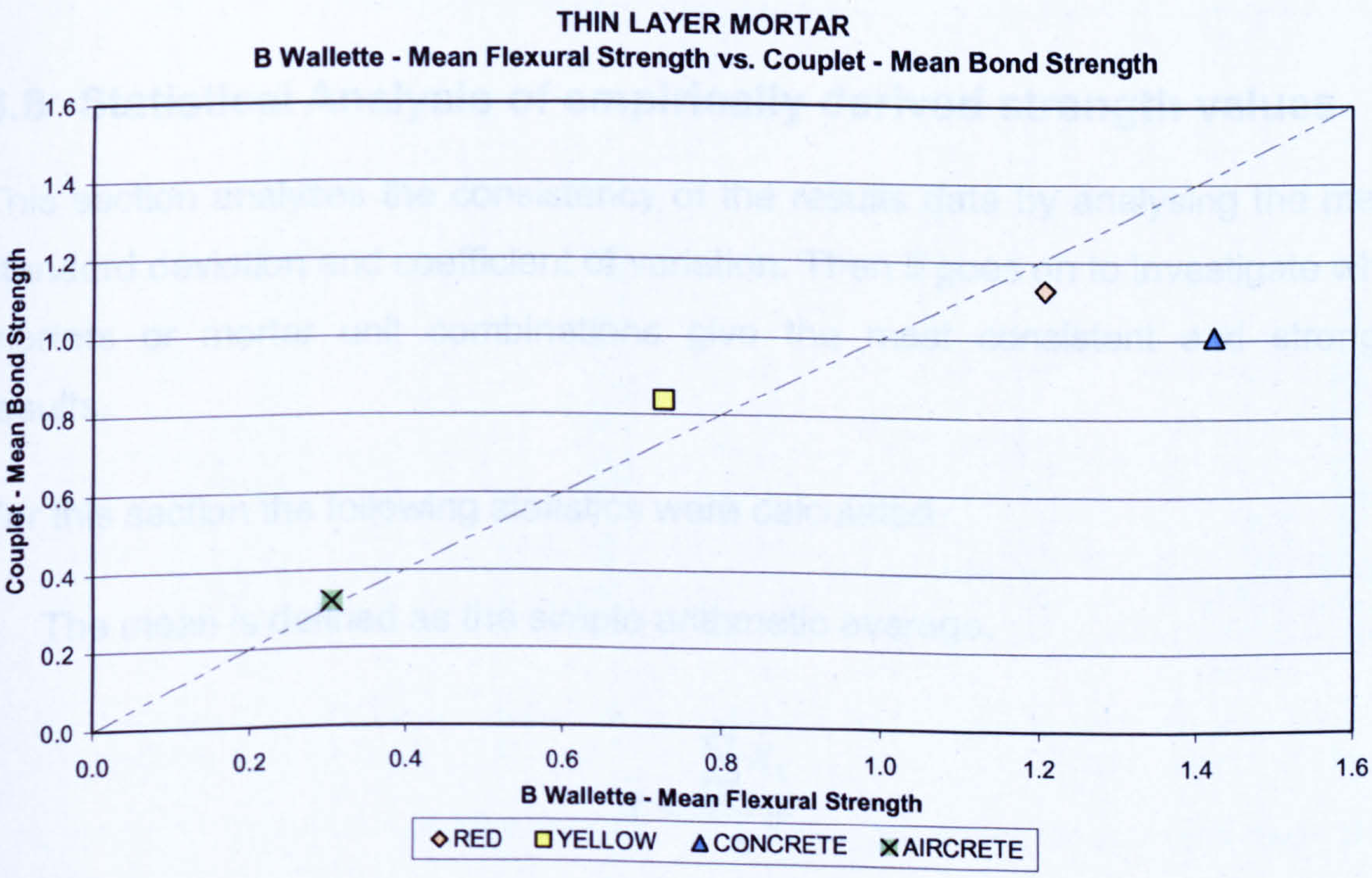


Figure 6.7.1.1 – B wallette – mean flexural strength vs. bond wrench – mean bond strength for TLM

Both red and concrete units are stronger in the B wallette test, whilst yellow and Aircrete units display a greater strength in comparison to the couplet bond wrench test.

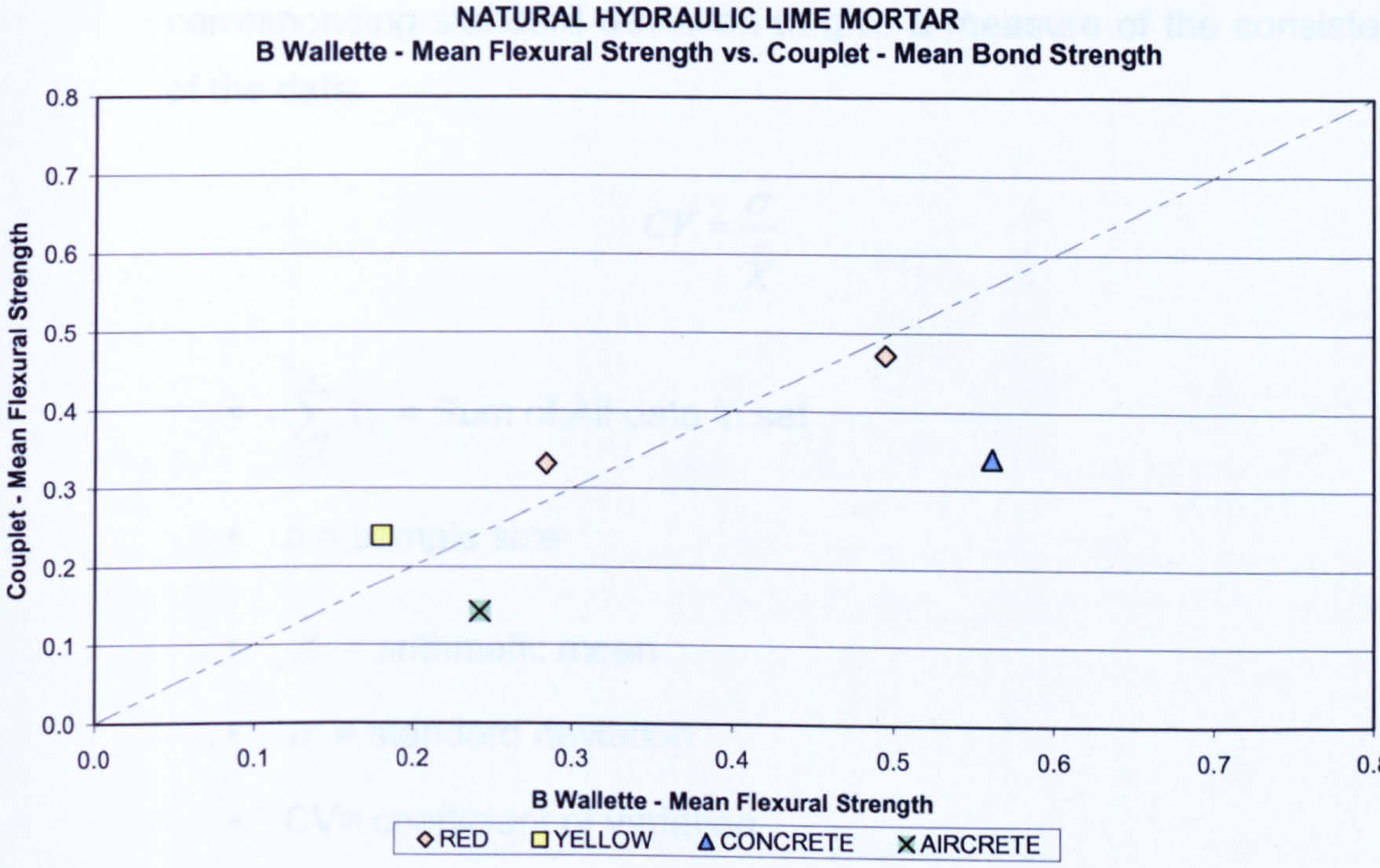


Figure 6.7.1.2 – B wallette – mean flexural strength vs. couplet – mean bond strength for NHL mortar

Aircrete and concrete display strength in B wallette that the yellow and the red display in the bond wrench test.

6.8 Statistical Analysis of empirically derived strength values

This section analyses the consistency of the results data by analysing the mean, standard deviation and coefficient of variation. Then it goes on to investigate which mortars or mortar unit combinations give the most consistent and strongest results.

For this section the following statistics were calculated:

- The mean is defined as the simple arithmetic average.

$$\bar{X} = \frac{\sum_{i=1}^{n} X_1}{n}$$

- Standard deviation is the spread of the data round the mean.

$$\sigma = \sqrt{\frac{\left(\sum_{i=1}^{n} X_1 - \bar{X}\right)^2}{n-1}}$$

- Coefficient of Variation removes the effect of a high mean and corresponding standard deviation to give a measure of the consistency of the data.

$$CV = \frac{\sigma}{\bar{X}}$$

- $\sum_{i=1}^{n} X_1$ = Sum of All data in set
- n = sample size
- $\bar{X}$ = arithmetic mean
- σ = standard deviation
- CV= coefficient of variation

6.8.1 Mean flexural strength

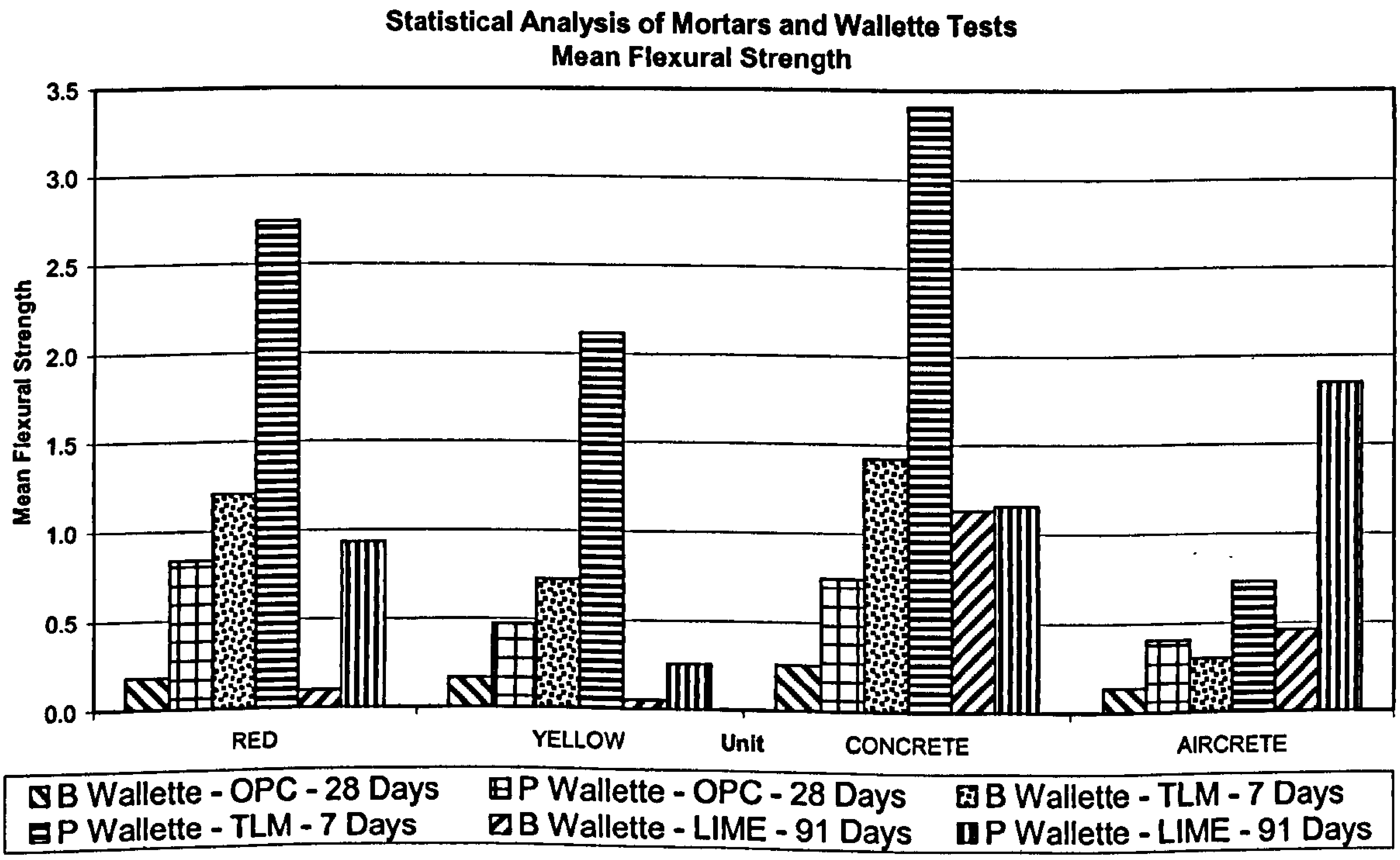


Figure 6.8.1.1 - Comparison of the effect of mortar and unit type on the mean flexural strength of P and B wallettes

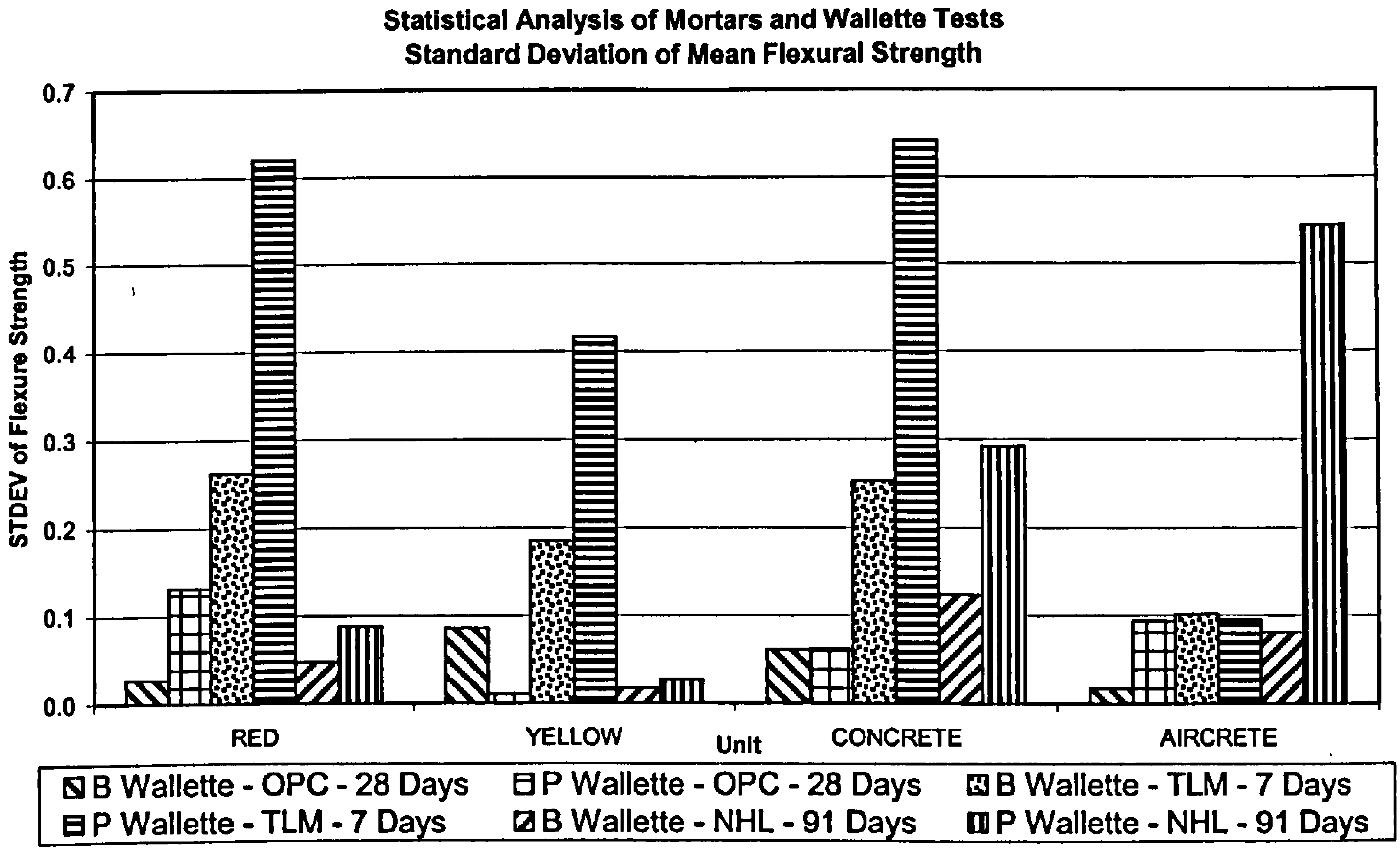


Figure 6.8.1.2 – Comparison of the effect of mortar and unit type on the standard deviation of the mean flexural strength of P and B wallettes

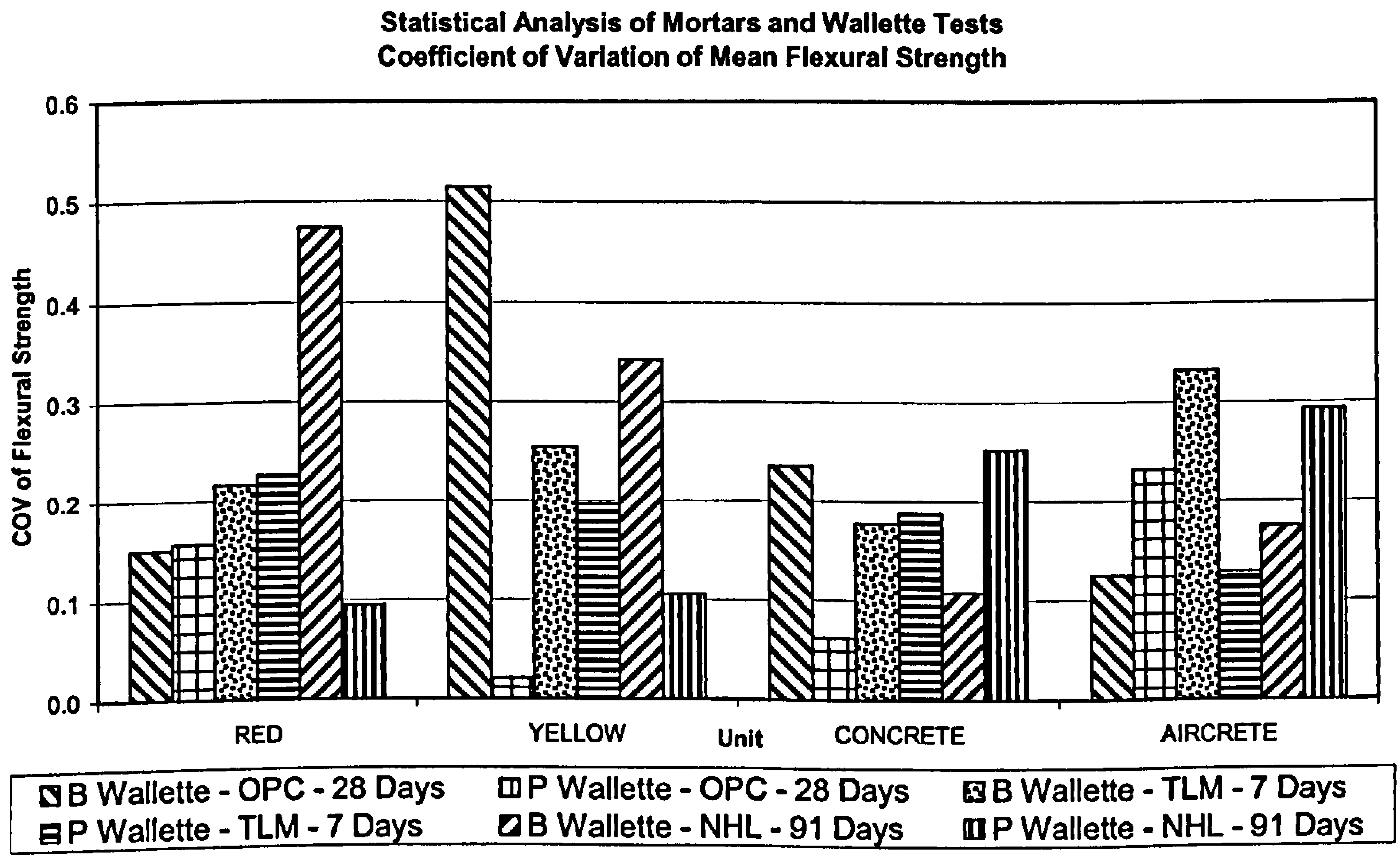


Figure 6.8.1.3 – Comparison of the effect of mortar and unit type on the coefficient of variation of the mean flexural strength of P and B wallettes

Overall the greatest mean flexural strength for all the B wallette mortar tests as demonstrated in Figure 6.8.1.1 was achieved using concrete and with P wallette TLM 7 days. For the other two P wallette tests the same trend did not apply, P wallette OPC 28 days performs best with red units whereas P wallette Lime 91 days performs best when combined with Aircrete. Another general trend which can be observed is that P wallette TLM at 7 days achieved the highest strength for all but Aircrete. Aircrete had the greatest strength for P wallette Lime at 91 days. The lowest mean flexural strength for red and yellow units is the B wallette Lime at 91 days. B wallette OPC at 28 days is the weakest with concrete and Aircrete.

On examination of the full set of results, data investigations into the distribution of the results were undertaken in relation to the mean. Figure 6.8.1.2 demonstrates that P wallette TLM at 7 days has the greatest standard deviation for red, yellow and concrete units. Aircrete has the greatest standard deviation with P wallette at 91 days. Similarly the lowest standard deviation for red, concrete and Aircrete is B wallette OPC at 28 days but conversely for yellow it is P wallette OPC at 28 days. As demonstrated by Figure 6.8.1.3 it can be noted that TLM gives fairly consistent results with the exception of Aircrete. Overall concrete was discovered to be less variable than the other units. The highest inconsistencies measured in terms of COV were for red, B wallette Lime at 91 days.

6.8.2 Mean bond strength

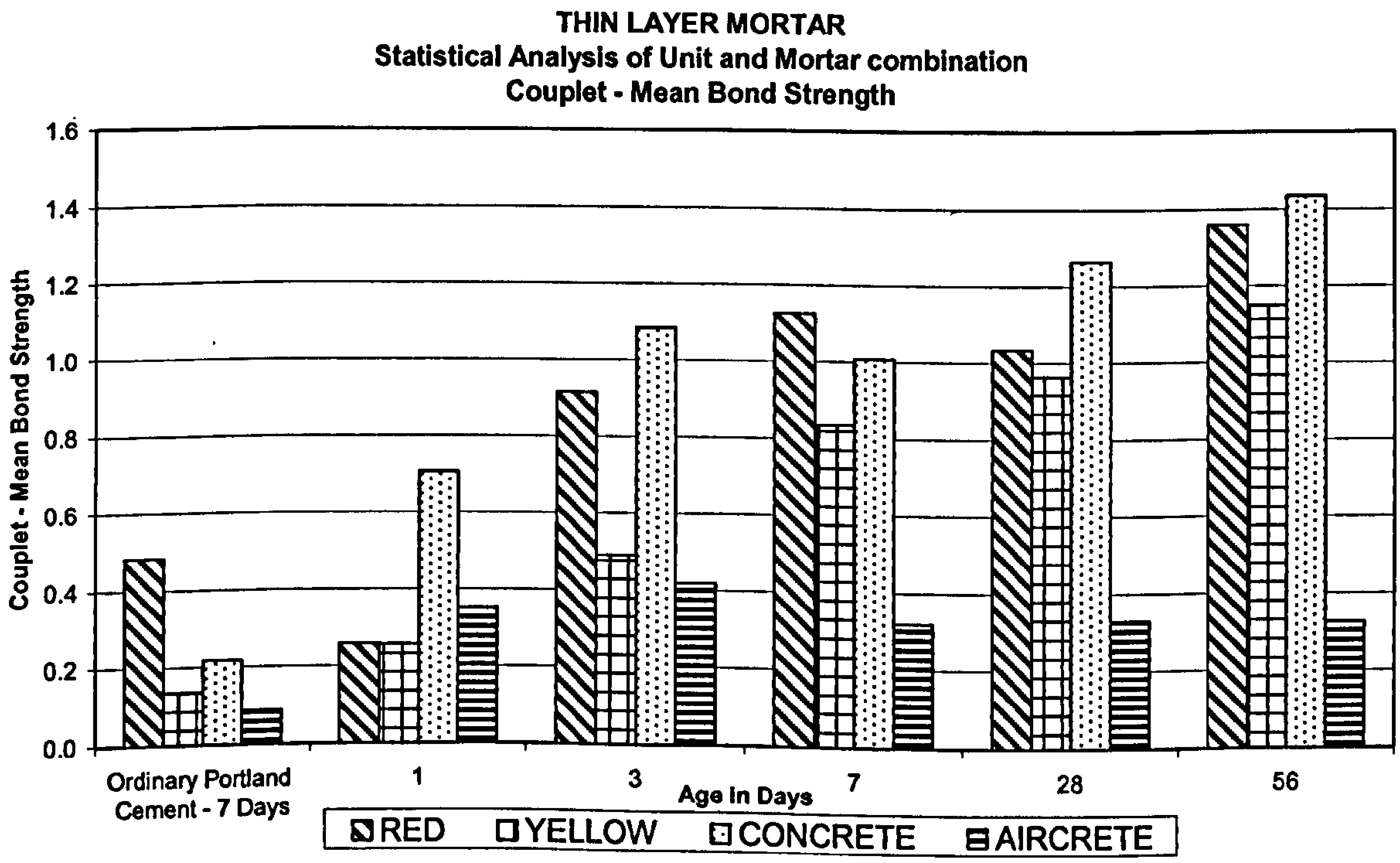


Figure 6.8.2.1 – Comparison of the effect of mortar and unit type on the mean bond strength of couplets for TLM

In Figure 6.8.2.1, the highest bond strength is achieved by TLM at 56 days for red, yellow and concrete units. Aircrete forms its strongest bond with TLM at 3 days. Conversely the lowest bond strength for concrete, yellow and Aircrete units was OPC at 7 days, and TLM at 1 day for red units. Figure 6.8.2.1 shows the overall effect whereas Figure 6.8.2.3 provides the direct comparison of age of specimen. By specifically comparing OPC and TLM at 7days, Figure 6.8.2.3 displays it is apparent that TLM has a faster rate of strength gain than OPC. This is most noticeable in yellow where the ratio is 6.13:1 (TLM: OPC). Analogulously to Figure 6.8.2.1, Figure 6.8.2.2, which demonstrates the means of the NHL, red units are strongest on all days. However, NHL is weakest at 91 days for concrete.

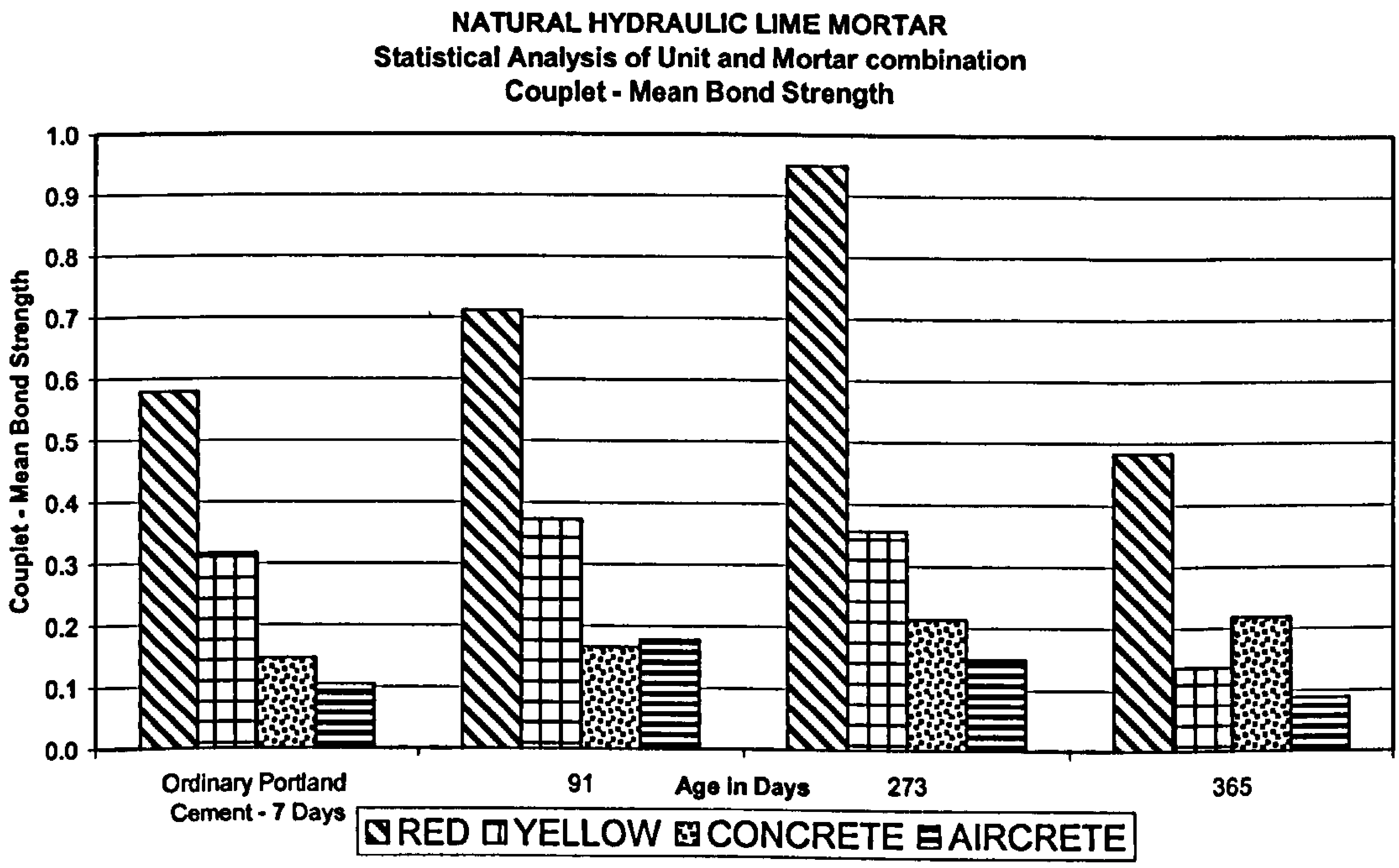


Figure 6.8.2.2 – Comparison of the effect of mortar and unit type on the mean bond strength of couplets for NHL

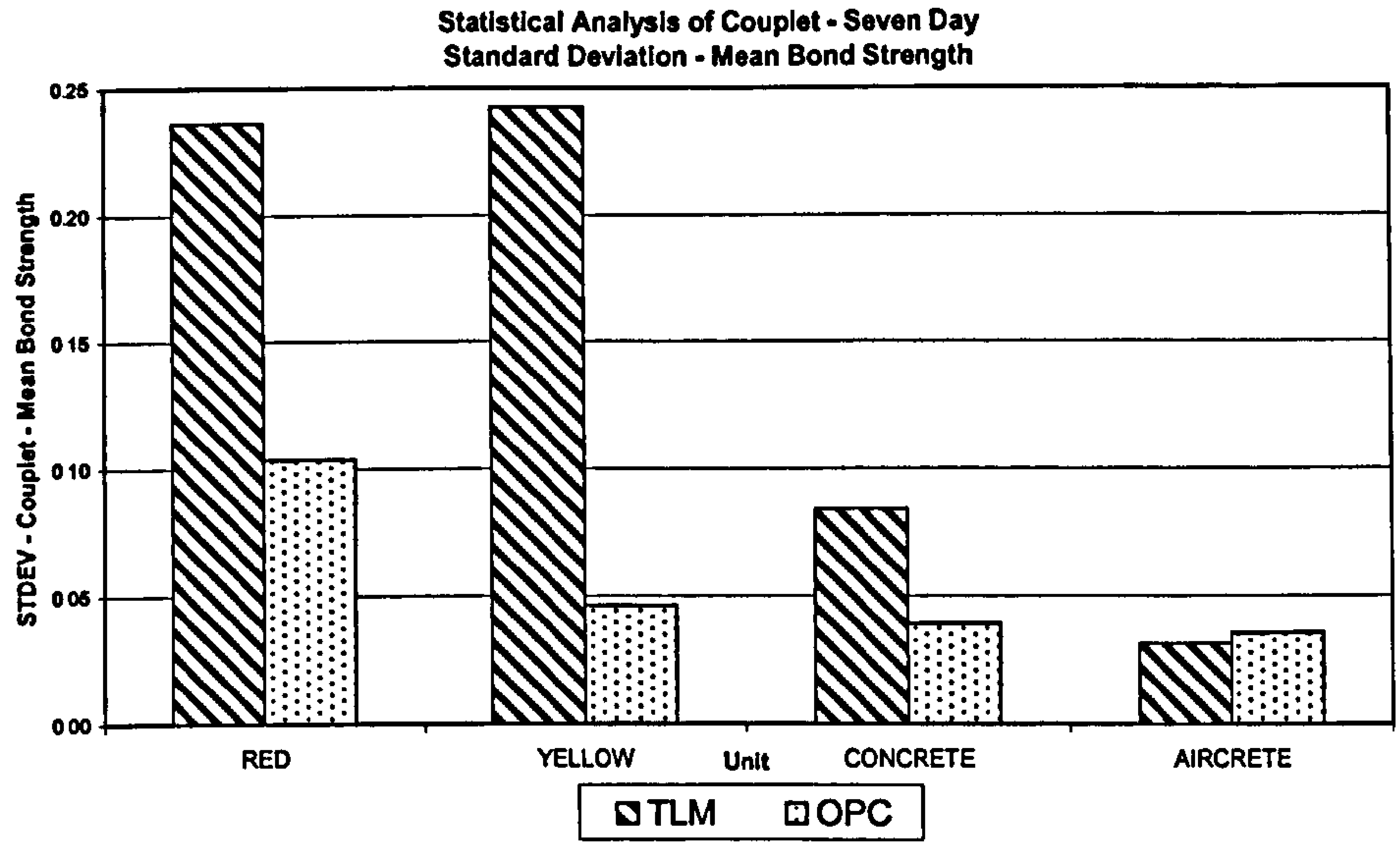


Figure 6.8.2.3 – Comparison of the effect of mortar and unit type on the mean bond strength of couplets at 7 days

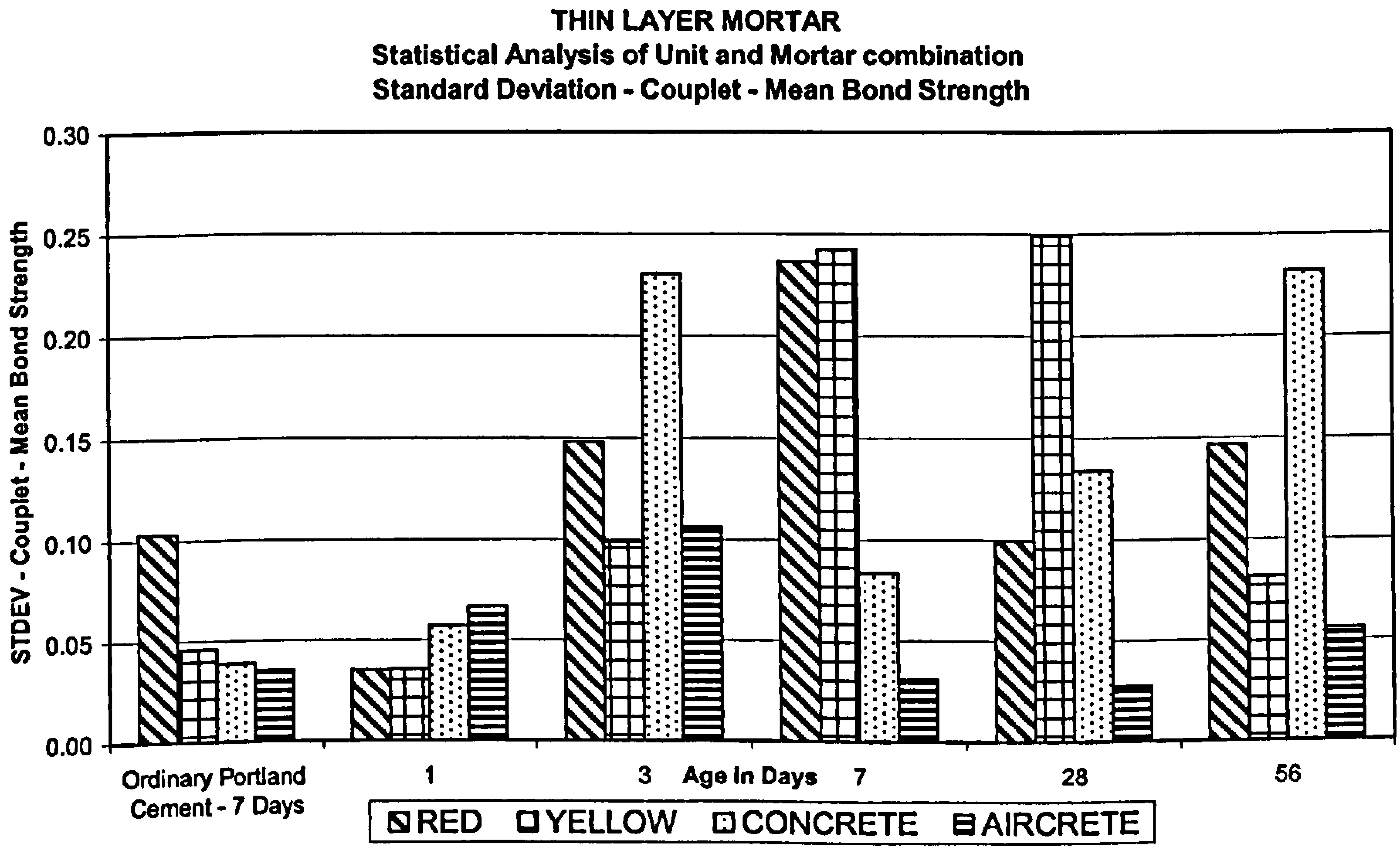


Figure 6.8.2.4 – TLM & OPC – Comparison of the effect of mortar and unit type on the standard deviation of the mean bond strength of couplets

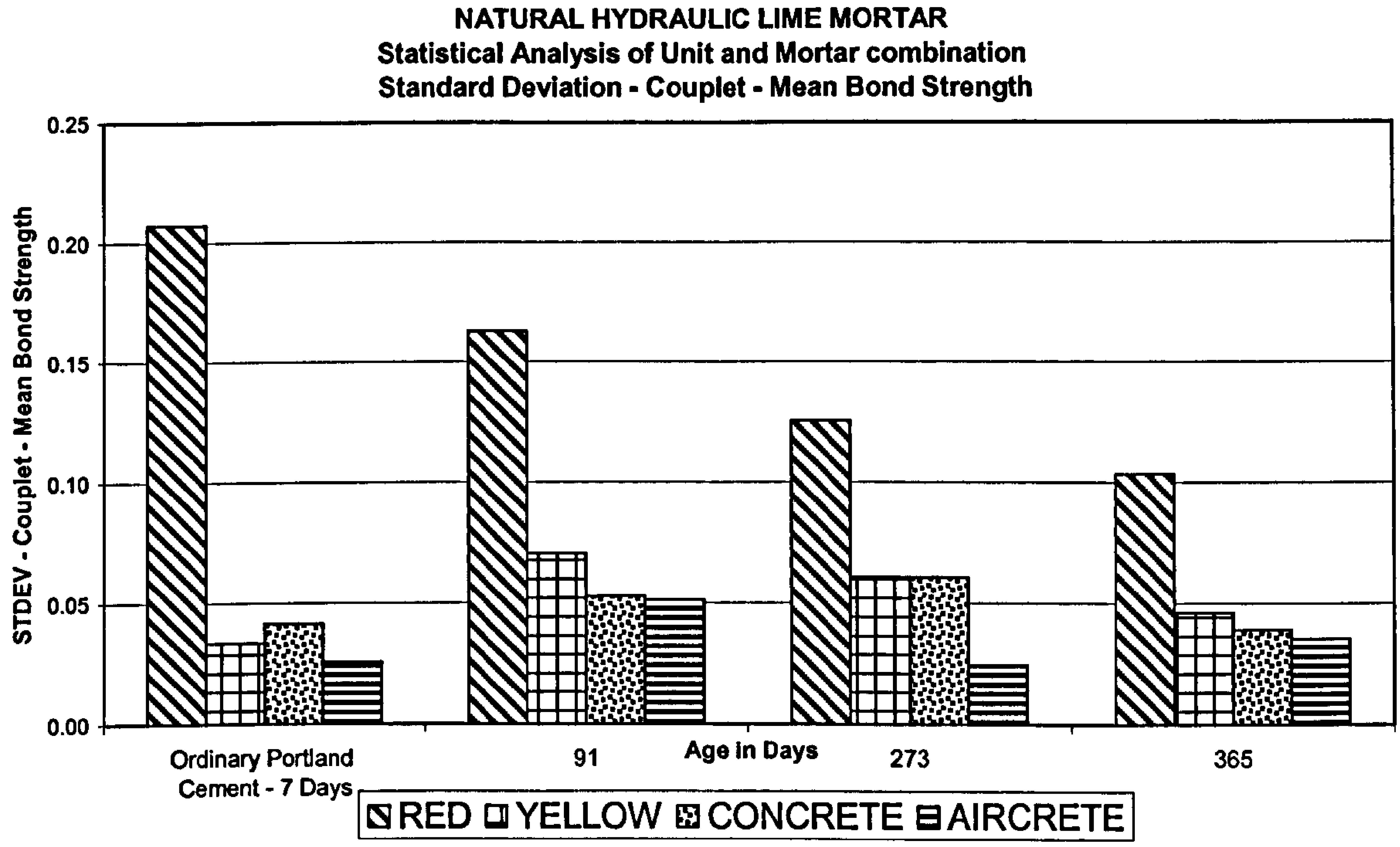


Figure 6.8.2.5 – NHL- Comparison of the effect of mortar and unit type on the standard deviation of the mean bond strength of couplets

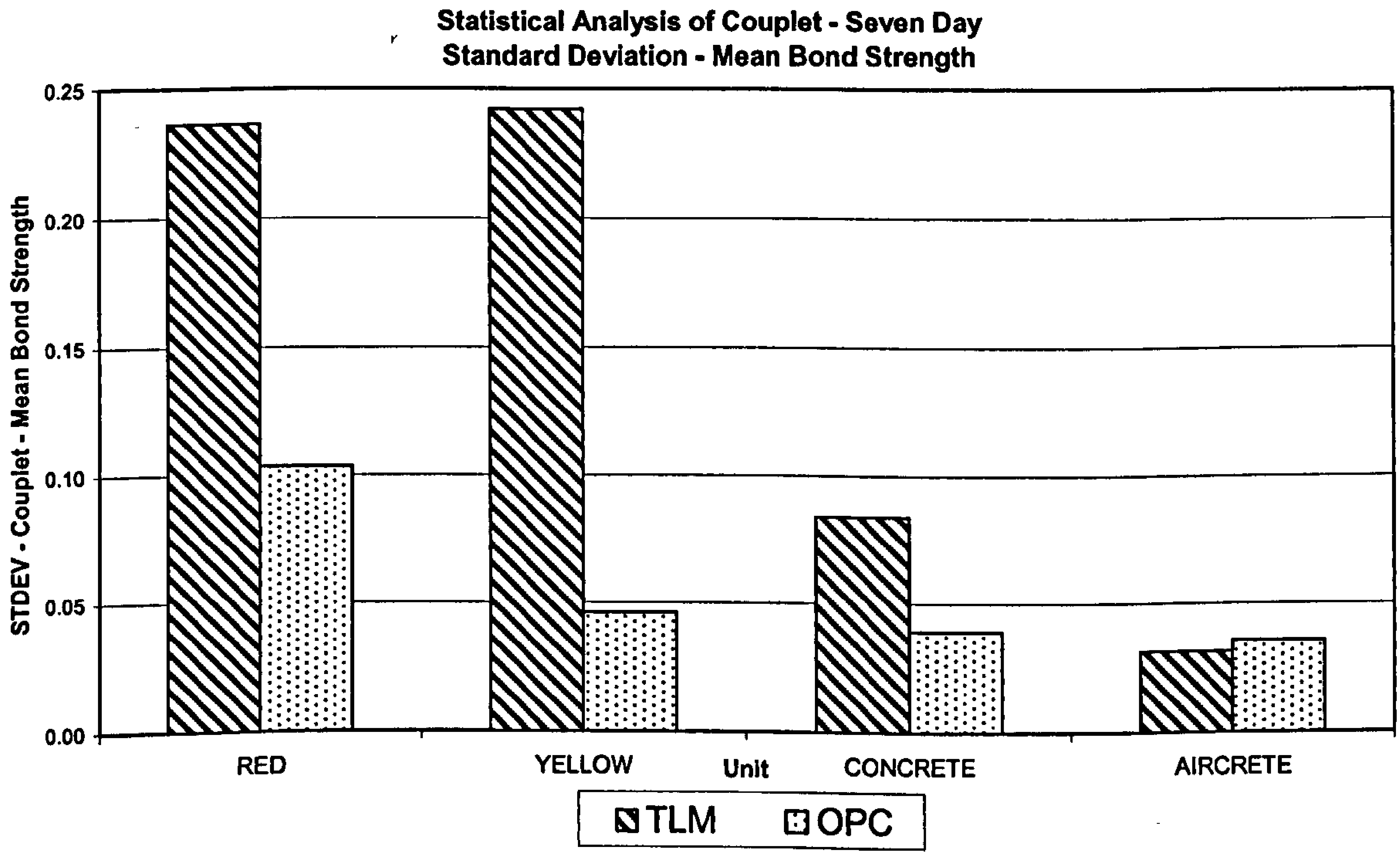


Figure 6.8.2.6 – Comparison of the effect of mortar and unit type on the standard deviation of the mean bond strength of couplets at 7 days

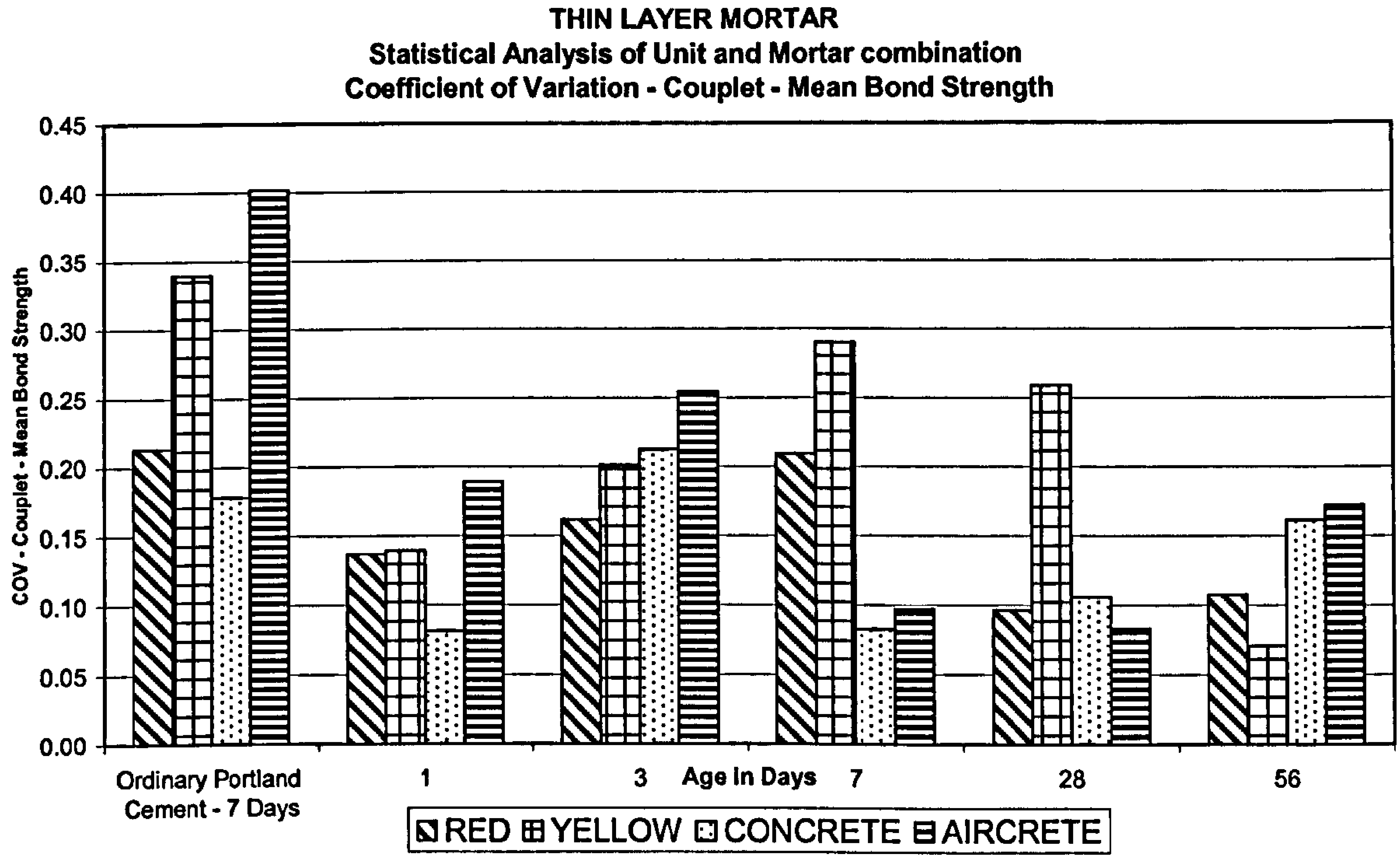


Figure 6.8.2.7 – TLM & OPC- Comparison of the effect of mortar and unit type on the coefficient of variation of the mean bond strength of couplets

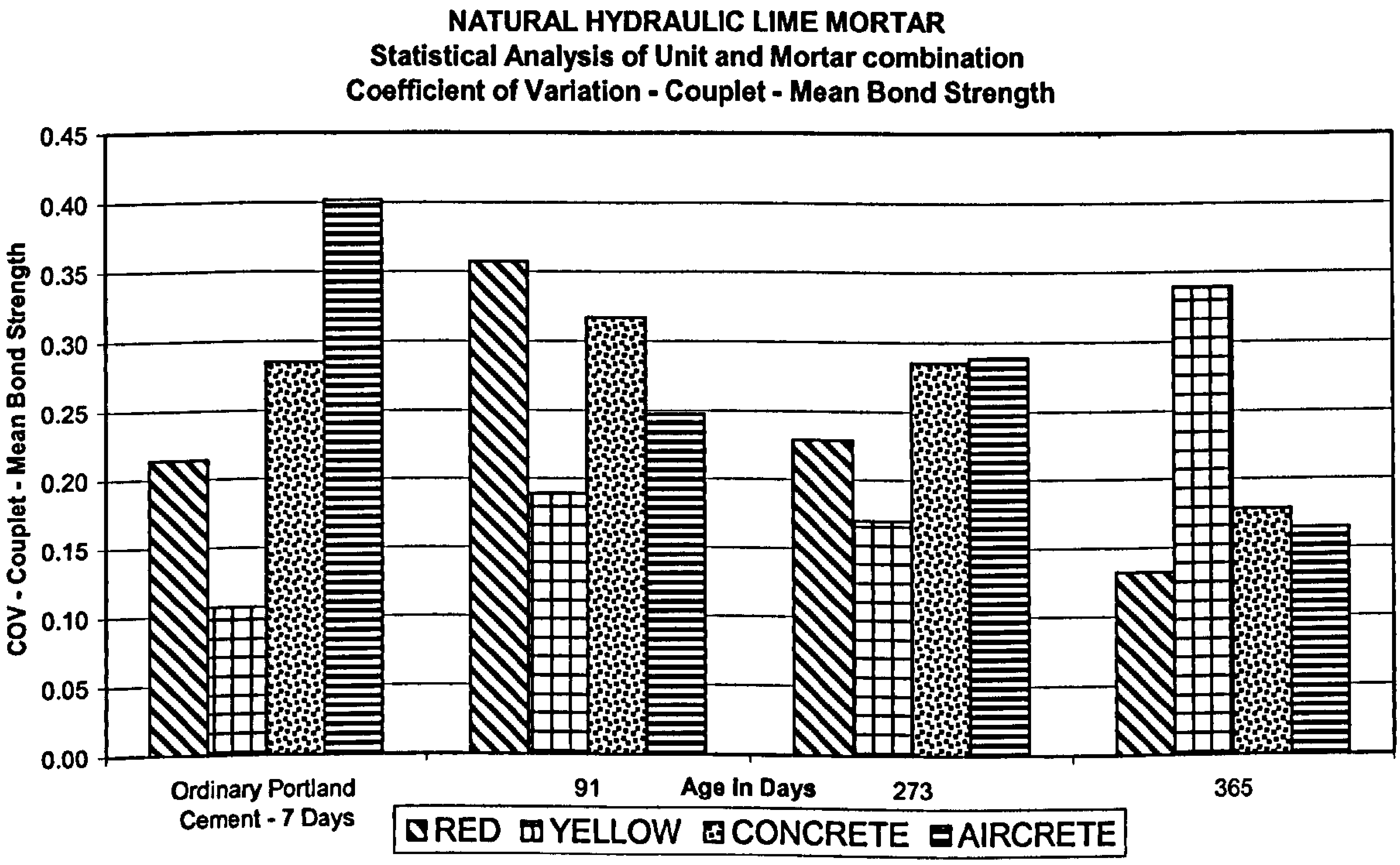


Figure 6.8.2.8 – NHL - Comparison of the effect of mortar and unit type on the coefficient of variation of the mean bond strength of couplets

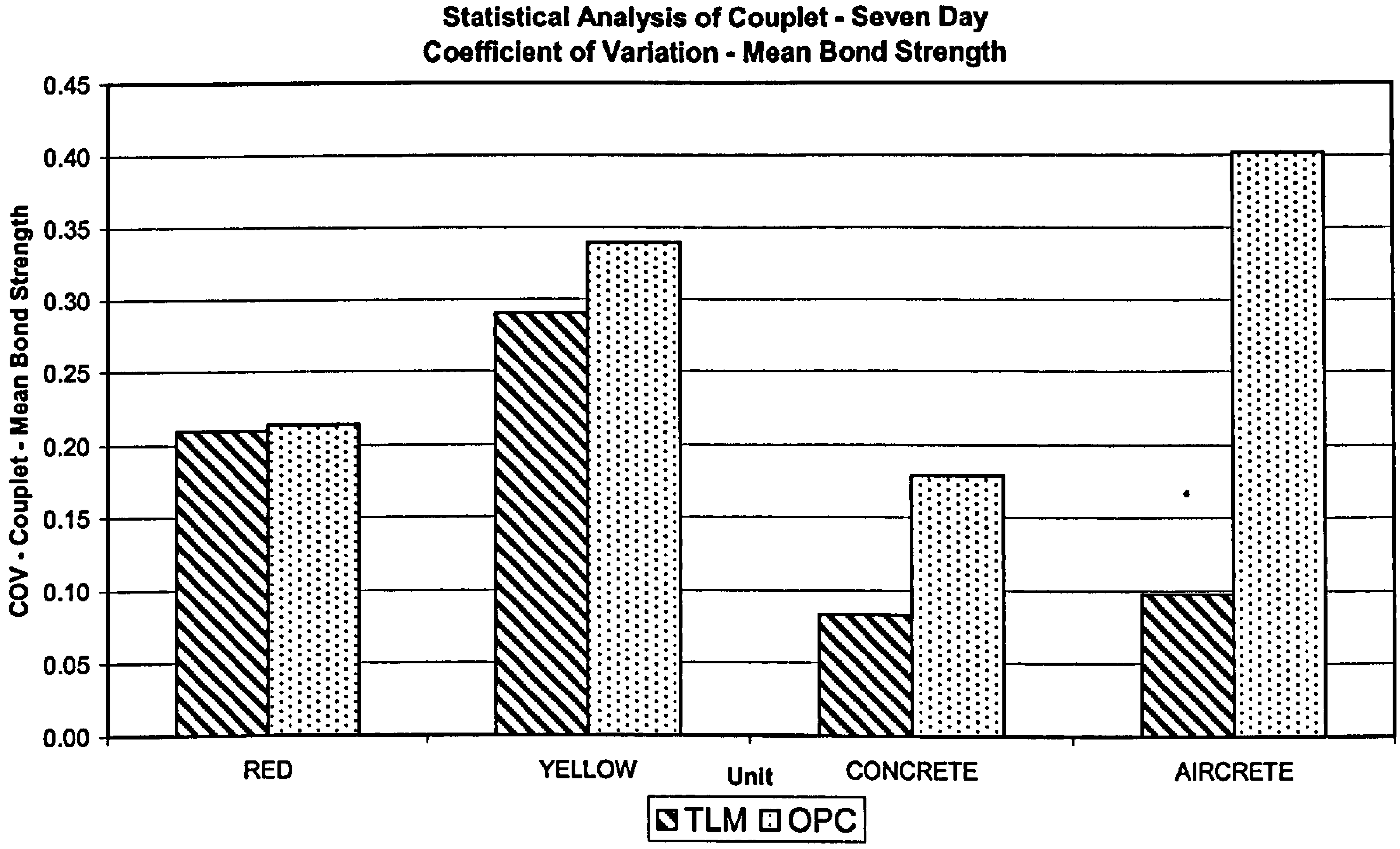


Figure 6.8.2.9 – Comparison of the effect of mortar and unit type on the coefficient of variation of the mean bond strength of couplets at 7 days

Distribution of data is often used as an indicator as to the quality of the data. Figure 6.8.2.4 in comparison to Figure 6.8.2.5 displays bigger standard deviations. This is especially apparent with the older ages, days 3 to 56 with TLM. The largest standard deviation is at 28 days using yellow units for Figure 6.8.2.4 with a standard deviation of 0.3. The NHL results have smaller standard deviations. In Figure 6.8.2.5 red units and OPC are the most variable with a value of just above 0.2. For both Figure 6.8.2.4 and 6.8.2.5 Aircrete overall has the smallest standard deviations. Figure 6.8.2.6 shows that apart from Aircrete, TLM has larger standard deviations than OPC. Red Units with OPC and yellow units with TLM gave the highest standard deviations in Figure 6.8.2.6. In figure 6.8.2.7 the most inconsistent result was Aircrete and OPC with 0.45, whereas the highest level of consistency was yellow units with TLM at 56 days. Analogulously to Figure 6.8.2.7, Figure 6.8.2.8 demonstrates the highest inconsistency with Aircrete and OPC however the most consistent result is OPC with yellow units at 0.15.Figure 6.8.2.9 – demonstrates that mean bond strength is most consistent at 7 days with concrete. Whereas the greatest variability occurs when TLM is combined with the yellow units and with Aircrete units using OPC.

Overall the distribution of the results indicates that there are fairly consistent trends with low standard deviations and COV values.

6.9 Statistical analysis of data using the T-Test

Owing to the large quantity of data the "Students T-Test" was used to analyse it for the purpose of finding NON-statistically significant results (that is similarities in data).

The form chosen to analyse the data was based on the "two sample with different variances" test. This test measures the standard error of the mean differences and is labelled as "Type 3" in the tables. The formula used to calculate it, is shown below:

$$t_{n_1+n_2-2} = \frac{m_1 - m_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}$$

Where:

- m_1 = Mean of group 1
- m_2 = Mean of group 2
- S_1 = Standard deviation for group 1
- S_2 = Standard deviation for group 2
- n_1 = Sample size of group 1
- n_2 = Sample size of group 2
- $n_1 + n_2 - 2$ = calculates the degrees of freedom where the total sample size less two constraints (i.e. the two means)
- t = Student's t statistics based on $n_1 + n_2 - 2$ degrees of freedom

The sets of data are heterogeneous (of a different kind) in nature. There are broadly distributions of the data to indicate that the two groups are similar. In the case of Figure 6.9.1.1 and 6.9.1.2 the two data groups being compared are the types of units.

6.9.1 Couplets Comparison

When comparing the red and yellow shown in the first line of the table a non statistically significant probability was calculated. Probabilities of 40%+ imply that the two sets of data are similar. When the raw data was visually inspected the data was so similar that both sets had very similar mean flexural bond strengths, standard deviation and coefficient of variation. This implies that for a one day test on clay units the properties of the unit itself has no significant impact on the bond strength.

Mortar	Unit Type	Property	Days	Test	Mortar	Unit Type	Property	Days	Test	Type 3 %	Star Rating
TLM	Red	Bond	1	BW	TLM	Yellow	Bond	1	BW	45	0
TLM	Yellow	Bond	3	BW	TLM	Aircrete	Bond	3	BW	7	B
TLM	Red	Bond	7	BW	TLM	Concrete	Bond	7	BW	8	B
TLM	Red	Bond	28	BW	TLM	Yellow	Bond	28	BW	21	0
TLM	Red	Bond	56	BW	TLM	Concrete	Bond	56	BW	20	0

Table 6.9.1.1 – T test – Couplets – thin layer mortar

Mortar	Unit Type	Property	Days	Test	Mortar	Unit Type	Property	Days	Test	Type 3 %	Star Rating
NHL	Concrete	Bond	273	BW	NHL	Aircrete	Bond	273	BW	32	0

Table 6.9.1.2 – T test – Couplets – natural hydraulic lime

7. Conclusions & Suggestions for Further Research

An assessment of masonry flexural bond strength and factors affecting it are described in this thesis. The strength characteristics of wallettes and couplets subjected to bending have been investigated.

7.1 Conclusions

The experimental investigation was initiated to study the flexural strength properties of masonry with different units and mortars. Conclusions concerning the analysis in chapter six are presented at the end of each section. However, on the basis of the experimental work, the following detailed conclusions can be drawn together for an overall understanding:

1. Thin layer mortar is highly sensitive to the timing used when applying to units. If the application takes more than a few minutes the strength of the bond decreases and tends to fail in the interface between the upper unit and the mortar.

2. Thin layer mortar bond is influenced mainly by the gross dry density of the unit. The denser and more complete the unit, gives the stronger bond.

3. Natural hydraulic lime bond gains in strength with increasing the contact surface area.

4. Natural hydraulic lime and ordinary Portland cement mortar bonds decrease significantly, when the initial rate of absorption of the unit increases.

5. Couplets yield a stronger bond with high absorption units in comparison to low absorption units – for all mortar types.

6. Transferring the workability and hard properties of mortar data from British Standards to European codes involves a conversion factor.

7. The Reutter bond wrench works well in ascertaining the bond strength with a wide range of mortar types without prematurely affecting the specimens and has good applications on building sites.

8. The scoop method for applying thin layer mortar should only be used on smooth surfaced units, when applied to units with rough surfaces this method yields a poor bond contact.

7.2 Suggestion for further research

The Reutter bond wrench manufactured in this thesis has proved to be a very successful and easy to use tool in testing flexural bond strength of masonry in the laboratory. However, using it on site and in range of situations is yet to be thoroughly considered. Some suggestions for further works are outlined below:

1. To investigate the micro level bond of thin layer mortar using an electron microscope with a wider range of absorbent units.

2. To quantify the conversion factors between British Standards (BS5628) and Eurocode 6 (EN1996), especially when detailing the relationship between compressive strength and water absorption; and initial rate of absorption.

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BS EN 771-2:2001 – Specification for Masonry Units – Part 2: Calcium silicate masonry units

BS EN 771-3:2003 – Specification for Masonry Units – Part 3: Aggregate concrete masonry units (dense and light-weight aggregates)

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BS EN 772-11:2000 – 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

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APPENDICES

APPENDIX A – BOND WRENCH DESIGNS

APPENDIX B – UNIT PROPERTIES

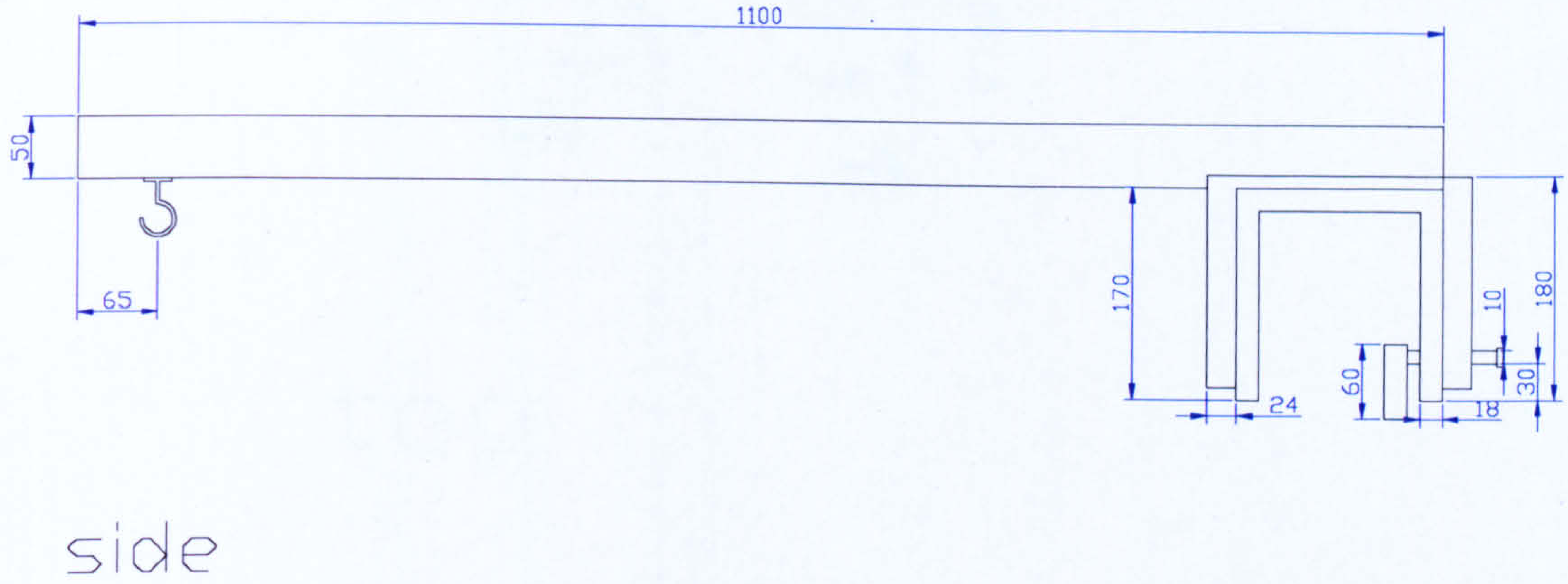
APPENDIX C – MORTAR– DATA

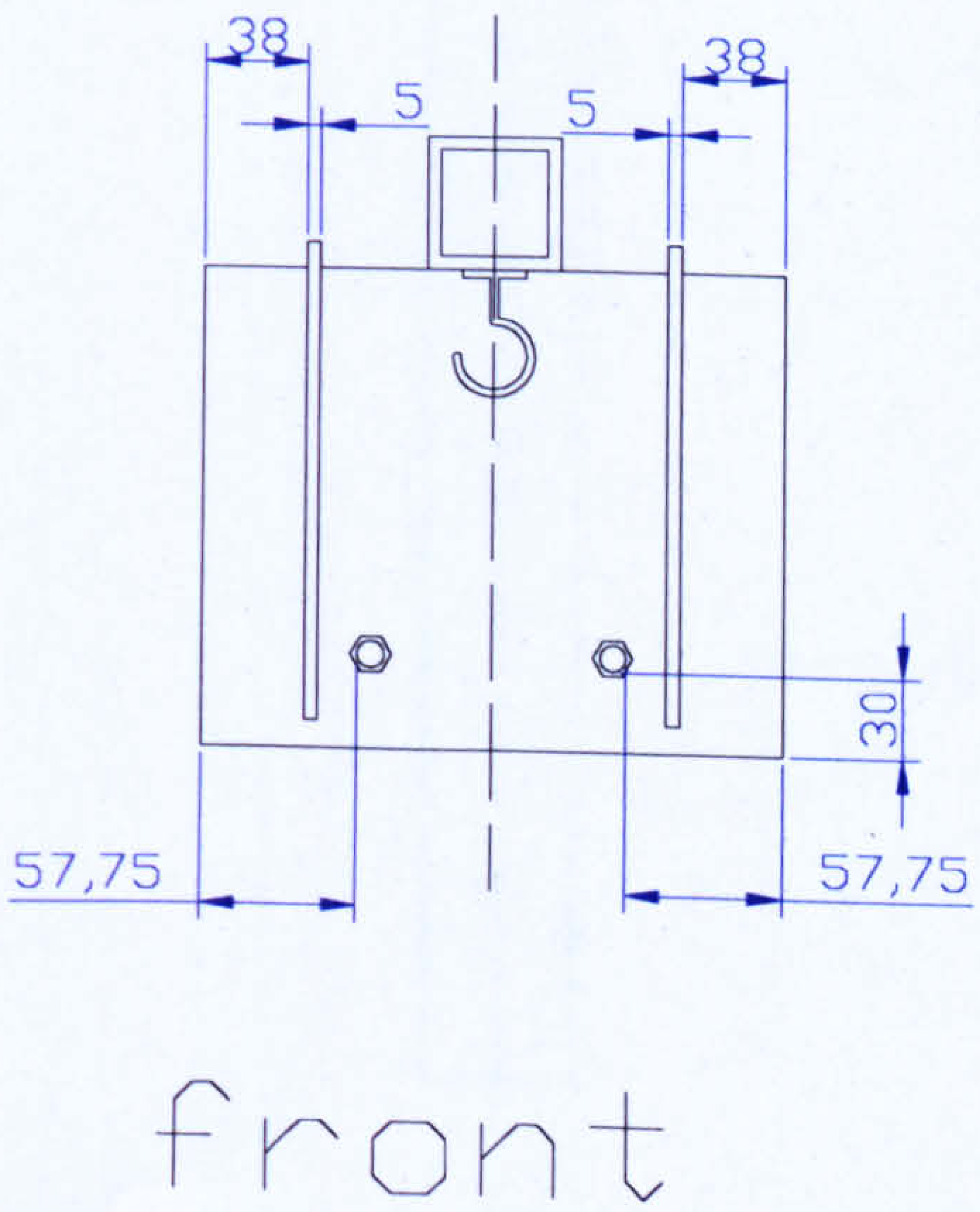
APPENDIX D – COUPLETS (BOND WRENCH) – DATA

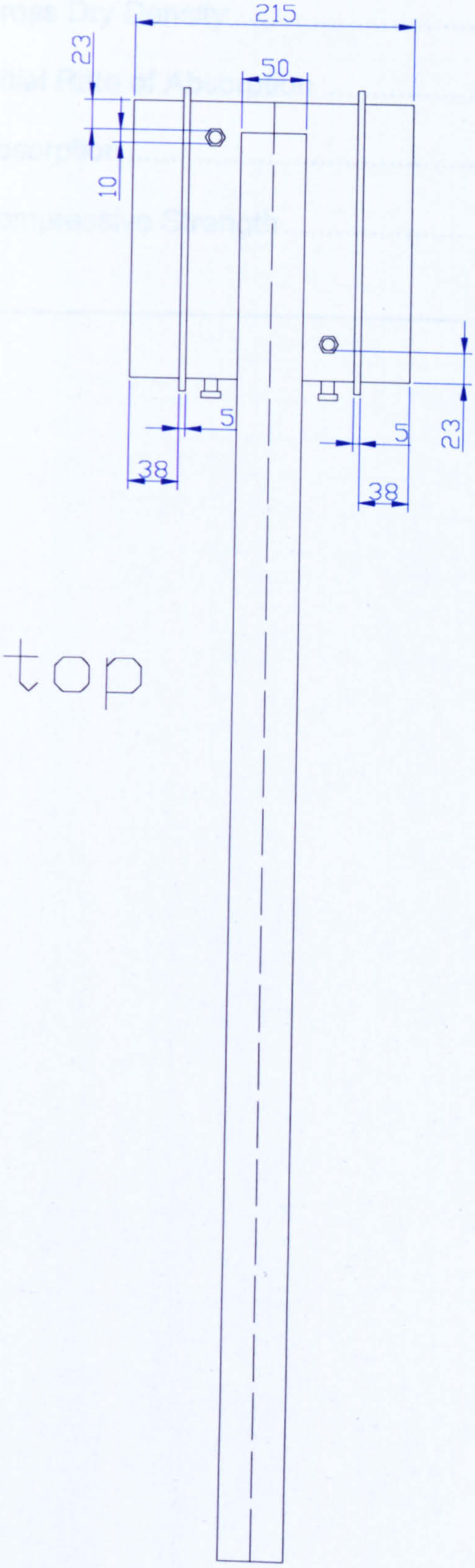
APPENDIX E – WALLETTE – DATA

APPENDIX A – BOND WRENCH DESIGNS

Appendix A – Ceram Bond Wrench – Schematic






215
23
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38
top

APPENDIX B – UNIT PROPERTIES

Appendix B.1 – Gross Dry Density

Red Brick Unit	
Area Correction	Values
π	3.142
Diameter/mm	20
Number of holes	10
Area	314.2
Total area correction	3141.6

Yellow Brick Unit	
Area Correction	Values
π	3.142
Diameter/mm	40
Number of holes	3
Area	1256.6
Total area correction	3769.9

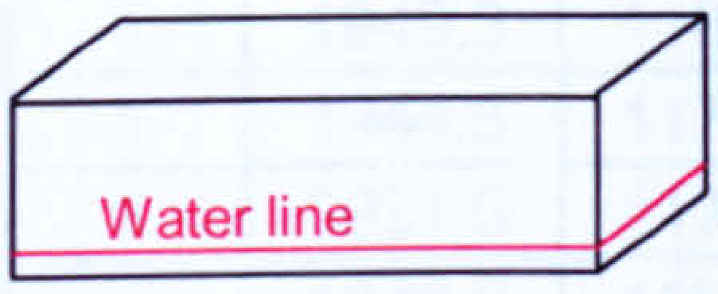
Experimental Data - Gross Dry Density
According to: BS EN 772-13:2000

Unit No	Gross Weight	Length	Depth	Height	Net Volume	Volume of Perforations	Gross Volume	Gross Dry Density
	g	mm	mm	mm	mm^3	mm^3	mm^3	kg/m^3
Red Brick Unit								
1	2513.5	216.0	105.4	65.0	1479114.0	204203.5	1274910.5	1972
2	2496.8	217.0	104.4	64.7	1463931.4	203104.0	1260827.4	1980
3	2506.8	218.0	104.8	65.6	1496867.0	205931.4	1290935.6	1942
4	2498.3	217.2	103.9	64.7	1458259.6	203104.0	1255155.7	1990
5	2483.5	214.5	103.9	64.7	1441939.8	203261.0	1238678.7	2005
6	2504.3	216.5	104.5	65.9	1489806.9	206873.9	1282933.0	1952
Avg	2500.5	216.5	104.5	65.1	1471606.7	204413.0	1267193.8	1973
Yellow Brick Unit								
1	1949.3	215.8	101.5	65.5	1433985.6	246929.2	1187056.4	1642
2	1944.5	216.0	101.2	65.2	1423423.3	245609.7	1177813.5	1651
3	1921.5	216.0	100.9	65.2	1420290.7	245798.2	1174492.5	1636
4	1946.0	215.7	102.1	65.5	1441403.4	246740.7	1194662.7	1629
5	1913.8	215.0	101.2	65.7	1427707.0	247494.7	1180212.3	1622
6	1921.3	216.6	100.8	65.8	1435538.2	247871.7	1187666.5	1618
Avg	1932.7	215.9	101.3	65.5	1430397.5	246740.7	1183656.8	1633
Concrete Brick Sized Unit								
1	3047.0	215.0	100.9	65.9	1428517.0	-	1428517.0	2133
2	2903.8	215.0	99.4	65.5	1399096.4	-	1399096.4	2075
3	2990.8	215.0	100.7	65.2	1410911.7	-	1410911.7	2120
4	2878.3	215.0	99.9	65.4	1403990.9	-	1403990.9	2050
5	2979.3	215.5	100.3	65.7	1418294.4	-	1418294.4	2101
6	3103.3	215.0	103.1	65.7	1455230.7	-	1455230.7	2132
Avg	2983.7	215.1	100.7	65.5	1419324.9	-	1419324.9	2102
Aircrete Brick Sized Unit								
1	879.3	211.8	98.1	64.1	1331842.9	-	1331842.9	660
2	955.3	212.0	99.7	67.1	1417541.2	-	1417541.2	674
3	910.3	212.0	101.1	64.1	1372796.5	-	1372796.5	663
4	865.3	212.0	96.5	64.1	1309656.0	-	1309656.0	661
5	883.0	211.5	99.2	64.2	1345918.3	-	1345918.3	656
6	905.8	212.0	100.0	64.0	1356121.6	-	1356121.6	668
Avg	899.8	211.9	99.1	64.6	1355580.4	-	1355580.4	664

Appendix B.2 – Initial Rate of Absorption

Unit - Initial Rate of Absorption Test - EN772-11:2000

Key	Description	Units
$m_{dry,s}$	mass of specimen after drying	g
$m_{so,s}$	mass of specimen in grams after soaking for time t	g
A_s	gross area of the face of the specimen immersed in water	mm^2
t_{so}	time of soaking	s
$c_{w,s}$	coefficient of water absorption due to capillary suction	$g/(m^2 x s^{0,5})$
$c_{wi,s}$	initial rate of water absorption for masonry units	$kg/(m^2 x min)$



Length	215.0	mm	
Width	102.5	mm	
Depth	5.0	mm	*Depth of unit immersed in water*

Brick Unit Areas	Bottom	22038	mm^2
	Front	1075	mm^2
	Left	513	mm^2
	Right	513	mm^2
	Back	1075	mm^2
Total area immersed		25213	mm^2

$$c_{w,s} = \frac{m_{so,s} - m_{dry,s}}{A_s \sqrt{t_{so}}} \times 10^6 [g/(m^2 \times s^{0,5})]$$

$$c_{wi,s} = \frac{m_{so,s} - m_{dry,s}}{A_s t} \times 10^3 [kg/(m^2 x \times \min)]$$

ABREVIATIONS		
	Diff	Difference
	Bef	Before
	Aft	After
	L	Left
	R	Right
	BK	Back
	FR	Front

Experimental Data - Initial Rate of Absorption According to: EN 772-11:2000						
Unit No	Weight	Volume	Dry Density	Time	$C_{w,s}$	$C_{wi,s}$
	g	mm^3	kg/m^3	sec	g/(m^2×s^{0,5})	kg/(m^2×min)
Red Brick Unit						
1	2513.5	1274910.5	1972	30	90.52	0.99
2	2496.8	1260827.4	1980	60	38.40	0.30
3	2506.8	1290935.6	1942	90	86.13	0.54
4	2498.3	1255155.7	1990	120	90.52	0.50
5	2483.5	1238678.7	2005	240	103.69	0.40
6	2504.3	1282933.0	1952	300	76.71	0.27
Yellow Brick Unit						
1	1949.3	1187056.4	1642	30	129.14	1.41
2	1944.5	1177813.5	1651	60	246.27*	1.91*
3	1921.5	1174492.5	1636	90	194.30	1.23
4	1946.0	1194662.7	1629	120	234.80	1.29
5	1913.8	1180212.3	1622	240	225.52	0.87
6	1921.3	1187666.5	1618	300	193.05	0.67
Concrete Brick Sized Unit						
1	3047.0	1428517.0	2133	120	171.98	0.94
2	2903.8	1399096.4	2075	300	140.83	0.49
3	2990.8	1410911.7	2120	600	98.77*	0.24*
4	2878.3	1403990.9	2050	900	81.31	0.16
5	2979.3	1418294.4	2101	1200	68.13	0.12
6	3103.3	1455230.7	2132	1800	59.36	0.08
Aircrete Brick Sized Unit						
1	879.3	1331842.9	660	120	141.21	0.77
2	955.3	1417541.2	674	300	121.37*	0.42*
3	910.3	1372796.5	663	600	119.01*	0.29*
4	865.3	1309656.0	661	900	124.94	0.25
5	883.0	1345918.3	656	1200	113.92*	0.20*
6	905.8	1356121.6	668	1800	117.79	0.17

Red Brick - Initial Rate of Absorption - EN772-11:2000

No	Time	Brick Unit		Diff	Tissue		Diff	Watermark Rise				Mean
		Bef	Aft		Bef	Aft		L	FR	R	BK	
	seconds	g		g	g		g	mm	mm	mm	mm	mm
1	30	2475.5	2488.0	12.5	8.0	10.5	2.5	6	6	6	6	6.0
2	60	2488.0	2495.5	7.5	8.0	11.0	3.0	8	8	8	8	8.0
3	90	2488.9	2509.5	20.6	7.5	11.5	4.0	7	6	10	12	8.8
4	120	2508.5	2533.5	25.0	8.0	11.0	3.0	13	10	10	11	11.0
5	240	2439.0	2479.5	40.5	7.5	12.0	4.5	14	14	14	14	14.0
6	300	2505.5	2539.0	33.5	8.0	11.5	3.5	14	14	15	14	14.3

No	$m_{dry,s}$	$m_{so,s}$	A_s	t_{so}	$c_{w,s}$	$c_{wi,s}$
	g	g	mm^2	s	$g/(m^2xs^{0.5})$	$kg/(m^2xmin)$
1	2475.5	2488.0	25212.5	30	90.52	0.0165
2	2488.0	2495.5	25212.5	60	38.40	0.0050
3	2488.9	2509.5	25212.5	90	86.13	0.0091
4	2508.5	2533.5	25212.5	120	90.52	0.0083
5	2439.0	2479.5	25212.5	240	103.69	0.0067
6	2505.5	2539.0	25212.5	300	76.71	0.0044

Formulas and Static Values	
All measurements in mm	
Circumference	πd
Area of a circle	πr^2
Depth of Imersion	5.0
π	3.142

Specified Standards Time

Area Correction	Values
Diameter/mm	20
Holes in bricks (Increase)	314.2
Holes in bricks (Decrease)	314.2
Change in Area	0.0
Number of holes	10
Total area change	0.0

No change in contact area as a result of the holes

Yellow Brick - Initial Rate of Absorption - EN772-11:2000

No	Time	Brick Unit		Diff	Tissue		Diff	Watermark Rise				Mean
		Bef	Aft		Bef	Aft		L	FR	R	BK	
	seconds	g		g	g		g	mm	mm	mm	mm	mm
1	30	1937.5	1954.0	16.5	8	10.5	2.5	17	13	8	8	11.5
2	60	1941.5	1986.0	44.5	8	11	3	18	19	20	15	18.0
3	90	1941.0	1984.0	43.0	8	11.5	3.5	19	17	21	13	17.5
4	120	1947.0	2007.0	60.0	8	10	2	24	21	24	21	22.5
5	240	1945.5	2027.0	81.5	8	11	3	31	29	28	22	27.5
6	300	1933.0	2011.0	78.0	8	11	3	26	26	23	24	24.8

No	$m_{dry,s}$	$m_{so,s}$	A_s	t_{so}	$c_{w,s}$	$c_{wi,s}$
	g	g	mm^2	s	$g/(m^2xs^{0.5})$	$kg/(m^2xmin)$
1	1937.5	1954.0	23327.5	30	129.14	0.0236
2	1941.5	1986.0	23327.5	60	246.27	0.0318
3	1941.0	1984.0	23327.5	90	194.30	0.0205
4	1947.0	2007.0	23327.5	120	234.80	0.0214
5	1945.5	2027.0	23327.5	240	225.52	0.0146
6	1933.0	2011.0	23327.5	300	193.05	0.0111

Formulas and Static Values	
All measurements in mm	
Circumference	πd
Area of a circle	πr^2
Depth of Imersion	5.0
π	3.142

Specified Standards Time

Area Correction	Values
Diameter/mm	40
Holes in bricks (Increase)	628.3
Holes in bricks (Decrease)	1256.6
Change in Area	-628.3
Number of holes	3
Total area change	-1885.0

Reduction in contact area as a result of the holes

Concrete Brick - Initial Rate of Absorption - EN772-11:2000

No	Time	Brick Unit		Diff	Tissue		Diff	Watermark Rise				Mean
		Bef	Aft		Bef	Aft		L	FR	R	BK	
	seconds	g		g	g		g	mm	mm	mm	mm	mm
1	120	3058.0	3105.5	47.5	8	11	3	26	18	32	19	23.8
2	300	3056.0	3117.5	61.5	8	12	4	34	22	33	25	28.5
3	600	3051.5	3112.5	61.0	8	12	4	25	20	33	29	26.8
4	900	3070.5	3132.0	61.5	8	12	4	48	65	65	65	60.8
5	1200	3182.5	3242.0	59.5	8	11	3	25	44	30	34	33.3
6	1800	3079.5	3143.0	63.5	8	11.5	3.5	60	49	60	35	51.0

No	$m_{dry,s}$	$m_{so,s}$	A_s	t_{so}	$c_{w,s}$	$c_{wi,s}$
	g	g	mm²	s	g/(m²xs$^{0.5}$)	kg/(m²xmin)
1	3058.0	3105.5	25212.5	120	171.98	0.0157
2	3056.0	3117.5	25212.5	300	140.83	0.0081
3	3051.5	3112.5	25212.5	600	98.77	0.0040
4	3070.5	3132.0	25212.5	900	81.31	0.0027
5	3182.5	3242.0	25212.5	1200	68.13	0.0020
6	3079.5	3143.0	25212.5	1800	59.36	0.0014

Specified Standards Time

No holes in units therefore area correction not applied

Aircrete Brick - Initial Rate of Absorption - EN772-11:2000

No	Time	Brick Unit		Diff	Tissue		Diff	Watermark Rise				Mean
		Bef	Aft		Bef	Aft		L	FR	R	BK	
	minutes	g		g	g		g	mm	mm	mm	mm	mm
1	120	902.0	941.0	39.0	8.0	12.0	4.0	14	25	12	38	22.3
2	300	854.5	907.5	53.0	8.0	12.5	4.5	17	10	34	35	24.0
3	600	880.5	954.0	73.5	7.5	12.0	4.5	23	31	20	23	24.3
4	900	848.0	942.5	94.5	8.0	13.5	5.5	23	28	34	34	29.8
5	1200	864.5	964.0	99.5	8.0	13.0	5.0	25	40	42	28	33.8
6	1800	867.5	993.5	126.0	8.0	12.5	4.5	45	52	30	23	37.5

No	$m_{dry,s}$	$m_{so,s}$	A_s	t_{so}	$c_{w,s}$	$c_{wi,s}$
	g	g	mm²	s	g/(m²xs$^{0.5}$)	kg/(m²xmin)
1	902.0	941.0	25212.5	120	141.21	0.0129
2	854.5	907.5	25212.5	300	121.37	0.0070
3	880.5	954.0	25212.5	600	119.01	0.0049
4	848.0	942.5	25212.5	900	124.94	0.0042
5	864.5	964.0	25212.5	1200	113.92	0.0033
6	867.5	993.5	25212.5	1800	117.79	0.0028

Specified Standards Time

No holes in units therefore area correction not applied

Appendix B.3 – Absorption

Experimental Data - Absorption
According to: BS EN 771-1:2003

	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m	Dry Mass m_d	Wet Mass m_w	Absorp'tion w_m
	g	g	%	g	g	%	g	g	%	g	g	%
Unit No	Red Brick Unit			Yellow Brick Unit			Concrete Brick Sized Unit			Aircrete Brick Sized Unit		
1	2513.5	2700.0	7	1949.3	2279.0	17	3047.0	3257.5	7	879.3	1257.0	43
2	2496.8	2666.0	7	1944.5	2279.0	17	2903.8	3126.0	8	955.3	1343.0	41
3	2506.8	2669.9	7	1921.5	2265.0	18	2990.8	3208.0	7	910.3	1313.5	44
4	2498.3	2670.5	7	1946.0	2290.0	18	2878.3	3103.0	8	865.3	1258.0	45
5	2483.5	2631.5	6	1913.8	2249.5	18	2979.3	3193.5	7	883.0	1291.5	46
6	2504.3	2678.0	7	1921.3	2262.0	18	3103.3	3313.0	7	905.8	1287.5	42
7	2498.3	2680.8	7	1946.8	2289.4	18	3048.1	3277.5	8	943.4	1339.3	42
8	2505.6	2679.7	7	1934.5	2273.6	18	2944.9	3159.4	7	917.7	1323.0	44
9	2503.5	2670.6	7	1939.7	2273.2	17	2969.1	3207.0	8	869.9	1269.3	46
10	2482.3	2657.9	7	1928.4	2273.2	18	3014.1	3225.0	7	935.0	1335.9	43
AVG	2499.3	2670.5	**6.9**	1934.6	2273.4	**18**	2987.8	3207.0	**7**	906.5	1301.8	**44**
STDEV	9.9	17.7	0.4	12.7	12.3	0.3	68.7	65.7	0.4	31.7	33.6	1.9
COV	0.00	0.01	0.06	0.01	0.01	0.02	0.02	0.02	0.06	0.03	0.03	0.04

Unit No	Weight in grams						
	Before inserting into oven	Difference Before & After	After 24 Hours in oven	After 24 Hours Cooling	Average of Dry State	After Cooling	After 24 Hours in Water	Water Absorbed
Red Brick Unit								
1	2514.5	1.0	2513.5	2513.5	2513.5	0.0	2700.0	186.5
2	2497.5	0.5	2497.0	2496.5	2496.8	0.5	2666.0	169.3
3	2507.5	1.0	2506.5	2507.0	2506.8	-0.5	2669.9	163.2
4	2499.0	0.5	2498.5	2498.0	2498.3	0.5	2670.5	172.3
5	2484.0	0.5	2483.5	2483.5	2483.5	0.0	2631.5	148.0
6	2505.0	1.0	2504.0	2504.5	2504.3	-0.5	2678.0	173.8
7	2498.3	0.0	2498.3	2498.3	2498.3	0.0	2680.8	182.5
8	2506.8	-0.2	2506.9	2506.8	2505.6	0.2	2679.7	174.1
9	2513.5	0.0	2513.5	2513.5	2503.5	0.0	2670.6	167.1
10	2496.8	0.0	2496.8	2496.8	2482.3	0.0	2657.9	175.6
Avg	2502.3	0.4	2501.8	2501.8	2499.3	0.0	2670.5	171.2
Yellow Brick Unit								
1	1949.0	0.5	1948.5	1950.0	1949.3	-1.5	2279.0	329.8
2	1941.0	1.9	1939.1	1945.0	1942.1	-5.9	2279.0	337.0
3	1922.0	1.0	1921.0	1922.0	1921.5	-1.0	2265.0	343.5
4	1945.5	0.5	1945.0	1947.0	1946.0	-2.0	2290.0	344.0
5	1913.5	0.5	1913.0	1914.5	1913.8	-1.5	2249.5	335.8
6	1921.5	0.5	1921.0	1921.5	1921.3	-0.5	2262.0	340.8
7	1946.8	0.6	1946.2	1946.8	1946.8	-0.6	2289.4	342.6
8	1934.5	0.5	1934.0	1934.5	1934.5	-0.5	2273.6	339.1
9	1939.7	0.2	1939.5	1939.7	1939.7	-0.2	2273.2	333.5
10	1928.4	0.6	1927.8	1928.4	1928.4	-0.6	2273.2	344.8
Avg	1934.2	0.7	1933.5	1934.9	1934.3	-1.4	2273.4	339.1
Concrete Brick Sized Unit								
1	3097.5	53.0	3044.5	3049.5	3047.0	-5.0	3257.5	210.5
2	2943.0	42.0	2901.0	2906.5	2903.8	-5.5	3126.0	222.3
3	3027.0	39.0	2988.0	2993.5	2990.8	-5.5	3208.0	217.3
4	2913.0	37.0	2876.0	2880.5	2878.3	-4.5	3103.0	224.8
5	3013.5	36.5	2977.0	2981.5	2979.3	-4.5	3193.5	214.3
6	3141.5	40.5	3101.0	3105.5	3103.3	-4.5	3313.0	209.8
7	3086.4	40.8	3045.6	3050.6	3048.1	-5.0	3277.5	229.4
8	2992.6	50.2	2942.4	2947.4	2944.9	-5.0	3159.4	214.5
9	3010.7	43.9	2966.8	2971.3	2969.1	-4.5	3207.0	237.9
10	3052.9	41.6	3011.3	3016.8	3014.1	-5.5	3225.0	210.9
Avg	3027.8	42.5	2985.4	2990.3	2987.8	-5.0	3207.0	219.1
Aircrete Brick Sized Unit								
1	918.0	43.0	875.0	883.5	879.3	-8.5	1257.0	377.8
2	1006.5	55.0	951.5	959.0	955.3	-7.5	1343.0	387.8
3	965.0	59.0	906.0	914.5	910.3	-8.5	1313.5	403.3
4	906.5	45.5	861.0	869.5	865.3	-8.5	1258.0	392.8
5	926.5	47.5	879.0	887.0	883.0	-8.0	1291.5	408.5
6	966.5	64.0	902.5	909.0	905.8	-6.5	1287.5	381.8
7	985.3	45.9	939.4	947.4	943.4	-8.0	1339.3	395.9
8	966.2	52.3	913.9	921.4	917.7	-7.5	1323.0	405.3
9	915.6	49.5	866.1	873.6	869.9	-7.5	1269.3	399.4
10	982.3	51.3	931.0	939.0	935.0	-8.0	1335.9	400.9
Avg	953.8	51.3	902.5	910.4	906.5	-7.9	1301.8	395.3

Appendix B.4 – Compressive Strength

Experimental Data - Compresive Strength
According to: EN 772-1:2000

Unit No	Units Mean Dimensions			Area	Compressive Strength		
	Length	Depth	Height	L x D	Weight	Load	Stress
	mm	mm	mm	mm²	g	N	N/mm²
Red Brick Unit							
1	216.0	105.4	65.0	19613.6	2516.0	1413.0	72.04
2	217.0	104.4	64.7	19502.0	2499.0	1410.0	72.30
3	218.0	104.8	65.6	19693.5	2509.0	1499.0	76.12
4	217.2	103.9	64.7	19414.2	2500.5	1450.0	74.69
5	214.5	103.9	64.7	19144.6	2486.0	1502.5	78.48
6	216.5	104.5	65.9	19482.3	2506.5	1490.0	76.48
7	217.0	104.4	64.9	19512.8	2499.0	1510.0	77.39
8	218.0	103.9	65.1	19508.2	2503.2	1493.0	76.53
9	217.6	104.2	65.0	19531.9	2510.0	1499.0	76.75
10	218.0	104.1	64.9	19551.8	2492.0	1509.0	77.18
Avg	217.0	104.3	65.0	19495.5	2502.1	1477.6	75.8
Yellow Brick Unit							
1	215.8	101.5	65.5	18123.0	1949.5	623.3	34.39
2	216.0	101.2	65.2	18078.5	1940.5	574.5	31.78
3	216.0	100.9	65.2	18013.7	1922.0	502.6	27.90
4	215.7	102.1	65.5	18253.1	1946.0	533.7	29.24
5	215.0	101.2	65.7	17977.3	1914.0	534.0	29.70
6	216.6	100.8	65.8	18063.4	1921.5	461.8	25.57
7	215.9	100.5	65.2	17928.0	1920.0	615.3	34.32
8	215.0	101.1	65.9	17966.6	1916.5	593.6	33.04
9	215.6	100.5	65.4	17897.9	1940.0	611.3	34.15
10	216.0	100.7	65.2	17981.3	1936.0	620.6	34.51
Avg	215.8	101.0	65.4	18028.3	1930.6	567.1	31.5
Concrete Brick Sized Unit							
1	215.0	100.9	65.9	21693.5	3047.0	846.6	39.03
2	215.0	99.4	65.5	21360.3	2905.0	580.9	27.20
3	215.0	100.7	65.2	21639.8	2992.0	667.9	30.86
4	215.0	99.9	65.4	21467.8	2879.5	502.9	23.43
5	215.5	100.3	65.7	21603.9	2980.0	622.8	28.83
6	215.0	103.1	65.7	22166.5	3103.0	772.4	34.85
7	215.0	100.0	65.2	21500.0	2993.0	698.4	32.48
8	215.0	101.9	65.9	21908.5	3010.3	706.9	32.27
9	215.5	100.5	65.8	21657.8	3044.0	813.5	37.56
10	215.0	100.8	65.3	21672.0	2991.8	825.2	38.08
Avg	215.1	100.7	65.5	21667.0	2994.6	703.8	32.5
Aircrete Brick Sized Unit							
1	211.8	98.1	64.1	20777.6	893.5	92.5	4.45
2	212.0	99.7	64.2	21125.8	874.5	81.2	3.84
3	212.0	101.1	64.1	21433.2	857.5	75.8	3.54
4	212.0	96.5	64.1	20447.4	902.0	95.4	4.67
5	211.5	99.2	64.2	20980.8	945.5	90.1	4.29
6	212.0	100.0	64.0	21189.4	872.5	106.2	5.01
7	212.0	96.5	64.1	20447.4	901.5	90.6	4.43
8	212.0	99.2	64.2	21030.4	886.9	89.4	4.25
9	211.5	99.2	64.0	20980.8	897.6	96.7	4.61
10	211.8	98.1	64.1	20777.6	901.3	102.9	4.95
Avg	211.9	98.7	64.1	20919.0	893.3	92.1	4.4

APPENDIX C – MORTAR – DATA

Appendix C.1 – Hard Properties – Thin Layer Mortar

TLM - 1 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.19	0.23	0.19	-	-	-	0.20	0.03	0.12
PRISM	N/mm^2	0.16	0.17	0.16	-	-	-	0.17	0.00	0.02
PRISM ENDS	N/mm^2	3.1	3.1	3.1	3.3	3.5	3.7	3.30	0.25	0.08
CUBE	N/mm^2	1.5	2.0	1.9	-	-	-	1.80	0.26	0.14

TLM - 3 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.51	0.49	0.50	-	-	-	0.50	0.01	0.03
PRISM	N/mm^2	0.57	0.46	0.47	-	-	-	0.50	0.06	0.13
PRISM ENDS	N/mm^2	5.0	5.1	4.5	4.4	4.2	4.7	4.65	0.35	0.08
CUBE	N/mm^2	2.2	2.5	1.9	-	-	-	2.22	0.30	0.13

TLM - 7 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	1.10	1.10	1.04	-	-	-	1.08	0.04	0.04
PRISM	N/mm^2	0.98	1.02	0.86	-	-	-	0.95	0.08	0.09
PRISM ENDS	N/mm^2	7.4	7.6	7.4	6.7	8.0	7.5	7.43	0.42	0.06
CUBE	N/mm^2	5.4	5.2	6.8	-	-	-	5.79	0.85	0.15

TLM - 28 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	1.36	1.25	1.32	1.28	1.53	-	1.35	0.11	0.08
PRISM	N/mm^2	1.32	1.36	1.35	-	-	-	1.34	0.02	0.02
PRISM ENDS	N/mm^2	14.6	14.8	15.9	15.7	16.1	16.5	15.60	0.75	0.05
CUBE	N/mm^2	15.9	15.1	14.2	12.4	12.7	-	15.04	0.87	0.06

Appendix C.2 – Hard Properties – Natural Hydraulic Lime

NHL MORTAR 91 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.51	0.49	0.52	-	-	-	0.51	0.02	0.03
PRISM	N/mm^2	0.41	0.40	0.45	-	-	-	0.42	0.02	0.06
PRISM ENDS	N/mm^2	1.30	1.40	1.40	1.40	1.50	1.50	1.42	0.08	0.05
CUBE	N/mm^2	1.30	1.20	1.20	-	-	-	1.23	0.06	0.05

NHL MORTAR 273 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.64	0.64	0.59	-	-	-	0.62	0.03	0.05
PRISM	N/mm^2	0.57	0.61	0.56	-	-	-	0.58	0.02	0.04
PRISM ENDS	N/mm^2	2.10	2.13	2.47	2.53	2.50	2.59	2.39	0.21	0.09
CUBE	N/mm^2	2.20	2.00	2.13	-	-	-	2.11	0.10	0.05

NHL MORTAR 365 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.70	0.80	0.53	-	-	-	0.68	0.14	0.20
PRISM	N/mm^2	0.59	0.72	0.62	-	-	-	0.64	0.07	0.11
PRISM ENDS	N/mm^2	2.26	2.76	2.33	2.35	3.04	2.76	2.58	0.31	0.12
CUBE	N/mm^2	2.22	2.56	2.12				2.30	0.23	0.10

Appendix C.3 – Hard Properties – Ordinary Portland Cement

OPC MORTAR - 273 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.77	0.68	0.82	-	-	-	0.76	0.07	0.10
PRISM	N/mm^2	0.70	0.72	0.65	-	-	-	0.69	0.04	0.05
PRISM ENDS	N/mm^2	4.62	4.86	4.08	4.95	4.61	4.20	4.55	0.35	0.08
CUBE	N/mm^2	3.74	3.94	3.95	-	-	-	3.88	0.12	0.03

OPC MORTAR - 365 DAY		1	2	3	4	5	6	Mean	Stdev	COV
DOG BONE	N/mm^2	0.93	0.73	0.88	-	-	-	0.85	0.10	0.12
PRISM	N/mm^2	0.92	0.81	0.60	-	-	-	0.78	0.16	0.21
PRISM ENDS	N/mm^2	4.33	4.30	4.51	5.22	4.95	4.74	4.68	0.36	0.08
CUBE	N/mm^2	4.06	4.21	4.10	-	-	-	4.12	0.08	0.02

Appendix C.4 – Wet Properties – Plunger Penetration

PLUNGER PENETRATION BSEN 1015-5:1999	Reading (mm)			Mean	STDEV	COV
	1	2	3			
NHL						
91 DAY	13	13	13	13	0.00	0.00
273 DAY	13	13	13	13	0.00	0.00
365 DAY	14	13	13	13	0.58	0.04
OVERALL				**13**	0.19	0.01
OPC						
273 DAY	13	13	13	13	0.00	0.00
365 DAY	8	8	8	8	0.00	0.00
OVERALL				**11**	0.00	0.00
TLM						
1 DAY	2.9	2.6	2.8	3	0.15	0.06
3 DAY	2.9	2.6	2.8	3	0.15	0.06
7 DAY	3.0	2.9	2.8	3	0.10	0.03
28 DAY	3.2	2.9	3.0	3	0.15	0.05
OVERALL				**3**	0.14	0.05

Appendix C.5 – Wet Properties – Flow Table BS4551

FLOW TABLE BS 4551-1:1998	Reading (mm)				Mean	STDEV	COV	% Flow
	1	2	3	4				
NHL								
91 DAY	198	199	197	198	198	0.82	0.00	96
273 DAY	198	199	197	198	198	0.82	0.00	96
365 DAY	196	196	196	197	196	0.50	0.00	94
OVERALL					**197**	0.71	0.00	**95**
OPC								
273 DAY	190	186	187	190	188	2.06	0.01	86
365 DAY	176	175	176	177	176	0.82	0.00	74
OVERALL					**182**	1.44	0.01	**80**
TLM								
1 DAY	235	230	240	220	231	8.54	0.04	129
3 DAY	235	230	240	220	231	8.54	0.04	129
7 DAY	190	187	175	185	184	6.50	0.04	82
28 DAY	187	188	188	189	188	0.82	0.00	86
OVERALL					**201**	5.29	0.03	**99**

Appendix C.6 – Wet Properties – Flow Table BSEN 1015-3

FLOW TABLE BSEN 1015-3:1999	Reading (mm)				Mean	STDEV	COV	% Flow
	1	2	3	4				
TLM								
1 DAY	215	212	210	208	211	2.99	0.01	109
3 DAY	218	217	209	205	212	6.29	0.03	110
7 DAY	215	204	217	220	214	6.98	0.03	112
28 DAY	194	210	198	199	200	6.85	0.03	98
OVERALL					**209**	6.71	0.03	**107**

Appendix C.7 – Wet Properties – Dropping Ball BS4551

DROPPING BALL BS 4551-1:1998	Reading (mm)			Mean	STDEV	COV
	1	2	3			
NHL						
91 DAY	13	13	13	13	0.00	0.00
273 DAY	13	13	13	13	0.00	0.00
365 DAY	14	13	13	13	0.58	0.04
OVERALL				**13**	0.19	0.01
OPC						
273 DAY	13	13	13	13	0.00	0.00
365 DAY	10	10	9	10	0.58	0.06
OVERALL				**11**	0.29	0.03
TLM						
1 DAY	10	11	11	11	0.46	0.04
3 DAY	10	10	10	10	0.21	0.02
7 DAY	10	11	11	11	0.46	0.04
28 DAY	12	12	11	12	0.58	0.05
OVERALL				**11**	0.43	0.04

APPENDIX D – COUPLETS (BOND WRENCH) – DATA

ABREVIATIONS & SPECIFICATIONS

Symbol	Units	Description
e_1	mm	Distance of applied load to tension face (mm)
e_2	mm	Distance from centre of gravity of lever/clamp to tension face (mm)
W	N	Weight of masonry unit and any adherent mortar pulled off of specimen (N)
F_1	N	Applied Load N
F_2	N	Weight of lever / clamp N
f_{wi}	N/mm^2	Individual bond strength N/mm^2
f_w	N/mm^2	Mean bond strength N/mm^2
f_{wk}	N/mm^2	Characteristic bond strength N/mm^2
d	mm	Mean depth of specimen
b	mm	Mean width of the bed joint tested
Z	mm^3	Section modulus of the projected plan area of the failure surface
T	g	Top
B	g	Bottom
BEF	g	Before Test
STDEV	-	Standard Deviation
COV	-	Coefficient of Variation

Key Values		
e_1	800	mm
e_2	51	mm
F_2	96	N
k	1.92	-

$$f_{wi} = \frac{F_1 e_1 + F_2 e_2 - \frac{2}{3} d \left(F_1 + F_2 + W/4\right)}{Z}$$

$$where\ Z = \frac{bd^2}{6}$$

Appendix D.1 – Thin Layer Mortar

SUMMARY SHEET
THIN LAYER MORTAR - COUPLETS (BOND WRENCH)

TEST DATA

MEAN FAILURE STRENGTH					
Unit \ Day	1	3	7	28	56
RED	85.50	291.50	415.50	325.00	429.17
YELLOW	79.50	157.50	286.50	330.00	399.50
CONCRETE	239.40	350.50	319.50	479.58	517.00
AIRCRETE	117.50	154.50	159.00	163.00	174.50

STANDARD DEVIATION FAILURE STRENGTH					
Unit \ Day	1	3	7	28	56
RED	11.41	54.27	73.95	28.96	50.69
YELLOW	11.89	35.06	92.02	90.28	35.31
CONCRETE	26.61	73.58	27.02	45.15	43.98
AIRCRETE	20.31	22.79	15.24	13.37	25.54

COEFFICIENT OF VARIATION FAILURE STRENGTH					
Unit \ Day	1	3	7	28	56
RED	0.13	0.19	0.18	0.09	0.12
YELLOW	0.15	0.22	0.32	0.27	0.09
CONCRETE	0.11	0.21	0.08	0.09	0.09
AIRCRETE	0.17	0.15	0.10	0.08	0.15

CHARACTERISTICS

CHARACTERISTIC BOND STRENGTH LOG NORMAL METHOD					
Unit \ Day	1	3	7	28	56
RED	0.19	0.64	0.73	0.86	1.11
YELLOW	0.20	0.32	0.47	0.57	1.00
CONCRETE	0.60	0.70	0.86	1.02	1.01
AIRCRETE	0.24	0.25	0.26	0.28	0.25

CHARACTERISTIC BOND STRENGTH NORMAL METHOD					
Unit \ Day	1	3	7	28	56
RED	0.20	0.67	0.74	0.87	1.12
YELLOW	0.20	0.33	0.44	0.55	1.02
CONCRETE	0.61	0.71	0.87	1.04	1.05
AIRCRETE	0.24	0.24	0.27	0.28	0.23

(hatched) Denotes total unit failure

DATA ANALYSIS

MEAN INDIVIDUAL BOND STRENGTH					
Unit \ Day	1	3	7	28	56
RED	0.26	0.91	1.13	1.03	1.36
YELLOW	0.26	0.49	0.84	0.96	1.15
CONCRETE	0.70	1.08	1.01	1.26	1.43
AIRCRETE	0.35	0.42	0.32	0.33	0.33

STANDARD DEVIATION INDIVIDUAL BOND STRENGTH					
Unit \ Day	1	3	7	28	56
RED	0.04	0.15	0.24	0.10	0.15
YELLOW	0.04	0.10	0.24	0.25	0.08
CONCRETE	0.06	0.23	0.08	0.13	0.23
AIRCRETE	0.07	0.11	0.03	0.03	0.06

COEFFICIENT OF VARIATION INDIVIDUAL BOND STRENGTH					
Unit \ Day	1	3	7	28	56
RED	0.14	0.16	0.21	0.10	0.11
YELLOW	0.14	0.20	0.29	0.26	0.07
CONCRETE	0.08	0.21	0.08	0.11	0.16
AIRCRETE	0.19	0.25	0.10	0.08	0.17

Log_{10} OF BOND STRENGTH = Y_{mean}					
Unit \ Day	1	3	7	28	56
RED	-0.59	-0.04	0.05	0.01	0.13
YELLOW	-0.59	-0.31	-0.08	-0.02	0.06
CONCRETE	-0.15	0.03	0.00	0.10	0.16
AIRCRETE	-0.45	-0.38	-0.49	-0.48	-0.49

STDEV - Log_{10} OF BOND STRENGTH = Y_{mean}					
Unit \ Day	1	3	7	28	56
RED	0.06	0.08	0.09	0.04	0.04
YELLOW	0.06	0.09	0.12	0.11	0.03
CONCRETE	0.04	0.09	0.03	0.04	0.08
AIRCRETE	0.08	0.11	0.04	0.04	0.07

C.O.V % - Log_{10} OF BOND STRENGTH					
Unit \ Day	1	3	7	28	56
RED	13.70	16.18	20.97	9.63	10.78
YELLOW	13.95	20.09	29.01	25.87	7.10
CONCRETE	8.16	21.26	8.29	10.61	16.17
AIRCRETE	18.90	25.39	9.73	8.35	17.25

RED BRICK - THIN LAYER MORTAR

1 DAY - TLM

BUILD DATE					TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005								
28 November 2005					29 November 2005				1									
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
			T	B														
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	135	5264	2563	2700	84	2	**A1/A4**	**105**	84	215	800	51	25.14	105	96	252840.0	**0.31**	-0.51
2	134	5122	2509	2613	78	2	**A1**	**80**	78	215	800	51	24.61	80	96	218010.0	**0.27**	-0.56
3	134	5164	2519	2643	84	2	**A1**	**90**	84	215	800	51	24.71	90	96	252840.0	**0.26**	-0.58
4	132	5203	2546	2659	82	2	**A1**	**95**	82	215	800	51	24.98	95	96	240943.3	**0.29**	-0.54
5	134	5173	2568	2604	85	2	**A4**	**65**	85	215	800	51	25.19	65	96	258895.8	**0.18**	-0.74
6	132	5206	2529	2679	84	2	**A1**	**95**	84	215	800	51	24.81	95	96	252840.0	**0.28**	-0.56
7	133	5235	2563	2673	82	2	**A1**	**75**	82	215	800	51	25.14	75	96	240943.3	**0.23**	-0.64
8	132	5158	2581	2576	80	2	**A1**	**85**	80	215	800	51	25.32	85	96	229333.3	**0.27**	-0.56
9	132	5154	2519	2640	84	2	**A1**	**80**	84	215	800	51	24.71	80	96	252840.0	**0.23**	-0.63
10	132	5107	2515	2593	81	2	**A1**	**85**	81	215	800	51	24.67	85	96	235102.5	**0.27**	-0.57
MEAN		5179	2541	2638	**MEAN**			**85.50**	Red						**MEAN**		**0.26**	-0.59
					STDEV			**11.41**							**STDEV**		**0.04**	0.06
					COV			**0.13**							**COV**		**0.14**	-0.11
															CHARACTERISTIC STRENGTH			0.19

RED BRICK - THIN LAYER MORTAR

3 DAY - TLM

BUILD DATE				TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
29 November 2005				02 December 2005				3										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	5126	2499	2631	85	2	**A1**	**380**	85	215	800	51	24.52	380	96	258895.8	**1.09**	0.04
2	132	5218	2591	2625	85	2	**A1**	**310**	85	215	800	51	25.42	310	96	258895.8	**0.89**	-0.05
3	133	5145	2532	2614	79	2	**A1**	**290**	79	215	800	51	24.84	290	96	223635.8	**0.97**	-0.01
4	132	5150	2491	2658	81	2	**A1**	**270**	81	215	800	51	24.44	270	96	235102.5	**0.85**	-0.07
5	132	5103	2519	2584	80	2	**A1**	**330**	80	215	800	51	24.71	330	96	229333.3	**1.07**	0.03
6	132	5253	2608	2645	80	2	**A1**	**280**	80	215	800	51	25.58	280	96	229333.3	**0.91**	-0.04
7	132	5289	2556	2733	82	2	**A4/A3**	**340**	82	215	800	51	25.07	340	96	240943.3	**1.05**	0.02
8	132	5276	2667	2608	80	2	**A1**	**180**	80	215	800	51	26.16	180	96	229333.3	**0.58**	-0.23
9	132	5223	2522	2699	80	2	**A1/A4**	**255**	80	215	800	51	24.74	255	96	229333.3	**0.83**	-0.08
10	132	5429	2618	2813	80	2	**A1**	**280**	80	215	800	51	25.68	280	96	229333.3	**0.91**	-0.04
MEAN		5221	2560	2661	**MEAN**			**291.50**	Red						**MEAN**		**0.91**	-0.04
					STDEV			**54.27**							**STDEV**		**0.15**	0.08
					COV			**0.19**							**COV**		**0.16**	-1.76
															CHARACTERISTIC STRENGTH			0.64

RED BRICK - THIN LAYER MORTAR

7 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
24 October 2005					31 October 2005			7										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	133	5288	2525	2758	95	2	**A1/A4**	**320**	95	215	800	51	24.77	320	96	323395.8	**0.72**	-0.14
2	132	5281	2533	2748	95	2	**A1**	**440**	95	215	800	51	24.85	440	96	323395.8	**1.00**	0.00
3	132	5241	2534	2708	88	2	**A1**	**455**	88	215	800	51	24.86	455	96	277493.3	**1.21**	0.08
4	132	5118	2530	2587	89	2	**A1/A4**	**355**	89	215	800	51	24.82	355	96	283835.8	**0.92**	-0.04
5	134	5166	2536	2627	90	2	**A1/A4**	**455**	90	215	800	51	24.88	455	96	290250.0	**1.16**	0.06
6	132	5112	2467	2640	82	2	**A1**	**490**	82	215	800	51	24.20	490	96	240943.3	**1.51**	0.18
7	132	5184	2519	2667	85	2	**A1/A7**	**500**	85	215	800	51	24.71	500	96	258895.8	**1.43**	0.16
8	132	5202	2528	2675	80	2	**A1**	**355**	80	215	800	51	24.80	355	96	229333.3	**1.15**	0.06
9	133	5110	2501	2607	91	2	**A1/A4**	**480**	91	215	800	51	24.53	480	96	296735.8	**1.19**	0.08
10	132	5182	2520	2664	81	2	**A1**	**305**	81	215	800	51	24.72	305	96	235102.5	**0.97**	-0.02
MEAN		5188	2519	2668	**MEAN**			**415.50**	Red						**MEAN**		**1.13**	0.04
					STDEV			**73.95**							**STDEV**		**0.24**	0.09
					COV			**0.18**							**COV**		**0.21**	2.20
															CHARACTERISTIC STRENGTH			0.73

RED BRICK - THIN LAYER MORTAR

28 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
01 November 2005					29 November 2005			28										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	5095	2507	2588	82	2	**A1 / A4**	**290**	82	215	800	51	24.59	290	96	240943.3	**0.89**	-0.05
2	132	5230	2540	2690	82	2	**A1 / A4**	**360**	82	215	800	51	24.92	360	96	240943.3	**1.11**	0.05
3	132	5169	2548	2621	79	2	**A1 / A4**	**330**	79	215	800	51	25.00	330	96	223635.8	**1.10**	0.04
4	132	5181	2528	2653	81	2	**A4 / A1**	**375**	81	215	800	51	24.80	375	96	235102.5	**1.19**	0.07
5	132	5195	2547	2648	80	2	**A1 / A4**	**300**	80	215	800	51	24.99	300	96	229333.3	**0.97**	-0.01
6	132	5171	2515	2656	80	2	**A1**	**355**	80	215	800	51	24.67	355	96	229333.3	**1.15**	0.06
7	132	5213	2576	2637	82	2	**A1**	**305**	82	215	800	51	25.27	305	96	240943.3	**0.94**	-0.03
8	132	5204	2516	2688	80	2	**A1 / A4**	**310**	80	215	800	51	24.68	310	96	229333.3	**1.01**	0.00
9	132	5178	2558	2620	80	2	**A1 / A4**	**320**	80	215	800	51	25.09	320	96	229333.3	**1.04**	0.02
10	132	5107	2480	2627	82	2	**A1**	**305**	82	215	800	51	24.33	305	96	240943.3	**0.94**	-0.03
MEAN		5174	2532	2643	**MEAN**			**325.00**	Red						**MEAN**		**1.03**	0.01
					STDEV			**28.96**							**STDEV**		**0.10**	0.04
					COV			**0.09**							**COV**		**0.10**	3.19
															CHARACTERISTIC STRENGTH			0.86

RED BRICK - THIN LAYER MORTAR

56 DAY - TLM

BUILD DATE	TEST DATE	DAY	Bond Wrench Test - According to: BS EN 1052-5:2005
24 October 2005	19 December 2005	**56**	

BW	H	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W	Mean Joint H	Failure Mode	Failure N	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	5213	2559	2654	81	2	**A1**	**429**	81	215	800	51	25.10	429	96	235102.5	**1.36**	0.13
2	132	5257	2543	2714	80	2	**A1**	**429**	80	215	800	51	24.95	429	96	229333.3	**1.39**	0.14
3	132	5275	2528	2747	83	2	**A1**	**429**	83	215	800	51	24.80	429	96	246855.8	**1.29**	0.11
4	132	5269	2547	2722	79	2	**A1**	**429**	79	215	800	51	24.99	429	96	223635.8	**1.43**	0.16
5	132	5200	2515	2685	78	2	**A1**	**360**	78	215	800	51	24.67	360	96	218010.0	**1.23**	0.09
6	132	5284	2536	2747	80	2	**A1**	**420**	80	215	800	51	24.88	420	96	229333.3	**1.37**	0.14
7	132	5252	2562	2689	82	2	**A1**	**380**	82	215	800	51	25.13	380	96	240943.3	**1.17**	0.07
8	132	5333	2594	2737	83	2	**A1**	**430**	83	215	800	51	25.45	430	96	246855.8	**1.29**	0.11
9	132	5167	2525	2642	82	2	**A1 / A4**	**555**	82	215	800	51	24.77	555	96	240943.3	**1.71**	0.23
10	132	5370	2595	2773	82	2	**A1**	**430**	82	215	800	51	25.46	430	96	240943.3	**1.33**	0.12
MEAN		5262	2550	2711			**MEAN**	**429.17**	Red							**MEAN**	**1.36**	0.13
							STDEV	**50.69**								**STDEV**	**0.15**	0.04
							COV	**0.12**								**COV**	**0.11**	0.34
																CHARACTERISTIC STRENGTH		1.11

YELLOW BRICK - THIN LAYER MORTAR

1 DAY - TLM

BUILD DATE					TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
03 November 2005					04 November 2005				1										
BW	H	Weight (g)			Mean Joint		Failure			Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H				d	b								
	mm		T	B	mm	mm	Mode		N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	3969	1931	2036	79	2	**A1**		**60**	79	215	800	51	18.94	60	96	223635.83	**0.20**	-0.70
2	133	3951	1957	1995	76	2	**A1**		**75**	76	215	800	51	19.20	75	96	206973.33	**0.27**	-0.57
3	130	4028	1946	2080	82	2	**A1**		**80**	82	215	800	51	19.09	80	96	240943.33	**0.25**	-0.61
4	132	3987	1935	2049	80	2	**A1**		**70**	80	215	800	51	18.98	70	96	229333.33	**0.23**	-0.65
5	134	4029	1961	2070	80	2	**A1**		**100**	80	215	800	51	19.24	100	96	229333.33	**0.32**	-0.49
6	131	4001	1949	2053	80	2	**A1**		**80**	80	215	800	51	19.12	80	96	229333.33	**0.26**	-0.59
7	132	4014	1941	2069	79	2	**A1/A4**		**80**	79	215	800	51	19.04	80	96	223635.83	**0.27**	-0.58
8	132	4027	1965	2066	83	2	**A1**		**85**	83	215	800	51	19.28	85	96	246855.83	**0.25**	-0.60
9	130	4027	1959	2070	81	2	**A1**		**95**	81	215	800	51	19.22	95	96	235102.50	**0.30**	-0.52
10	131	3975	1969	2008	79	2	**A1**		**70**	79	215	800	51	19.32	70	96	223635.83	**0.23**	-0.63
MEAN		4001	1951	2050	**MEAN**				**79.50**	Yellow						**MEAN**		**0.26**	-0.59
					STDEV				**11.89**							**STDEV**		**0.04**	0.06
					COV				**0.15**							**COV**		**0.14**	-0.10
																CHARACTERISTIC STRENGTH			0.20

YELLOW BRICK - THIN LAYER MORTAR

3 DAY - TLM

BUILD DATE					TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005								
29 November 2005					02 December 2005				3									
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	131	3968	1949	2019	84	2	**A1**	**155**	84	215	800	51	19.12	155	96	252840.00	**0.45**	-0.34
2	133	3903	1956	1947	80	2	**A1**	**100**	80	215	800	51	19.19	100	96	229333.33	**0.32**	-0.49
3	132	3997	1962	2035	84	2	**A1**	**175**	84	215	800	51	19.25	175	96	252840.00	**0.51**	-0.29
4	134	3945	1961	1984	82	2	**A1 / A4**	**185**	82	215	800	51	19.24	185	96	240943.33	**0.57**	-0.24
5	133	3922	1956	1966	80	2	**A4**	**165**	80	215	800	51	19.19	165	96	229333.33	**0.54**	-0.27
6	131	4002	1964	2038	80	2	**A1**	**135**	80	215	800	51	19.27	135	96	229333.33	**0.44**	-0.36
7	132	3950	1964	1986	79	2	**A1**	**110**	79	215	800	51	19.27	110	96	223635.83	**0.37**	-0.44
8	132	3952	1930	2022	80	2	**A1**	**150**	80	215	800	51	18.93	150	96	229333.33	**0.49**	-0.31
9	132	3919	1923	1996	80	2	**A1 / A4**	**190**	80	215	800	51	18.86	190	96	229333.33	**0.62**	-0.21
10	130	4025	1962	2063	84	2	**A1**	**210**	84	215	800	51	19.25	210	96	252840.00	**0.62**	-0.21
MEAN		3958	1953	2006	**MEAN**			**157.50**	Yellow						**MEAN**		**0.49**	-0.32
					STDEV			**35.06**							**STDEV**		**0.10**	0.09
					COV			**0.22**							**COV**		**0.20**	-0.29
															CHARACTERISTIC STRENGTH			0.32

YELLOW BRICK - THIN LAYER MORTAR

7 DAY - TLM

BUILD DATE	TEST DATE	DAY	
24 October 2005	31 October 2005	7	Bond Wrench Test - According to: BS EN 1052-5:2005

BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	130	3965	1964	2000	85	2	**A4**	**425**	85	215	800	51	19.27	425	96	258895.83	**1.22**	0.09
2	131	4029	1942	2089	80	2	**A1**	**250**	80	215	800	51	19.05	250	96	229333.33	**0.81**	-0.09
3	131	4038	1981	2057	88	2	**A1**	**475**	88	215	800	51	19.43	475	96	277493.33	**1.27**	0.10
4	130	4062	1952	2108	82	2	**A1**	**300**	82	215	800	51	19.15	300	96	240943.33	**0.93**	-0.03
5	132	4046	1928	2119	85	2	**A1**	**200**	85	215	800	51	18.91	200	96	258895.83	**0.57**	-0.24
6	130	4028	1926	2101	87	2	**A1**	**200**	87	215	800	51	18.89	200	96	271222.50	**0.54**	-0.26
7	131	4075	1946	2129	89	2	**A1**	**275**	89	215	800	51	19.09	275	96	283835.83	**0.71**	-0.15
8	132	4037	1932	2106	81	2	**A1**	**240**	81	215	800	51	18.95	240	96	235102.50	**0.76**	-0.12
9	132	4050	1965	2083	80	2	**A1**	**255**	80	215	800	51	19.28	255	96	229333.33	**0.83**	-0.08
10	131	4108	1955	2150	84	2	**A1**	**245**	84	215	800	51	19.18	245	96	252840.00	**0.72**	-0.14
MEAN		4044	1949	2094			**MEAN**	**286.50**	Yellow							**MEAN**	**0.84**	-0.09
							STDEV	**92.02**								**STDEV**	**0.24**	0.12
							COV	**0.32**								**COV**	**0.29**	-1.29
																CHARACTERISTIC STRENGTH		0.47

YELLOW BRICK - THIN LAYER MORTAR

28 DAY - TLM

BUILD DATE: 01 November 2005 | TEST DATE: 29 November 2005 | DAY: **28**

Bond Wrench Test - According to: BS EN 1052-5:2005

BW	H (mm)	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W (mm)	Mean Joint H (mm)	Failure Mode	Failure N	Mortar d (mm)	Mortar b (mm)	e_1 (mm)	e_2 (mm)	w (N)	F_1 (N)	F_2 (N)	z ($bd^2/6$)	fwi (N/mm^2)	Y_i (Log_{10})
1	132	4030	1958	2071	85	2	**A1**	**205**	85	215	800	51	19.21	205	96	258895.83	**0.59**	-0.23
2	130	4074	1963	2111	86	2	**A1**	**430**	86	215	800	51	19.26	430	96	265023.33	**1.20**	0.08
3	131	4036	1959	2076	83	2	**A1**	**305**	83	215	800	51	19.22	305	96	246855.83	**0.92**	-0.04
4	132	3968	1959	2006	80	2	**A1**	**255**	80	215	800	51	19.22	255	96	229333.33	**0.83**	-0.08
5	131	4029	1963	2067	86	2	**A1/A7**	**305**	86	215	800	51	19.26	305	96	265023.33	**0.85**	-0.07
6	131	4068	1953	2113	87	2	**A1/A7**	**490**	87	215	800	51	19.16	490	96	271222.50	**1.34**	0.13
7	132	4062	1968	2094	84	2	**A1**	**305**	84	215	800	51	19.31	305	96	252840.00	**0.89**	-0.05
8	133	4145	1949	2199	82	2	**A1**	**310**	82	215	800	51	19.12	310	96	240943.33	**0.96**	-0.02
9	132	4072	1943	2127	82	2	**A1/A7**	**430**	82	215	800	51	19.06	430	96	240943.33	**1.33**	0.12
10	131	4074	1966	2109	86	2	**A1**	**265**	86	215	800	51	19.29	265	96	265023.33	**0.74**	-0.13
MEAN		4056	1958	2097	**MEAN**			**330.00**	Yellow						**MEAN**		**0.96**	-0.03
					STDEV			**90.28**							**STDEV**		**0.25**	0.11
					COV			**0.27**							**COV**		**0.26**	-3.89
															CHARACTERISTIC STRENGTH			0.57

YELLOW BRICK - THIN LAYER MORTAR

56 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005										
24 October 2005					19 December 2005			56											
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	4029	1927	2102	85	2	**A1**	**440**	85	215	800	51	18.90	440	96	258895.83	**1.26**	0.10
2	131	4054	1929	2125	88	2	**A1**	**450**	88	215	800	51	18.92	450	96	277493.33	**1.20**	0.08
3	132	4063	1943	2121	85	2	**A1**	**390**	85	215	800	51	19.06	390	96	258895.83	**1.12**	0.05
4	132	3964	1945	2019	84	2	**A1**	**380**	84	215	800	51	19.08	380	96	252840.00	**1.12**	0.05
5	132	4012	1942	2068	90	2	**A1**	**420**	90	215	800	51	19.05	420	96	290250.00	**1.07**	0.03
6	132	4045	1927	2118	85	2	**A1**	**420**	85	215	800	51	18.90	420	96	258895.83	**1.20**	0.08
7	132	4002	1953	2048	88	2	**A1**	**410**	88	215	800	51	19.16	410	96	277493.33	**1.09**	0.04
8	131	3968	1903	2064	83	2	**A1**	**340**	83	215	800	51	18.67	340	96	246855.83	**1.02**	0.01
9	131	3975	1934	2040	80	2	**A1**	**355**	80	215	800	51	18.97	355	96	229333.33	**1.15**	0.06
10	132	3982	1933	2049	80	2	**A1**	**390**	80	215	800	51	18.96	390	96	229333.33	**1.27**	0.10
MEAN		4009	1934	2075	**MEAN**			**399.50**	Yellow						**MEAN**		**1.15**	0.06
					STDEV			**35.31**							**STDEV**		**0.08**	0.03
					COV			**0.09**							**COV**		**0.07**	0.52
															CHARACTERISTIC STRENGTH			1.00

CONCRETE BRICK - THIN LAYER MORTAR

1 DAY - TLM

BUILD DATE			TEST DATE				DAY		Bond Wrench Test - According to: BS EN 1052-5:2005									
03 November 2005			04 November 2005				1											
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
			T	B														
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	133	6330	3146	3184	87	2	**A4**	**255**	87	215	800	51	30.86	255	96	271222.50	**0.69**	-0.16
2	132	6355	3189	3167	86	2	**A4**	**255**	86	215	800	51	31.28	255	96	265023.33	**0.71**	-0.15
3	132	6422	3156	3267	85	2	**A4**	**264**	85	215	800	51	30.96	264	96	258895.83	**0.75**	-0.12
4	133	6177	3083	3097	85	2	**A4**	**245**	85	215	800	51	30.24	245	96	258895.83	**0.70**	-0.16
5	131	6133	3050	3079	78	2	**A1/A4**	**180**	78	215	800	51	29.92	180	96	218010.00	**0.62**	-0.21
6	132	6239	3159	3081	82	2	**A4**	**215**	82	215	800	51	30.99	215	96	240943.33	**0.66**	-0.18
7	134	6328	3064	3264	85	2	**A2/A4**	**255**	85	215	800	51	30.06	255	96	258895.83	**0.73**	-0.14
8	132	6281	3079	3205	85	2	**A1/A3**	**225**	85	215	800	51	30.20	225	96	258895.83	**0.64**	-0.19
9	132	6297	3114	3179	82	2	**A4**	**265**	82	215	800	51	30.55	265	96	240943.33	**0.82**	-0.09
10	132	6276	3114	3168	82	2	**A4**	**235**	82	215	800	51	30.55	235	96	240943.33	**0.72**	-0.14
MEAN		6284	3115	3169	**MEAN**			**239.40**	Concrete						**MEAN**		**0.70**	-0.15
					STDEV			**26.61**							**STDEV**		**0.06**	0.04
					COV			**0.11**							**COV**		**0.08**	-0.23
															CHARACTERISTIC STRENGTH			0.60

CONCRETE BRICK - THIN LAYER MORTAR

3 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
29 November 2005					02 December 2005			3										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	133	6368	3182	3188	87	2	**A1**	**490**	87	215	800	51	31.22	490	96	271222.50	**1.34**	0.13
2	130	6049	2996	3051	83	2	**A1**	**305**	83	215	800	51	29.39	305	96	246855.83	**0.92**	-0.04
3	134	6029	2998	3027	80	2	**A5/A7**	**440**	80	215	800	51	29.41	440	96	229333.33	**1.43**	0.16
4	132	6195	2977	3217	78	2	**A1/A3**	**380**	78	215	800	51	29.20	380	96	218010.00	**1.30**	0.11
5	133	6245	3089	3155	80	2	**A1/A4**	**380**	80	215	800	51	30.30	380	96	229333.33	**1.23**	0.09
6	132	6065	3062	3002	82	2	**A1/A5**	**305**	82	215	800	51	30.04	305	96	240943.33	**0.94**	-0.03
7	132	6158	2966	3191	81	2	**A1**	**280**	81	215	800	51	29.10	280	96	235102.50	**0.89**	-0.05
8	131	6123	2910	3215	83	2	**A1/A5**	**255**	83	215	800	51	28.55	255	96	246855.83	**0.77**	-0.12
9	131	6301	3134	3166	85	2	**A1**	**315**	85	215	800	51	30.74	315	96	258895.83	**0.90**	-0.05
10	132	6163	3176	2985	81	2	**A1**	**355**	81	215	800	51	31.16	355	96	235102.50	**1.12**	0.05
MEAN		6170	3049	3120	**MEAN**			**350.50**	Concrete						**MEAN**		**1.08**	0.03
					STDEV			**73.58**							**STDEV**		**0.23**	0.09
					COV			**0.21**							**COV**		**0.21**	3.58
															CHARACTERISTIC STRENGTH			0.70

CONCRETE BRICK - THIN LAYER MORTAR

7 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
24 October 2005					31 October 2005			7										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	6346	3173	3173	80	2	**A1 / A4**	**320**	80	215	800	51	31.13	320	96	229333.33	**1.04**	0.02
2	132	6202	3127	3075	80	2	**A1 / A4**	**280**	80	215	800	51	30.68	280	96	229333.33	**0.91**	-0.04
3	134	6111	3047	3064	78	2	**A1 / A3**	**305**	78	215	800	51	29.89	305	96	218010.00	**1.04**	0.02
4	133	6254	3160	3094	79	2	**A1**	**315**	79	215	800	51	31.00	315	96	223635.83	**1.05**	0.02
5	132	6249	3062	3187	84	2	**A3**	**340**	84	215	800	51	30.04	340	96	252840.00	**1.00**	0.00
6	130	6331	3148	3183	84	2	**A1 / A3**	**330**	84	215	800	51	30.88	330	96	252840.00	**0.97**	-0.01
7	131	6382	3257	3125	82	2	**A4 / A1**	**310**	82	215	800	51	31.95	310	96	240943.33	**0.96**	-0.02
8	134	6297	3163	3134	80	2	**A1 / A4**	**370**	80	215	800	51	31.03	370	96	229333.33	**1.20**	0.08
9	132	6143	3057	3086	80	2	**A1**	**285**	80	215	800	51	29.99	285	96	229333.33	**0.93**	-0.03
10	131	6171	3018	3153	84	2	**A1**	**340**	84	215	800	51	29.61	340	96	252840.00	**1.00**	0.00
MEAN		6249	3121	3127	**MEAN**			**319.50**	Concrete						**MEAN**		**1.01**	0.00
					STDEV			**27.02**							**STDEV**		**0.08**	0.03
					COV			**0.08**							**COV**		**0.08**	13.91
															CHARACTERISTIC STRENGTH			0.86

CONCRETE BRICK - THIN LAYER MORTAR

28 DAY - TLM

BUILD DATE				TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
01 November 2005				29 November 2005				**28**										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	131	5929	2936	2993	90	2	**A1**	**480**	90	215	800	51	28.8	480	96	290250.00	**1.22**	0.09
2	131	6093	2939	3154	90	2	**A1**	**520**	90	215	800	51	28.83	520	96	290250.00	**1.32**	0.12
3	130	5940	2941	2998	88	2	**A1**	**540**	88	215	800	51	28.85	540	96	277493.33	**1.44**	0.16
4	131	5996	2969	3028	86	2	**A1**	**436**	86	215	800	51	29.13	435.8	96	265023.33	**1.22**	0.09
5	132	6126	2712	3008	90	2	**A1**	**430**	90	215	800	51	26.6	430	96	290250.00	**1.09**	0.04
6	131	5980	2966	3013	90	2	**A1**	**420**	90	215	800	51	29.1	420	96	290250.00	**1.07**	0.03
7	131	5988	2972	3014	88	2	**A1**	**450**	88	215	800	51	29.16	450	96	277493.33	**1.20**	0.08
8	132	6123	2966	3156	90	2	**A1**	**470**	90	215	800	51	29.1	470	96	290250.00	**1.19**	0.08
9	132	6126	2918	3206	90	2	**A1 / A5**	**530**	90	215	800	51	28.63	530	96	290250.00	**1.35**	0.13
10	132	6274	3225	3049	87	2	**A5 / A3**	**520**	87	215	800	51	31.64	520	96	271222.50	**1.42**	0.15
MEAN		6058	2954	3062	**MEAN**			**479.58**	Concrete						**MEAN**		**1.26**	0.10
					STDEV			**45.15**							**STDEV**		**0.13**	0.04
					COV			**0.09**							**COV**		**0.11**	0.46
															CHARACTERISTIC STRENGTH			1.02

CONCRETE BRICK - THIN LAYER MORTAR

56 DAY - TLM

BUILD DATE	TEST DATE	DAY	Bond Wrench Test - According to: BS EN 1052-5:2005
24 October 2005	19 December 2005	56	

BW	H	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W	Mean Joint H	Failure Mode	Failure N	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm				mm	mm		N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	132	5897	5897	n/a	100	2	**A7**	**540**	100	215	800	51	57.85	540	96	358333.33	**1.10**	0.04
2	133	6370	3106	3267	82	2	**A4/A7**	**540**	82	215	800	51	30.47	540	96	240943.33	**1.67**	0.22
3	132	6032	3084	2953	84	2	**A4/A5**	**505**	84	215	800	51	30.25	505	96	252840.00	**1.48**	0.17
4	134	6224	3271	2951	85	2	**A4/A5**	**540**	85	215	800	51	32.09	540	96	258895.83	**1.55**	0.19
5	132	5860	5860	n/a	100	2	**A7**	**610**	100	215	800	51	57.49	610	96	358333.33	**1.24**	0.09
6	132	6311	3158	3152	80	2	**A4**	**455**	80	215	800	51	30.98	455	96	229333.33	**1.48**	0.17
7	132	6211	2954	3258	78	2	**A4/A5**	**465**	78	215	800	51	28.98	465	96	218010.00	**1.59**	0.20
8	131	6046	3142	2902	80	2	**A4/A5**	**505**	80	215	800	51	30.82	505	96	229333.33	**1.64**	0.22
9	132	6293	6293	n/a	100	2	**A7**	**500**	100	215	800	51	61.73	500	96	358333.33	**1.02**	0.01
10	133	6428	3134	3293	82	2	**A3**	**510**	82	215	800	51	30.74	510	96	240943.33	**1.57**	0.20
MEAN		6167	3990	3111			**MEAN**	**517.00**	Concrete							**MEAN**	**1.43**	0.15
							STDEV	**43.98**								**STDEV**	**0.23**	0.08
							COV	**0.09**								**COV**	**0.16**	0.51
																CHARACTERISTIC STRENGTH		1.01

AIRCRETE BRICK - THIN LAYER MORTAR

1 DAY - TLM

BUILD DATE	TEST DATE	DAY	Bond Wrench Test - According to: BS EN 1052-5:2005
02 November 2005	03 November 2005	1	

BW	H	Weight (g) BEF	After T	After B	Mean Joint W	Mean Joint H	Failure Mode	Failure N	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm				mm	mm		N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	135	2347	1123	1224	82	2	**A4**	**120**	82	215	800	51	11.02	120	96	240943.33	**0.37**	-0.43
2	132	2362	1241	1130	84	2	**A4**	**90**	84	215	800	51	12.17	90	96	252840.00	**0.26**	-0.58
3	130	2361	1257	1105	78	2	**A1/A4**	**115**	78	215	800	51	12.33	115	96	218010.00	**0.39**	-0.41
4	130	2302	1156	1149	79	2	**A4**	**110**	79	215	800	51	11.34	110	96	223635.83	**0.37**	-0.44
5	131	2377	1180	1201	80	2	**A4**	**115**	80	215	800	51	11.58	115	96	229333.33	**0.37**	-0.43
6	129	2408	1208	1205	82	2	**A4/A5**	**95**	82	215	800	51	11.85	95	96	240943.33	**0.29**	-0.53
7	130	2328	1241	1087	82	2	**A1/A4**	**125**	82	215	800	51	12.17	125	96	240943.33	**0.38**	-0.41
8	129	2442	1205	1238	84	2	**A4**	**105**	84	215	800	51	11.82	105	96	252840.00	**0.31**	-0.51
9	131	2319	251	2063	100	2	**A7**	**145**	100	215	800	51	2.46	145	96	358333.33	**0.29**	-0.53
10	130	2292	1125	1170	81	2	**A1/A4**	**155**	81	215	800	51	11.04	155	96	235102.50	**0.49**	-0.31
MEAN		2354	1099	1257	**MEAN**			**117.50**	Aircrete							**MEAN**	**0.35**	-0.46
					STDEV			**20.31**								**STDEV**	**0.07**	0.08
					COV			**0.17**								**COV**	**0.19**	-0.18
																CHARACTERISTIC STRENGTH		0.24

AIRCRETE BRICK - THIN LAYER MORTAR

3 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
29 November 2005					02 December 2005			3										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	129	2079	968	1111	80	2	**A1 / A5**	**155**	80	215	800	51	9.50	155	96	229333.33	**0.50**	-0.30
2	130	2137	1010	1127	73	2	**A1 / A5**	**145**	73	215	800	51	9.91	145	96	190955.83	**0.57**	-0.24
3	132	2184	352	1832	100	2	**A7**	**175**	100	215	800	51	3.45	175	96	358333.33	**0.35**	-0.45
4	132	2105	310	1795	100	2	**A7**	**150**	100	215	800	51	3.04	150	96	358333.33	**0.30**	-0.52
5	130	2068	1073	995	90	2	**A5 / A4**	**150**	90	215	800	51	10.53	150	96	290250.00	**0.38**	-0.42
6	129	2153	1150	1003	80	2	**A4 / A3**	**150**	80	215	800	51	11.28	150	96	229333.33	**0.49**	-0.31
7	129	2058	936	1122	80	2	**A1 / A4**	**100**	80	215	800	51	9.18	100	96	229333.33	**0.32**	-0.49
8	130	2100	397	1703	100	2	**A7**	**170**	100	215	800	51	3.89	170	96	358333.33	**0.34**	-0.46
9	131	2187	971	1216	80	2	**A5 / A3**	**180**	80	215	800	51	9.53	180	96	229333.33	**0.58**	-0.23
10	133	2176	414	1762	100	2	**A7**	**170**	100	215	800	51	4.06	170	96	358333.33	**0.34**	-0.46
MEAN		2125	758	1367	**MEAN**			**154.50**	Aircrete						**MEAN**		**0.42**	-0.39
					STDEV			**22.79**							**STDEV**		**0.11**	0.11
					COV			**0.15**							**COV**		**0.25**	-0.27
															CHARACTERISTIC STRENGTH			0.25

AIRCRETE BRICK - THIN LAYER MORTAR

7 DAY - TLM

BUILD DATE			TEST DATE				DAY		Bond Wrench Test - According to: BS EN 1052-5:2005									
24 October 2005			31 October 2005				7											
BW	H	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W	Mean Joint H	Failure Mode	Failure N	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	130	2093	346	1744	100	2	**A7**	**180**	100	215	800	51	3.39	180	96	358333.33	**0.36**	-0.44
2	129	2134	1136	1183	100	2	**A5**	**155**	100	215	800	51	11.14	155	96	358333.33	**0.31**	-0.51
3	129	2252	235	1919	100	2	**A7**	**130**	100	215	800	51	2.31	130	96	358333.33	**0.26**	-0.58
4	130	2231	315	1909	100	2	**A7**	**165**	100	215	800	51	3.09	165	96	358333.33	**0.33**	-0.48
5	131	2182	378	1799	100	2	**A7**	**155**	100	215	800	51	3.71	155	96	358333.33	**0.31**	-0.50
6	130	2060	1183	877	100	2	**A5**	**145**	100	215	800	51	11.61	145	96	358333.33	**0.29**	-0.53
7	130	1963	479	1480	100	2	**A7**	**155**	100	215	800	51	4.70	155	96	358333.33	**0.31**	-0.50
8	129	1976	429	1542	100	2	**A7**	**175**	100	215	800	51	4.21	175	96	358333.33	**0.35**	-0.45
9	131	2082	412	1667	100	2	**A7**	**175**	100	215	800	51	4.04	175	96	358333.33	**0.35**	-0.45
10	130	2079	323	1755	100	2	**A7**	**155**	100	215	800	51	3.17	155	96	358333.33	**0.31**	-0.50
MEAN		2105	524	1588	**MEAN**			**159.00**	Aircrete						**MEAN**		**0.32**	-0.50
					STDEV			**15.24**							**STDEV**		**0.03**	0.04
					COV			**0.10**							**COV**		**0.10**	-0.09
															CHARACTERISTIC STRENGTH			0.26

AIRCRETE BRICK - THIN LAYER MORTAR

28 DAY - TLM

BUILD DATE				TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
01 November 2005				29 November 2005				28										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	129	2119	943	1133	100	2	**A5**	**155**	100	215	800	51	9.25	155	96	358333.33	**0.31**	-0.50
2	130	2354	507	1761	100	2	**A7**	**180**	100	215	800	51	4.97	180	96	358333.33	**0.36**	-0.44
3	132	2472	363	1964	100	2	**A7**	**165**	100	215	800	51	3.56	165	96	358333.33	**0.33**	-0.48
4	130	2422	352	1953	100	2	**A7**	**175**	100	215	800	51	3.45	175	96	358333.33	**0.35**	-0.45
5	131	3309	1180	1092	100	2	**A5**	**155**	100	215	800	51	11.58	155	96	358333.33	**0.31**	-0.51
6	130	2261	389	1800	100	2	**A7**	**180**	100	215	800	51	3.82	180	96	358333.33	**0.36**	-0.44
7	130	2315	510	1804	100	2	**A7**	**170**	100	215	800	51	5.00	170	96	358333.33	**0.34**	-0.46
8	130	2328	437	1803	100	2	**A7**	**150**	100	215	800	51	4.29	150	96	358333.33	**0.30**	-0.52
9	131	2249	536	1633	100	2	**A7**	**160**	100	215	800	51	5.26	160	96	358333.33	**0.32**	-0.49
10	129	2337	1263	1018	100	2	**A5**	**140**	100	215	800	51	12.39	140	96	358333.33	**0.28**	-0.55
MEAN		2417	648	1596	**MEAN**			**163.00**	Aircrete						**MEAN**		**0.33**	-0.48
					STDEV			**13.37**							**STDEV**		**0.03**	0.04
					COV			**0.08**							**COV**		**0.08**	-0.08
															CHARACTERISTIC STRENGTH			0.28

AIRCRETE BRICK - THIN LAYER MORTAR

56 DAY - TLM

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005										
24 October 2005					19 December 2005			56											
BW	H	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W	Mean Joint H	Failure Mode	Failure	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	131	2114	1003	1111	100	2	**A5 / A3**	**210**	100	215	800	51	9.84	210	96	358333.33	**0.43**	-0.37
2	131	2057	1392	665	100	2	**A2 / A5**	**190**	100	216	800	51	13.66	190	96	360000.00	**0.38**	-0.42
3	132	2055	351	1704	100	2	**A5**	**180**	100	217	800	51	3.44	180	96	361666.67	**0.36**	-0.44
4	132	2054	460	1594	100	2	**A5**	**170**	100	218	800	51	4.51	170	96	363333.33	**0.34**	-0.47
5	131	2093	868	1224	100	2	**A5**	**175**	100	219	800	51	8.52	175	96	365000.00	**0.35**	-0.46
6	131	2079	1064	1014	100	2	**A5**	**175**	100	220	800	51	10.44	175	96	366666.67	**0.35**	-0.46
7	132	2016	1108	907	100	2	**A5**	**200**	100	221	800	51	10.87	200	96	368333.33	**0.39**	-0.40
8	132	2095	993	1101	100	2	**A5**	**125**	100	222	800	51	9.74	125	96	370000.00	**0.24**	-0.61
9	131	2214	1080	1133	100	2	**A5**	**140**	100	223	800	51	10.59	140	96	371666.67	**0.27**	-0.57
10	131	2189	986	1202	100	2	**A5**	**180**	100	224	800	51	9.67	180	96	373333.33	**0.35**	-0.46
MEAN		2097	931	1166			**MEAN**	**174.50**	Aircrete							**MEAN**	**0.33**	-0.47
							STDEV	**25.54**								**STDEV**	**0.06**	0.07
							COV	**0.15**								**COV**	**0.17**	-0.16
																CHARACTERISTIC STRENGTH		0.25

Appendix D.2 – Natural Hydraulic Lime Mortar

SUMMARY SHEET

NATURAL HYDRAULIC LIME MORTAR - COUPLETS (BOND WRENCH)

TEST DATA

MEAN FAILURE STRENGTH

Unit \ Day	91	273	365
RED	229.0	280.5	374.0
YELLOW	125.5	147.5	141.5
CONCRETE	59.0	77.5	85.5
AIRCRETE	42.0	71.0	59.5

STANDARD DEVIATION FAILURE STRENGTH

Unit \ Day	91	273	365
RED	81.30	63.83	49.20
YELLOW	13.22	27.61	23.81
CONCRETE	16.30	20.17	23.86
AIRCRETE	10.06	20.11	9.56

COEFFICIENT OF VARIATION FAILURE STRENGTH

Unit \ Day	91	273	365
RED	0.36	0.23	0.13
YELLOW	0.11	0.19	0.17
CONCRETE	0.28	0.26	0.28
AIRCRETE	0.24	0.28	0.16

CHARACTERISTICS

CHARACTERISTIC BOND STRENGTH LOG NORMAL METHOD

Unit \ Day	91	273	365
RED	0.25	0.41	0.72
YELLOW	0.25	0.25	0.25
CONCRETE	0.08	0.08	0.12
AIRCRETE	0.06	0.09	0.11

CHARACTERISTIC BOND STRENGTH NORMAL METHOD

Unit \ Day	91	273	365
RED	0.24	0.44	0.74
YELLOW	0.26	0.26	0.26
CONCRETE	0.08	0.08	0.11
AIRCRETE	0.06	0.09	0.11

DATA ANALYSIS

MEAN INDIVIDUAL BOND STRENGTH

Unit \ Day	91	273	365
RED	0.58	0.71	0.95
YELLOW	0.32	0.37	0.36
CONCRETE	0.15	0.17	0.21
AIRCRETE	0.10	0.18	0.15

Log_{10} OF BOND STRENGTH = Y_{mean}

Unit \ Day	91	273	365
RED	-0.27	-0.16	-0.03
YELLOW	-0.50	-0.44	-0.45
CONCRETE	-0.85	-0.80	-0.69
AIRCRETE	-1.00	-0.77	-0.83

STDEV - INDIVIDUAL BOND STRENGTH

Unit \ Day	91	273	365
RED	0.21	0.16	0.13
YELLOW	0.03	0.07	0.06
CONCRETE	0.04	0.05	0.06
AIRCRETE	0.03	0.05	0.02

STDEV - Log_{10} OF BOND STRENGTH = Y_{mean}

Unit \ Day	91	273	365
RED	0.18	0.12	0.06
YELLOW	0.05	0.09	0.07
CONCRETE	0.13	0.15	0.13
AIRCRETE	0.11	0.14	0.07

COV - INDIVIDUAL BOND STRENGTH

Unit \ Day	91	273	365
RED	0.36	0.23	0.13
YELLOW	0.11	0.19	0.17
CONCRETE	0.28	0.32	0.28
AIRCRETE	0.25	0.29	0.16

C.O.V % - BOND STRENGTH

Unit \ Day	91	273	365
RED	36	23	13
YELLOW	11	19	17
CONCRETE	28	32	28
AAC	25	29	16

RED BRICK - NHL

91 DAY - NHL

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
15 August 2005					14 November 2005			91										
BW	H	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W	Mean Joint H	Failure Mode	Failure N	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	5735	2460	3275	90	10	**A1**	**180**	90	215	800	51	24.13	180	96	290250.0	**0.455**	-0.34
2	140	5806	2810	2996	90	10	**A4/A2**	**280**	90	215	800	51	27.57	280	96	290250.0	**0.710**	-0.15
3	140	5742	2553	3189	90	10	**A3**	**190**	90	215	800	51	25.04	190	96	290250.0	**0.480**	-0.32
4	140	5725	2765	2960	90	10	**A1**	**155**	90	215	800	51	27.12	155	96	290250.0	**0.391**	-0.41
5	140	5863	2546	3317	90	10	**A4**	**90**	90	215	800	51	24.98	90	96	290250.0	**0.225**	-0.65
6	140	5685	2716	2969	90	10	**A1**	**370**	90	215	800	51	26.64	370	96	290250.0	**0.939**	-0.03
7	140	5812	2465	3347	90	10	**A3**	**250**	90	215	800	51	24.18	250	96	290250.0	**0.633**	-0.20
8	140	5763	2756	3007	90	10	**A3**	**215**	90	215	800	51	27.04	215	96	290250.0	**0.544**	-0.26
9	140	5746	2549	3197	90	10	**A1**	**315**	90	215	800	51	25.01	315	96	290250.0	**0.799**	-0.10
10	140	5914	2896	3018	90	10	**A1**	**245**	90	215	800	51	28.41	245	96	290250.0	**0.620**	-0.21
MEAN		5779	2652	3128	**MEAN**			**229.00**	Red						**MEAN**		**0.58**	-0.27
					STDEV			**81.30**							**STDEV**		**0.21**	0.18
					COV			**0.36**							**COV**		**0.36**	-0.66
															CHARACTERISTIC STRENGTH			0.25

RED BRICK - NHL

273 DAY - NHL

BUILD DATE				TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
15 August 2005				15 May 2006				**273**										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	5933	2540	3392	90	10	**A1**	**145**	90	215	800	51	24.92	145	96	290250.0	**0.365**	-0.44
2	140	5726	2686	3041	90	10	**A4**	**355**	90	215	800	51	26.34	355	96	290250.0	**0.901**	-0.05
3	140	5735	2717	3026	90	10	**A3**	**205**	90	215	800	51	26.65	205	96	290250.0	**0.518**	-0.29
4	140	5744	2783	2961	90	10	**A3 (A2)**	**330**	90	215	800	51	27.30	330	96	290250.0	**0.837**	-0.08
5	140	5684	2650	3035	90	10	**A3 (A1)**	**270**	90	215	800	51	25.99	270	96	290250.0	**0.684**	-0.16
6	140	5720	2732	2986	90	10	**A3 (A2)**	**260**	90	215	800	51	26.80	260	96	290250.0	**0.659**	-0.18
7	140	5732	2756	2976	90	10	**A3**	**320**	90	215	800	51	27.04	320	96	290250.0	**0.812**	-0.09
8	140	5802	2539	3263	90	10	**A1**	**290**	90	215	800	51	24.91	290	96	290250.0	**0.735**	-0.13
9	140	5883	2355	3528	90	10	**A1**	**310**	90	215	800	51	23.10	310	96	290250.0	**0.786**	-0.10
10	140	5724	2862	2862	90	10	**A1**	**320**	90	215	800	51	28.08	320	96	290250.0	**0.812**	-0.09
MEAN		5768	2662	3107	**MEAN**			**280.50**	Red						**MEAN**		**0.71**	-0.16
					STDEV			**63.83**							**STDEV**		**0.16**	0.12
					COV			**0.23**							**COV**		**0.23**	-0.74
															CHARACTERISTIC STRENGTH			0.41

RED BRICK - NHL

365 DAY - NHL

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
16 August 2005					16 August 2006			365										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
			T	B														
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	5396	2540	2856	90	10	**A1**	**390**	90	215	800	51	24.92	390	96	290250.0	**0.990**	0.00
2	140	5669	2686	2983	90	10	**A2**	**355**	90	215	800	51	26.34	355	96	290250.0	**0.901**	-0.05
3	140	5593	2717	2876	90	10	**A1**	**450**	90	215	800	51	26.65	450	96	290250.0	**1.143**	0.06
4	140	5729	2765	2964	90	10	**A3**	**375**	90	215	800	51	27.12	375	96	290250.0	**0.952**	-0.02
5	140	5760	2746	3014	90	10	**A3 (A1)**	**290**	90	215	800	51	26.94	290	96	290250.0	**0.735**	-0.13
6	140	5574	2782	2792	90	10	**A3 (A2)**	**310**	90	215	800	51	27.29	310	96	290250.0	**0.786**	-0.10
7	140	5798	2823	2975	90	10	**A3**	**420**	90	215	800	51	27.69	420	96	290250.0	**1.066**	0.03
8	140	5915	2952	2963	90	10	**A1**	**350**	90	215	800	51	28.96	350	96	290250.0	**0.888**	-0.05
9	140	5750	2746	3004	90	10	**A1**	**390**	90	215	800	51	26.94	390	96	290250.0	**0.990**	0.00
10	140	5639	2694	2945	90	10	**A1**	**410**	90	215	800	51	26.43	410	96	290250.0	**1.041**	0.02
MEAN		5682	2745	2937	**MEAN**			**374.00**	Red						**MEAN**		**0.95**	-0.03
					STDEV			**49.20**							**STDEV**		**0.13**	0.06
					COV			**0.13**							**COV**		**0.13**	-2.26
															CHARACTERISTIC STRENGTH			0.72

YELLOW BRICK - NHL

91 DAY - NHL

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
17 August 2005					16 November 2005			**91**										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	4807	2363	2446	90	10	**A2/A4**	**115**	90	215	800	51	23.18	115	96	290250.0	**0.289**	-0.54
2	140	4824	2409	2418	90	10	**A2/A4**	**145**	90	215	800	51	23.63	145	96	290250.0	**0.366**	-0.44
3	140	4803	2330	2474	90	10	**A2/A4**	**140**	90	215	800	51	22.86	140	96	290250.0	**0.353**	-0.45
4	140	4684	2344	2344	90	10	**A4**	**130**	90	215	800	51	22.99	130	96	290250.0	**0.327**	-0.48
5	140	4751	1936	2817	90	10	**A1**	**120**	90	215	800	51	18.99	120	96	290250.0	**0.302**	-0.52
6	140	4766	2352	2413	90	10	**A2**	**100**	90	215	800	51	23.07	100	96	290250.0	**0.251**	-0.60
7	140	4810	2410	2400	90	10	**A2**	**120**	90	215	800	51	23.64	120	96	290250.0	**0.302**	-0.52
8	140	4756	2359	2397	90	10	**A2/A4**	**135**	90	215	800	51	23.14	135	96	290250.0	**0.340**	-0.47
9	140	4792	1996	2796	90	10	**A1**	**120**	90	215	800	51	19.58	120	96	290250.0	**0.302**	-0.52
10	140	4763	2423	2340	90	10	**A2**	**130**	90	215	800	51	23.77	130	96	290250.0	**0.327**	-0.49
MEAN		4776	2292	2485	**MEAN**			**125.50**	Yellow						**MEAN**		**0.32**	-0.50
					STDEV			**13.22**							**STDEV**		**0.03**	0.05
					COV			**0.11**							**COV**		**0.11**	-0.09
															CHARACTERISTIC STRENGTH			0.25

YELLOW BRICK - NHL

	BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
	16 August 2005					16 May 2006			**273**										
	BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
			BEF	After		W	H			d	b								
		mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
273 DAY - NHL	1	140	4743	1943	2800	90	10	**A1**	**100**	90	215	800	51	19.06	100	96	290250.0	**0.251**	-0.60
	2	140	4725	2312	2413	90	10	**A2**	**130**	90	215	800	51	22.68	130	96	290250.0	**0.327**	-0.48
	3	140	4809	2385	2424	90	10	**A2**	**160**	90	215	800	51	23.40	160	96	290250.0	**0.404**	-0.39
	4	140	4812	1992	2820	90	10	**A1**	**180**	90	215	800	51	19.54	180	96	290250.0	**0.455**	-0.34
	5	140	4781	2124	2657	90	10	**A2**	**150**	90	215	800	51	20.84	150	96	290250.0	**0.378**	-0.42
	6	140	4725	2294	2431	90	10	**A1**	**110**	90	215	800	51	22.50	110	96	290250.0	**0.276**	-0.56
	7	140	4716	2108	2608	90	10	**A2**	**140**	90	215	800	51	20.68	140	96	290250.0	**0.353**	-0.45
	8	140	4824	2087	2737	90	10	**A2**	**180**	90	215	800	51	20.47	180	96	290250.0	**0.455**	-0.34
	9	140	4790	2271	2519	90	10	**A4/A2**	**170**	90	215	800	51	22.28	170	96	290250.0	**0.429**	-0.37
	10	140	4823	2342	2481	90	10	**A2**	**155**	90	215	800	51	22.98	155	96	290250.0	**0.391**	-0.41
	MEAN		4775	2186	2589	**MEAN**			**147.50**	Yellow						**MEAN**		**0.37**	-0.44
						STDEV			**27.61**							**STDEV**		**0.07**	0.09
						COV			**0.19**							**COV**		**0.19**	-0.20
																CHARACTERISTIC STRENGTH			0.25

YELLOW BRICK - NHL

365 DAY - NHL

BUILD DATE					TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
16 August 2005					16 August 2006				365										
BW	H	Weight (g)			Mean Joint		Failure			Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H				d	b								
			T	B															
	mm				mm	mm	Mode	N		mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	4790	1946	2842	90	10	**A1**	**185**		90	215	800	51	19.09	185	96	290250.0	**0.468**	-0.33
2	140	4754	1924	2830	90	10	**A1**	**125**		90	215	800	51	18.87	125	96	290250.0	**0.315**	-0.50
3	140	4770	1968	2802	90	10	**A1**	**155**		90	215	800	51	19.31	155	96	290250.0	**0.391**	-0.41
4	140	4832	1968	2864	90	10	**A1**	**145**		90	215	800	51	19.31	145	96	290250.0	**0.366**	-0.44
5	140	4762	1932	2828	90	10	**A1**	**130**		90	215	800	51	18.95	130	96	290250.0	**0.328**	-0.48
6	140	4786	1944	2840	90	10	**A1**	**140**		90	215	800	51	19.07	140	96	290250.0	**0.353**	-0.45
7	140	4788	1943	2845	90	10	**A1**	**150**		90	215	800	51	19.06	150	96	290250.0	**0.379**	-0.42
8	140	4812	1985	2827	90	10	**A1**	**165**		90	215	800	51	19.47	165	96	290250.0	**0.417**	-0.38
9	140	4735	1962	2773	90	10	**A1**	**110**		90	215	800	51	19.25	110	96	290250.0	**0.277**	-0.56
10	140	4841	1984	2857	90	10	**A1**	**110**		90	215	800	51	19.46	110	96	290250.0	**0.277**	-0.56
MEAN		4787	1956	2831	**MEAN**			**141.50**		Yellow							**MEAN**	**0.36**	-0.45
					STDEV			**23.81**									**STDEV**	**0.06**	0.07
					COV			**0.17**									**COV**	**0.17**	-0.16
																	CHARACTERISTIC STRENGTH		0.25

CONCRETE BRICK - NHL

91 DAY - NHL

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
28 November 2005					27 February 2006			91										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	6311	3214	3097	90	10	**A1**	**80**	90	215	800	51	31.53	80	96	290250.0	**0.199**	-0.70
2	140	6476	3050	3426	90	10	**A1**	**85**	90	215	800	51	29.92	85	96	290250.0	**0.212**	-0.67
3	140	6501	3060	3441	90	10	**A1**	**70**	90	215	800	51	30.02	70	96	290250.0	**0.174**	-0.76
4	140	6425	3124	3301	90	10	**A1**	**50**	90	215	800	51	30.65	50	96	290250.0	**0.123**	-0.91
5	140	6587	3484	3103	90	10	**A2**	**35**	90	215	800	51	34.18	35	96	290250.0	**0.085**	-1.07
6	140	6354	3142	3212	90	10	**A1**	**60**	90	215	800	51	30.82	60	96	290250.0	**0.148**	-0.83
7	140	6310	3087	3223	90	10	**A1**	**40**	90	215	800	51	30.28	40	96	290250.0	**0.098**	-1.01
8	140	6591	3192	3399	90	10	**A1**	**55**	90	215	800	51	31.31	55	96	290250.0	**0.136**	-0.87
9	140	6425	3273	3152	90	10	**A2**	**65**	90	215	800	51	32.11	65	96	290250.0	**0.161**	-0.79
10	140	6255	3009	3246	90	10	**A1**	**50**	90	215	800	51	29.52	50	96	290250.0	**0.123**	-0.91
MEAN		6424	3164	3260	**MEAN**			**59.00**	Concrete						**MEAN**		**0.15**	-0.85
					STDEV			**16.30**							**STDEV**		**0.04**	0.13
					COV			**0.28**							**COV**		**0.28**	-0.15
															CHARACTERISTIC STRENGTH			0.08

CONCRETE BRICK - NHL

273 DAY - NHL

BUILD DATE	TEST DATE	DAY	Bond Wrench Test - According to: BS EN 1052-5:2005
16 August 2005	16 May 2006	273	

BW	H	Weight (g) BEF	Weight (g) After T	Weight (g) After B	Mean Joint W	Mean Joint H	Failure Mode	Failure N	Mortar d	Mortar b	e_1	e_2	w	F_1	F_2	z	fwi	Y_i
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	6529	3238	3291	90	10	**A2**	**60**	90	215	800	51	31.76	80	96	290250.0	**0.199**	-0.70
2	140	6411	3270	3141	90	10	**A2**	**80**	90	215	800	51	32.08	85	96	290250.0	**0.212**	-0.67
3	140	6512	3219	3293	90	10	**A1**	**90**	90	215	800	51	31.58	70	96	290250.0	**0.174**	-0.76
4	140	6684	3375	3309	90	10	**A2**	**110**	90	215	800	51	33.11	50	96	290250.0	**0.123**	-0.91
5	140	6382	3082	3300	90	10	**A1**	**65**	90	215	800	51	30.23	35	96	290250.0	**0.085**	-1.07
6	140	6429	3197	3232	90	10	**A1**	**80**	90	215	800	51	31.36	60	96	290250.0	**0.148**	-0.83
7	140	6554	3250	3304	90	10	**A1**	**40**	90	215	800	51	31.88	40	96	290250.0	**0.097**	-1.01
8	140	6397	3390	3007	90	10	**A2**	**100**	90	215	800	51	33.26	100	96	290250.0	**0.250**	-0.60
9	140	6345	3226	3119	90	10	**A2**	**70**	90	215	800	51	31.65	70	96	290250.0	**0.174**	-0.76
10	140	6584	3198	3386	90	10	**A1**	**80**	90	215	800	51	31.37	80	96	290250.0	**0.199**	-0.70
MEAN		6483	3245	3238	**MEAN**			**77.50**	Concrete						**MEAN**		**0.17**	-0.80
					STDEV			**20.17**							**STDEV**		**0.05**	0.15
					COV			**0.26**							**COV**		**0.32**	-0.19
															CHARACTERISTIC STRENGTH			0.08

CONCRETE BRICK - NHL

365 DAY - NHL

BUILD DATE				TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
16 August 2005				16 August 2006				365										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
			T	B														
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	6390	3090	3300	90	10	**A3/A1**	**50**	90	215	800	51	30.31	50	96	290250.0	**0.123**	-0.91
2	140	6476	3426	3050	90	10	**A2**	**125**	90	215	800	51	33.61	125	96	290250.0	**0.314**	-0.50
3	140	6438	3394	3044	90	10	**A2**	**110**	90	215	800	51	33.30	110	96	290250.0	**0.276**	-0.56
4	140	6538	3182	3356	90	10	**A3/A1**	**75**	90	215	800	51	31.22	75	96	290250.0	**0.187**	-0.73
5	140	6608	3302	3306	90	10	**A3/A1**	**55**	90	215	800	51	32.39	55	96	290250.0	**0.136**	-0.87
6	140	6568	3480	3088	90	10	**A2**	**75**	90	215	800	51	34.14	75	96	290250.0	**0.187**	-0.73
7	140	6396	3351	3045	90	10	**A3/A1**	**100**	90	215	800	51	32.87	100	96	290250.0	**0.250**	-0.60
8	140	6493	3247	3246	90	10	**A3/A1**	**75**	90	215	800	51	31.85	75	96	290250.0	**0.187**	-0.73
9	140	6504	3369	3135	90	10	**A2**	**90**	90	215	800	51	33.05	90	96	290250.0	**0.225**	-0.65
10	140	6590	3138	3452	90	10	**A1**	**100**	90	215	800	51	30.78	100	96	290250.0	**0.250**	-0.60
MEAN		6500	3298	3202	**MEAN**			**85.50**	Concrete						**MEAN**		**0.21**	-0.69
					STDEV			**23.86**							**STDEV**		**0.06**	0.13
					COV			**0.28**							**COV**		**0.28**	-0.19
															CHARACTERISTIC STRENGTH			0.12

AIRCRETE BRICK - NHL

91 DAY - NHL

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
05 September 2005					05 December 2005			91										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	2587	1514	1073	90	10	**A1**	**45**	90	215	800	51	14.85	45	96	290250.0	**0.111**	-0.95
2	140	2533	998	1535	90	10	**A1**	**60**	90	215	800	51	9.79	60	96	290250.0	**0.150**	-0.83
3	140	2552	1042	1510	90	10	**A1**	**45**	90	215	800	51	10.22	45	96	290250.0	**0.111**	-0.95
4	140	2414	1103	1311	90	10	**A1**	**55**	90	215	800	51	10.82	55	96	290250.0	**0.137**	-0.86
5	140	2314	924	1390	90	10	**A1/A3**	**35**	90	215	800	51	9.06	35	96	290250.0	**0.086**	-1.07
6	140	2515	1015	1500	90	10	**A1**	**40**	90	215	800	51	9.96	40	96	290250.0	**0.099**	-1.01
7	140	2464	1017	1447	90	10	**A1**	**35**	90	215	800	51	9.98	35	96	290250.0	**0.086**	-1.07
8	140	2398	979	1419	90	10	**A1**	**40**	90	215	800	51	9.60	40	96	290250.0	**0.099**	-1.01
9	140	2413	988	1425	90	10	**A1**	**25**	90	215	800	51	9.69	25	96	290250.0	**0.060**	-1.22
10	140	2345	922	1423	90	10	**A1**	**40**	90	215	800	51	9.04	40	96	290250.0	**0.099**	-1.01
MEAN		2454	1050	1403	**MEAN**			**42.00**	Aircrete						**MEAN**		**0.10**	-1.00
					STDEV			**10.06**							**STDEV**		**0.03**	0.11
					COV			**0.24**							**COV**		**0.25**	-0.11
															CHARACTERISTIC STRENGTH			0.06

AIRCRETE BRICK - NHL

273 DAY - NHL

BUILD DATE			TEST DATE				DAY		Bond Wrench Test - According to: BS EN 1052-5:2005									
16 August 2005			16 May 2006				**273**											
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	2258	913	1345	90	10	**A1**	**50**	90	215	800	51	8.96	50	96	290250.0	**0.124**	-0.91
2	140	2424	990	1434	90	10	**A1**	**35**	90	215	800	51	9.71	35	96	290250.0	**0.086**	-1.07
3	140	2417	998	1419	90	10	**A1**	**65**	90	215	800	51	9.79	65	96	290250.0	**0.162**	-0.79
4	140	2346	1188	1158	90	10	**A2**	**55**	90	215	800	51	11.65	55	96	290250.0	**0.137**	-0.86
5	140	2466	1249	1217	90	10	**A2**	**80**	90	215	800	51	12.25	80	96	290250.0	**0.200**	-0.70
6	140	2402	955	1447	90	10	**A1**	**95**	90	215	800	51	9.37	95	96	290250.0	**0.239**	-0.62
7	140	2404	1210	1194	90	10	**A2**	**90**	90	215	800	51	11.87	90	96	290250.0	**0.226**	-0.65
8	140	2379	1064	1315	90	10	**A1**	**95**	90	215	800	51	10.44	95	96	290250.0	**0.239**	-0.62
9	140	2406	1078	1328	90	10	**A1**	**70**	90	215	800	51	10.58	70	96	290250.0	**0.175**	-0.76
10	140	2384	988	1396	90	10	**A1**	**75**	90	215	800	51	9.69	75	96	290250.0	**0.188**	-0.73
MEAN		2389	1063	1325	**MEAN**			**71.00**	Aircrete						**MEAN**		**0.18**	-0.77
					STDEV			**20.11**							**STDEV**		**0.05**	0.14
					COV			**0.28**							**COV**		**0.29**	-0.18
															CHARACTERISTIC STRENGTH			0.09

AIRCRETE BRICK - NHL

365 DAY - NHL

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
16 August 2005					16 August 2006			**365**										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	w	F_1	F_2	z	fwi	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	2216	902	1314	90	10	**A1**	**65**	90	215	800	51	8.85	65	96	290250.0	**0.162**	-0.79
2	140	2224	918	1306	90	10	**A1**	**55**	90	215	800	51	9.01	55	96	290250.0	**0.137**	-0.86
3	140	2260	902	1358	90	10	**A1**	**45**	90	215	800	51	8.85	45	96	290250.0	**0.111**	-0.95
4	140	2278	934	1344	90	10	**A1/A4**	**70**	90	215	800	51	9.16	70	96	290250.0	**0.175**	-0.76
5	140	2202	1276	926	90	10	**A2**	**75**	90	215	800	51	12.52	75	96	290250.0	**0.188**	-0.73
6	140	2312	1378	934	90	10	**A2**	**60**	90	215	800	51	13.52	60	96	290250.0	**0.149**	-0.83
7	140	2468	1021	1447	90	10	**A1**	**60**	90	215	800	51	10.02	60	96	290250.0	**0.150**	-0.83
8	140	2450	1031	1419	90	10	**A1**	**50**	90	215	800	51	10.11	50	96	290250.0	**0.124**	-0.91
9	140	2421	996	1425	90	10	**A2**	**50**	90	215	800	51	9.77	50	96	290250.0	**0.124**	-0.91
10	140	2415	1094	1369	90	10	**A1**	**65**	90	215	800	51	10.73	65	96	290250.0	**0.162**	-0.79
MEAN		2325	1045	1284			**MEAN**	**59.50**	Aircrete						**MEAN**		**0.15**	-0.83
							STDEV	**9.56**							**STDEV**		**0.02**	0.07
							COV	**0.16**							**COV**		**0.16**	-0.09
															CHARACTERISTIC STRENGTH			0.11

Appendix D.3 – Ordinary Portland Cement Mortar

SUMMARY SHEET
ORDINARY PORTLAND CEMENT (iii) - COUPLETS (BOND WRENCH)

MEAN FAILURE STRENGTH	
Unit \ Day	7
RED	239.00
YELLOW	69.00
CONCRETE	109.50
AIRCRETE	45.50

MEAN BOND STRENGTH	
Unit \ Day	7
RED	0.48
YELLOW	0.14
CONCRETE	0.22
AIRCRETE	0.09

CHARACTERISTIC STRENGTH NORMAL	
Unit \ Day	7
RED	0.31
YELLOW	0.06
CONCRETE	0.15
AIRCRETE	0.03

STDEV FAILURE STRENGTH	
Unit \ Day	7
RED	50.54
YELLOW	22.58
CONCRETE	19.07
AIRCRETE	17.39

STDEV BOND STRENGTH	
Unit \ Day	7
RED	0.10
YELLOW	0.05
CONCRETE	0.04
AIRCRETE	0.04

CHARACTERISTIC STRENGTH LOG NORMAL	
Unit \ Day	7
RED	0.30
YELLOW	0.06
CONCRETE	0.15
AIRCRETE	0.03

COV FAILURE STRENGTH	
Unit \ Day	7
RED	0.21
YELLOW	0.33
CONCRETE	0.17
AIRCRETE	0.38

COV BOND STRENGTH	
Unit \ Day	7
RED	0.21
YELLOW	0.34
CONCRETE	0.18
AIRCRETE	0.40

RED BRICK - OPCiii

7 DAY - OPC

BUILD DATE					TEST DATE				DAY	Bond Wrench Test - According to: BS EN 1052-5:2005								
18 August 2005					25 August 2005				**7**									
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	W	F_1	F_2	Z	f_{wi}	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	140	5950	2603	3348	100	10	**A1**	**150**	100	215	800	51	25.54	150	96	358333.3	**0.30**	-0.52
2	140	5773	2646	3127	100	10	**A3**	**260**	100	215	800	51	25.96	260	96	358333.3	**0.53**	-0.28
3	140	5878	2772	3106	100	10	**A3**	**280**	100	215	800	51	27.19	280	96	358333.3	**0.57**	-0.25
4	140	5824	2738	3089	100	10	**A3**	**245**	100	215	800	51	26.86	245	96	358333.3	**0.50**	-0.30
5	140	5854	2523	3333	100	10	**A3**	**210**	100	215	800	51	24.75	210	96	358333.3	**0.42**	-0.37
6	140	5838	2727	3114	100	10	**A3**	**280**	100	215	800	51	26.75	280	96	358333.3	**0.57**	-0.25
7	140	5866	2498	3374	100	10	**A1**	**155**	100	215	800	51	24.51	155	96	358333.3	**0.31**	-0.51
8	140	5872	2505	3372	100	10	**A1**	**255**	100	215	800	51	24.57	255	96	358333.3	**0.52**	-0.29
9	140	5856	2665	3197	100	10	**A1**	**270**	100	215	800	51	26.14	270	96	358333.3	**0.55**	-0.26
10	140	5807	2537	3274	100	10	**A1**	**285**	100	215	800	51	24.89	285	96	358333.3	**0.58**	-0.24
MEAN		5852	2621	3233	**MEAN**			**239.00**	Red						**MEAN**		**0.48**	-0.33
					STDEV			**50.54**							**STDEV**		**0.10**	0.11
					COV			**0.21**							**COV**		**0.21**	-0.33
															CHARACTERISTIC STRENGTH			0.30

YELLOW BRICK - OPCiii

7 DAY - OPC

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
18 August 2005					25 August 2005			7										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	W	F_1	F_2	Z	f_{wi}	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	143	4890	1923	2948	100	10	**A1**	**70**	100	215	800	51	18.86	70	96	358333.3	**0.14**	-0.86
2	144	4860	1936	2924	100	10	**A1**	**80**	100	215	800	51	18.99	80	96	358333.3	**0.16**	-0.80
3	141	4912	1964	2953	100	10	**A1**	**70**	100	215	800	51	19.27	70	96	358333.3	**0.14**	-0.86
4	141	4843	1940	2906	100	10	**A1**	**110**	100	215	800	51	19.03	110	96	358333.3	**0.22**	-0.66
5	144	4879	1916	2965	100	10	**A1**	**30**	100	215	800	51	18.80	30	96	358333.3	**0.06**	-1.25
6	143	4841	1984	2856	100	10	**A1**	**55**	100	215	800	51	19.46	55	96	358333.3	**0.11**	-0.97
7	144	4840	1935	2906	100	10	**A1**	**55**	100	215	800	51	18.98	55	96	358333.3	**0.11**	-0.97
8	142	4854	1940	2910	100	10	**A1**	**55**	100	215	800	51	19.03	55	96	358333.3	**0.11**	-0.97
9	143	4868	1973	2895	100	10	**A1**	**95**	100	215	800	51	19.36	95	96	358333.3	**0.19**	-0.72
10	142	4848	1974	2875	100	10	**A1**	**70**	100	215	800	51	19.36	70	96	358333.3	**0.14**	-0.86
MEAN		4864	1949	2914	**MEAN**			**69.00**	Yellow						**MEAN**		**0.14**	-0.89
					STDEV			**22.58**							**STDEV**		**0.05**	0.16
					COV			**0.33**							**COV**		**0.34**	-0.18
															CHARACTERISTIC STRENGTH			0.06

CONCRETE BRICK - OPCiii

7 DAY - OPC

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005										
18 August 2005					25 August 2005			7											
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	W	F_1	F_2	Z	f_{wi}	Y_i
		BEF	After		W	H			d	b								
			T	B														
	mm				mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	143	6595	3517	3078	100	10	**A2**	**125**	100	215	800	51	34.50	125	96	358333.3	**0.25**	-0.60
2	144	6467	3253	3214	100	10	**A3**	**120**	100	215	800	51	31.91	120	96	358333.3	**0.24**	-0.62
3	141	6513	3436	3075	100	10	**A2**	**110**	100	215	800	51	33.71	110	96	358333.3	**0.22**	-0.66
4	141	6526	3048	3477	100	10	**A1**	**135**	100	215	800	51	29.90	135	96	358333.3	**0.27**	-0.57
5	144	6566	3039	3527	100	10	**A1**	**110**	100	215	800	51	29.81	110	96	358333.3	**0.22**	-0.66
6	143	6480	3284	3195	100	10	**A3**	**100**	100	215	800	51	32.22	100	96	358333.3	**0.20**	-0.70
7	144	6552	3500	3054	100	10	**A2**	**105**	100	215	800	51	34.34	105	96	358333.3	**0.21**	-0.68
8	142	6524	3296	3234	100	10	**A3**	**130**	100	215	800	51	32.33	130	96	358333.3	**0.26**	-0.58
9	143	6493	3463	3034	100	10	**A2**	**80**	100	215	800	51	33.97	80	96	358333.3	**0.16**	-0.80
10	142	6494	3051	3442	100	10	**A1**	**80**	100	215	800	51	29.93	80	96	358333.3	**0.16**	-0.80
MEAN		6521	3289	3233	**MEAN**			**109.50**	Concrete						**MEAN**		**0.22**	-0.67
					STDEV			**19.07**							**STDEV**		**0.04**	0.08
					COV			**0.17**							**COV**		**0.18**	-0.12
															CHARACTERISTIC STRENGTH			0.15

AIRCRETE BRICK - OPCiii

7 DAY - OPC

BUILD DATE					TEST DATE			DAY	Bond Wrench Test - According to: BS EN 1052-5:2005									
18 August 2005					25 August 2005			7										
BW	H	Weight (g)			Mean Joint		Failure		Mortar		e_1	e_2	W	F_1	F_2	Z	f_{wi}	Y_i
		BEF	After		W	H			d	b								
	mm		T	B	mm	mm	Mode	N	mm	mm	mm	mm	N	N	N	$bd^2/6$	N/mm^2	Log_{10}
1	139	2731	1154	1574	100	10	**A1**	**35**	100	215	800	51	11.32	35	96	358333.3	**0.07**	-1.17
2	141	2776	1573	1203	100	10	**A2**	**50**	100	215	800	51	15.43	50	96	358333.3	**0.10**	-1.01
3	141	2746	1193	1550	100	10	**A1**	**55**	100	215	800	51	11.70	55	96	358333.3	**0.11**	-0.97
4	143	2778	1191	1589	100	10	**A1**	**35**	100	215	800	51	11.68	35	96	358333.3	**0.07**	-1.17
5	142	2841	1597	1244	100	10	**A2**	**70**	100	215	800	51	15.67	70	96	358333.3	**0.14**	-0.86
6	140	2844	1184	1660	100	10	**A2**	**30**	100	215	800	51	11.62	30	96	358333.3	**0.06**	-1.25
7	139	2818	1180	1637	100	10	**A1**	**50**	100	215	800	51	11.58	50	96	358333.3	**0.10**	-1.01
8	143	2816	1659	1154	100	10	**A2**	**70**	100	215	800	51	16.27	70	96	358333.3	**0.14**	-0.86
9	142	2751	1226	1525	100	10	**A1**	**45**	100	215	800	51	12.03	45	96	358333.3	**0.09**	-1.06
10	139	2830	1167	1660	100	10	**A1**	**15**	100	215	800	51	11.45	15	96	358333.3	**0.03**	-1.58
MEAN		2793	1312	1480	**MEAN**			**45.50**	Aircrete						**MEAN**		**0.09**	-1.09
					STDEV			**17.39**							**STDEV**		**0.04**	0.22
					COV			**0.38**							**COV**		**0.40**	-0.20
															CHARACTERISTIC STRENGTH			0.03

APPENDIX E – WALLETTE – DATA

WALLETTE
ABREVIATIONS & SPECIFICATIONS

Symbol	Description
NHL	Natural Hydraulic Lime
OPC	Ordinary Porltand Cement
TLM	Thin Layer Mortar
D.B.	Drop Ball
P.P.	Plunger Penetration
V.C.	Vernier Caliper
F.T.	Flow Table
H_20	Water

Description	Value	Units
Width of unit	102.5	mm
B - Support Span	675	mm
B - Load Span	405	mm
P - Support Span	790	mm
P - Load Span	558	mm

Appendix E.1 – Thin Layer Mortar

SUMMARY SHEET
THIN LAYER MORTAR - WALLETTES

TEST DATA

B	MEAN FAILURE STRENGTH	
Unit \ Day	1	7
RED	4.96	10.46
YELLOW	-	6.30
CONCRETE	-	12.32
AIRCRETE	-	2.65

P	MEAN FAILURE STRENGTH	
Unit \ Day	1	7
RED	4.07	10.96
YELLOW	-	8.45
CONCRETE	-	13.59
AIRCRETE	-	2.89

B	STDEV FAILURE STRENGTH	
Unit \ Day	1	7
RED	0.22	2.26
YELLOW	-	1.59
CONCRETE	-	2.21
AIRCRETE	-	0.88

P	STDEV FAILURE STRENGTH	
Unit \ Day	1	7
RED	0.74	2.48
YELLOW	-	1.65
CONCRETE	-	2.53
AIRCRETE	-	0.37

B	COV FAILURE STRENGTH	
Unit \ Day	1	7
RED	0.04	0.22
YELLOW	-	0.25
CONCRETE	-	0.18
AIRCRETE	-	0.33

P	COV FAILURE STRENGTH	
Unit \ Day	1	7
RED	0.18	0.23
YELLOW	-	0.20
CONCRETE	-	0.19
AIRCRETE	-	0.13

WALLETTE DATA ANALYSIS

B	MEAN FLEXURAL STRENGTH	
Unit \ Day	1	7
RED	0.57	1.21
YELLOW	-	0.73
CONCRETE	-	1.42
AIRCRETE	-	0.31

P	MEAN FLEXURAL STRENGTH	
Unit \ Day	1	7
RED	1.02	2.75
YELLOW	-	2.12
CONCRETE	-	3.41
AIRCRETE	-	0.73

B	STDEV FAILURE STRENGTH	
Unit \ Day	1	7
RED	0.02	0.26
YELLOW	-	0.19
CONCRETE	-	0.25
AIRCRETE	-	0.10

P	STDEV FAILURE STRENGTH	
Unit \ Day	1	7
RED	0.19	0.62
YELLOW	-	0.42
CONCRETE	-	0.64
AIRCRETE	-	0.09

B	COV FLEXURAL STRENGTH	
Unit \ Day	1	7
RED	0.04	0.22
YELLOW	-	0.25
CONCRETE	-	*0.18*
AIRCRETE	-	0.33

P	COV FLEXURAL STRENGTH	
Unit \ Day	1	7
RED	0.18	0.23
YELLOW	-	0.20
CONCRETE	-	0.19
AIRCRETE	-	*0.13*

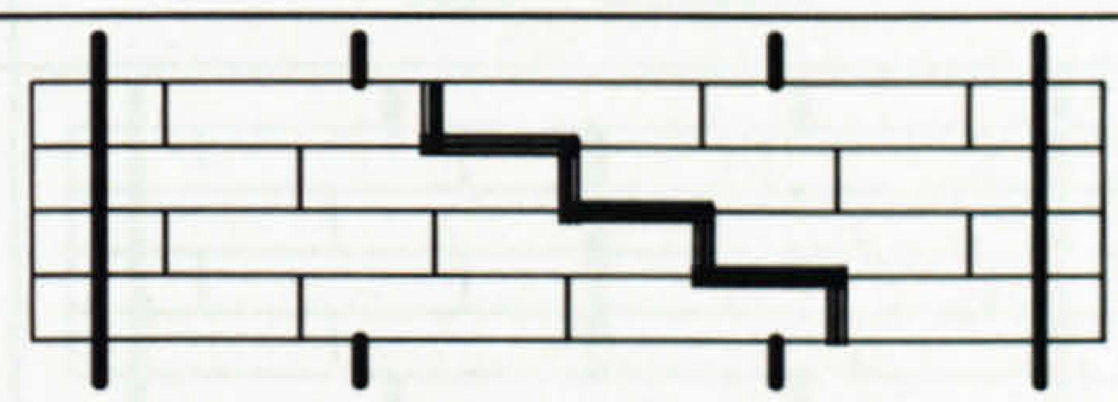
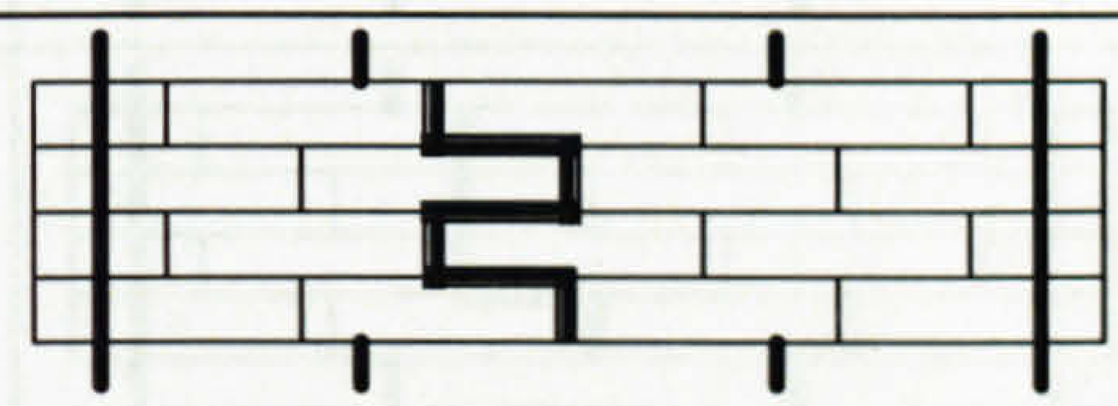
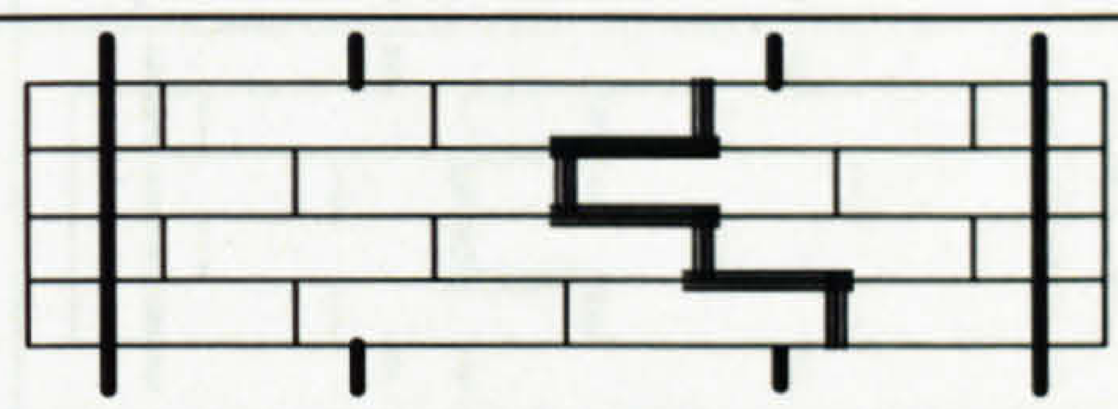
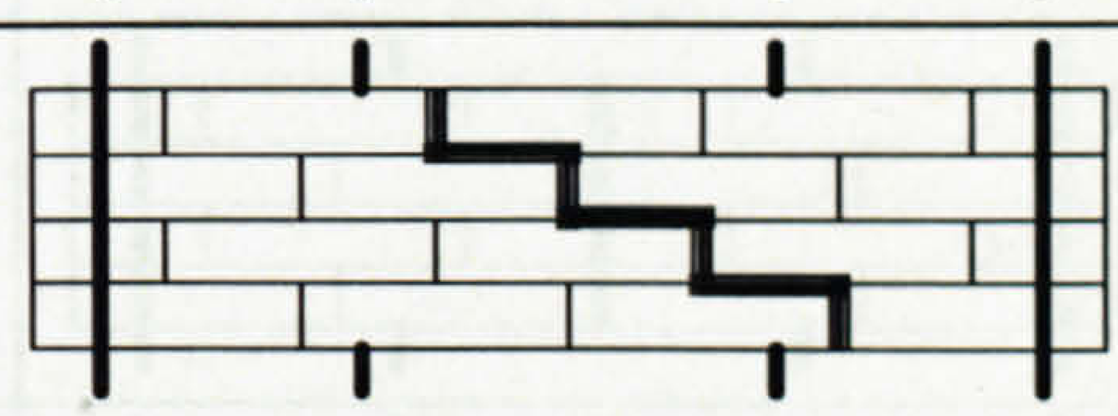
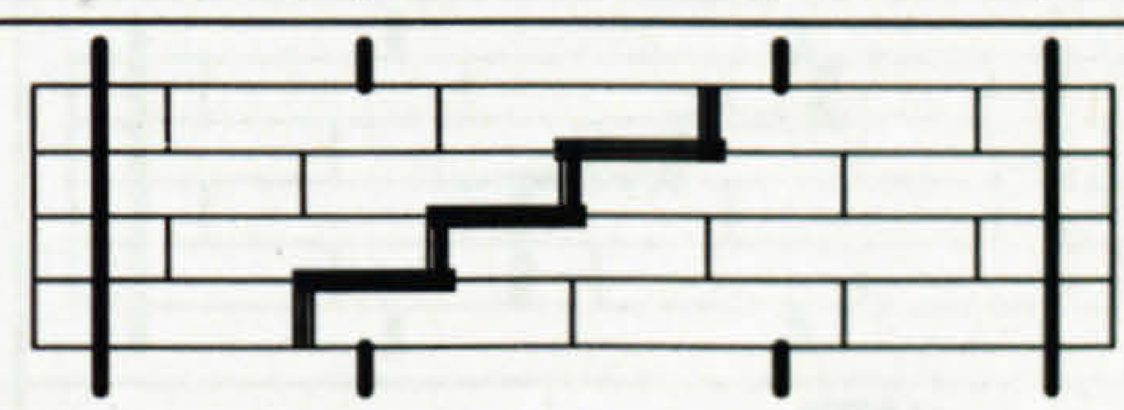
CHARACTERISTICS

B	MEAN CHARACTERISTIC STRENGTH	
Unit \ Day	1	7
RED	0.53	0.78
YELLOW	-	0.42
CONCRETE	-	1.01
AIRCRETE	-	0.14

P	MEAN CHARACTERISTIC STRENGTH	
Unit \ Day	1	7
RED	0.71	1.73
YELLOW	-	1.43
CONCRETE	-	2.36
AIRCRETE	-	0.58

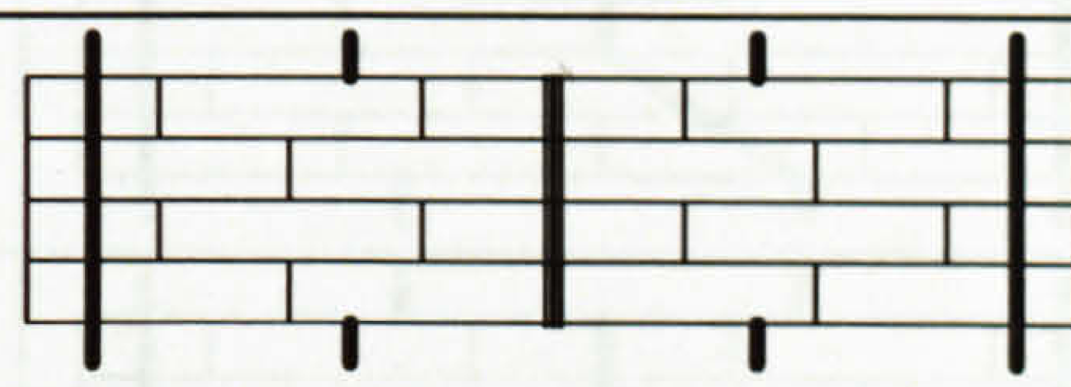
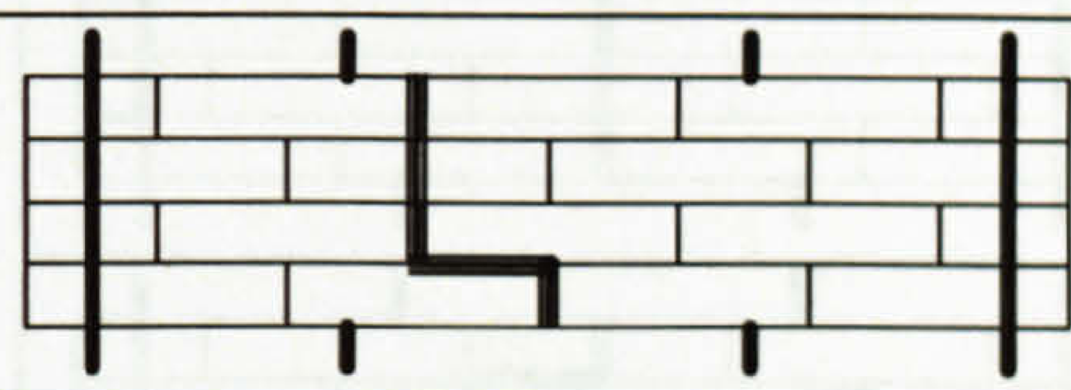
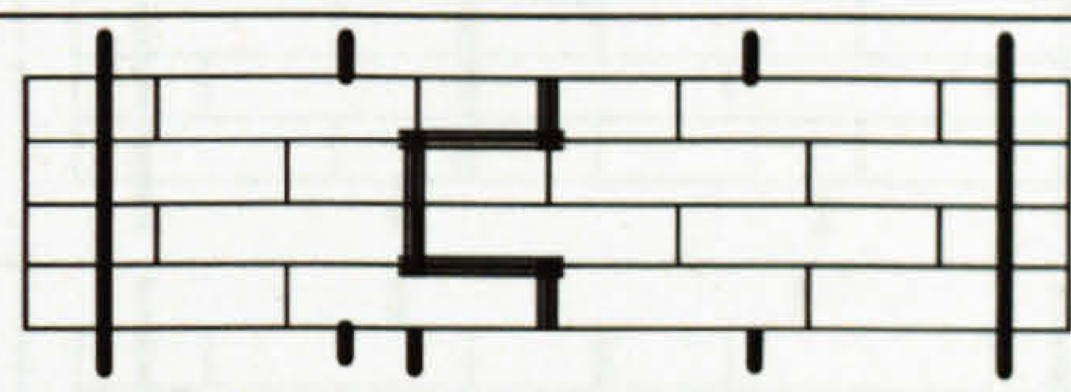
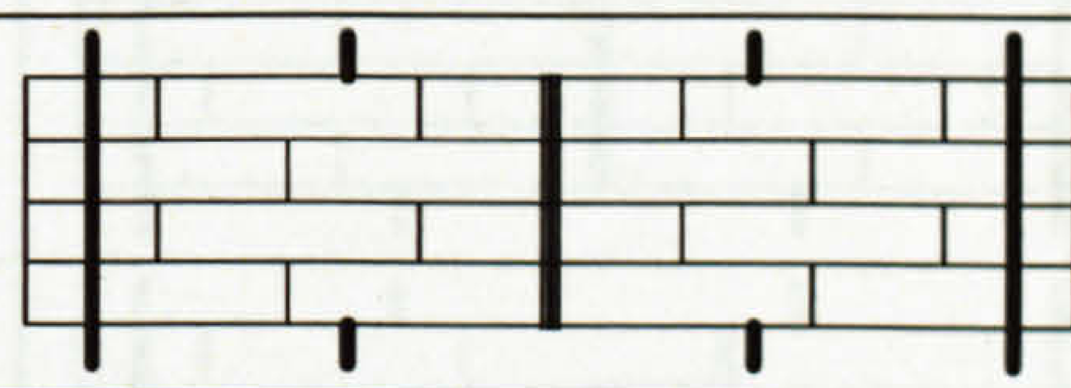
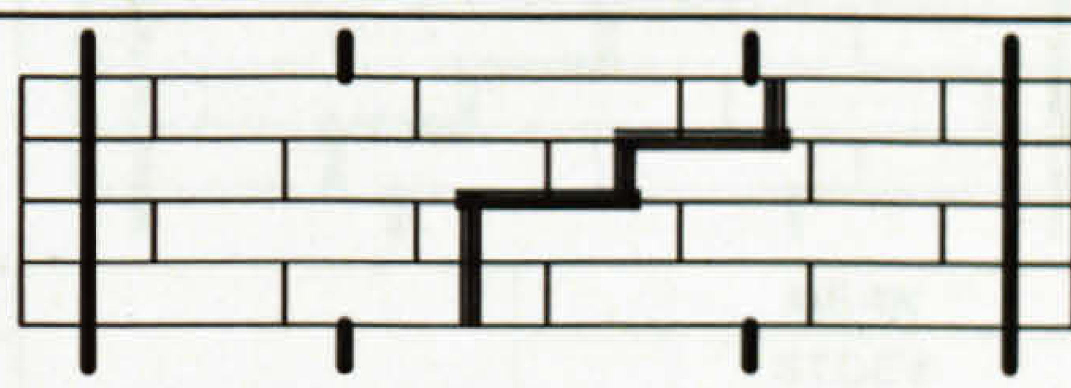
RED BRICK - TLM

B	BUILD DATE		TEST DATE		DAY	1	
	02-Nov-05		03-Nov-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
2111	433	669	669	5.14	5	1171446.9	**0.59**
2112	434	668	668	4.68	5	1169695.8	**0.54**
2113	433	668	667	4.99	4	1168820.3	**0.58**
2114	434	669	669	5.20	2	1171446.9	**0.60**
2115	433	667	667	4.80	4	1167944.8	**0.55**
Red		MEAN		4.96	**MEAN**	1169870.9	**0.57**
		STDEV		0.22	**STDEV**	1566.18	**0.02**
		COV		0.04	**COV**	0.00	**0.04**
					CHARACTERISTIC STRENGTH		0.53

P	BUILD DATE		TEST DATE		DAY 1		
	2-Nov-05		3-Nov-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
2111	864	265	265	4.05		464026.0	**1.01**
2112	864	264	265	3.21		463150.5	**0.80**
2113	865	265	265	4.37		464026.0	**1.09**
2114	865	264	264	5.12		462275.0	**1.28**
2115	865	265	265	3.58		464026.0	**0.89**
Red		MEAN		4.07	**MEAN**	463500.7	**1.02**
		STDEV		0.74	**STDEV**	783.09	**0.19**
		COV		0.18	**COV**	0.00	**0.18**
					CHARACTERISTIC STRENGTH		0.71

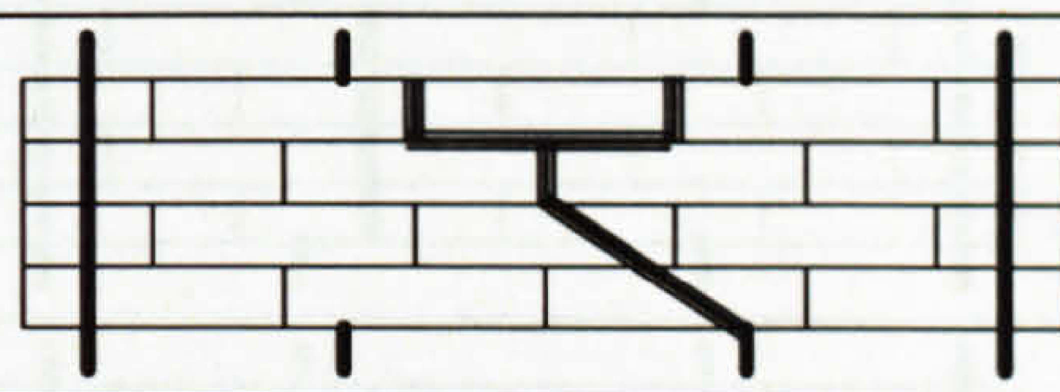
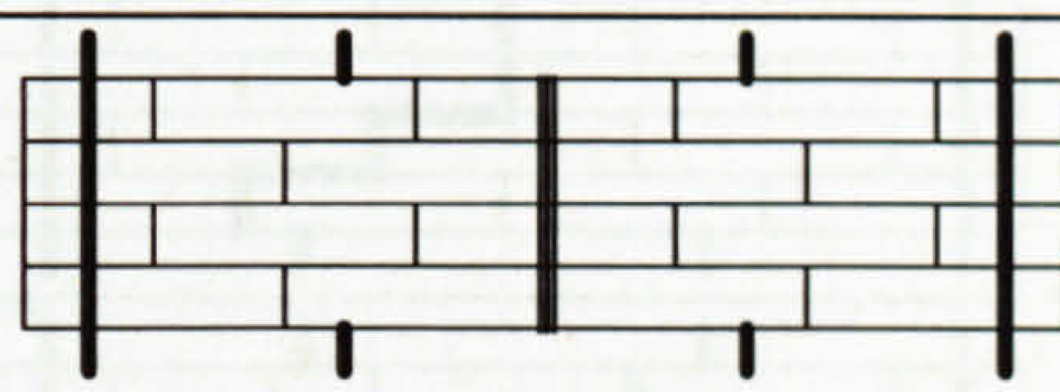
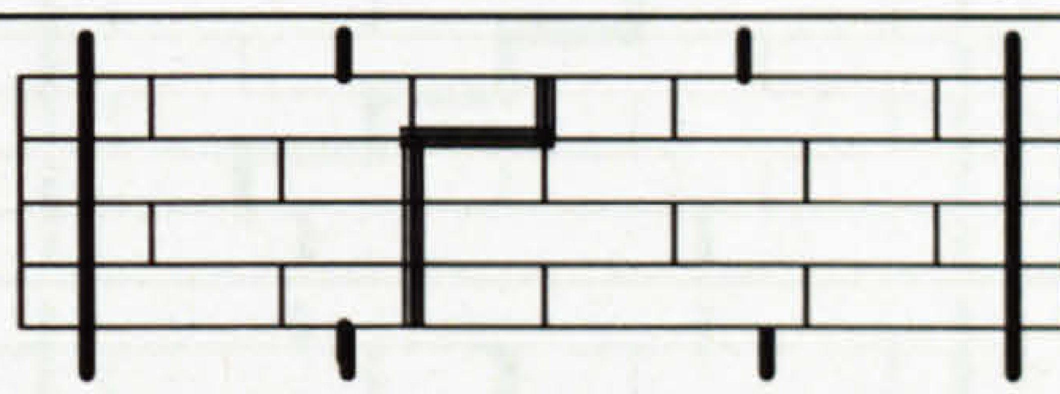
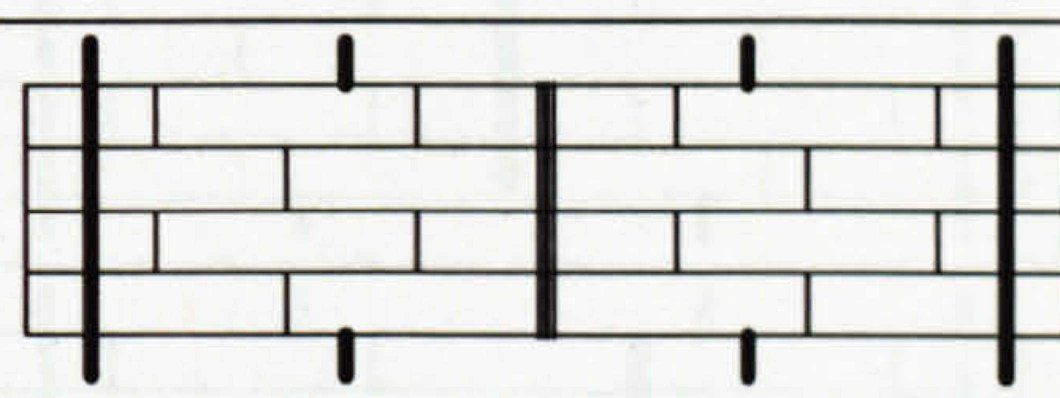
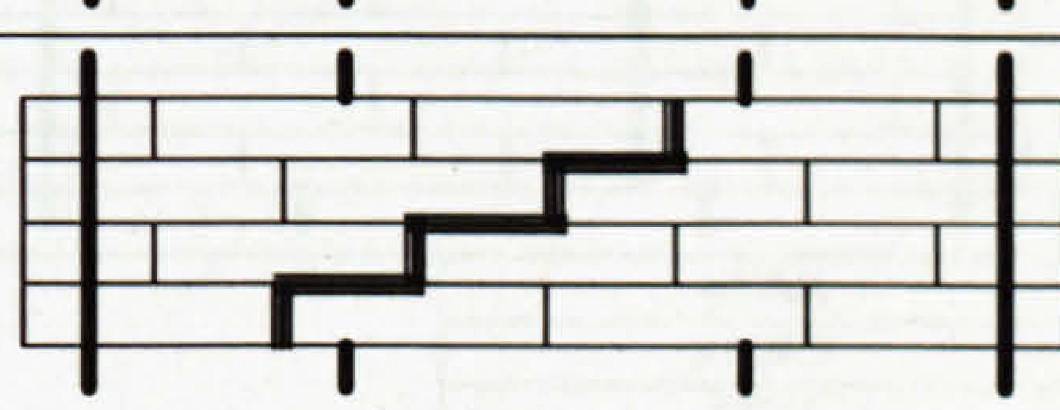
RED BRICK - TLM

B	BUILD DATE		TEST DATE		DAY	7	
	24-Oct-05		31-Oct-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
24101	432	668	667	14.11	5	1168820.3	**1.63**
24102	434	668	668	8.85	4	1169695.8	**1.02**
24103	432	667	666	8.64	3	1167069.3	**1.00**
24104	433	671	671	9.58	4	1174949.0	**1.10**
24105	432	667	667	11.12	5	1167944.8	**1.29**
Red		MEAN		10.46	**MEAN**	1169695.8	**1.21**
		STDEV		2.26	**STDEV**	3095.43	**0.26**
		COV		0.22	**COV**	0.00	**0.22**
					CHARACTERISTIC STRENGTH		0.78

P	BUILD DATE		TEST DATE		DAY 7		
	24-Oct-05		31-Oct-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
24101	865	264	265	13.02		463150.5	**3.26**
24102	864	264	265	9.56		463150.5	**2.39**
24103	865	264	264	8.89		462275.0	**2.23**
24104	865	264	265	14.23		463150.5	**3.56**
24105	865	264	265	9.09		463150.5	**2.28**
Red		MEAN		10.96	**MEAN**	462975.4	**2.75**
		STDEV		2.48	**STDEV**	391.54	**0.62**
		COV		0.23	**COV**	0.00	**0.23**
					CHARACTERISTIC STRENGTH		1.73

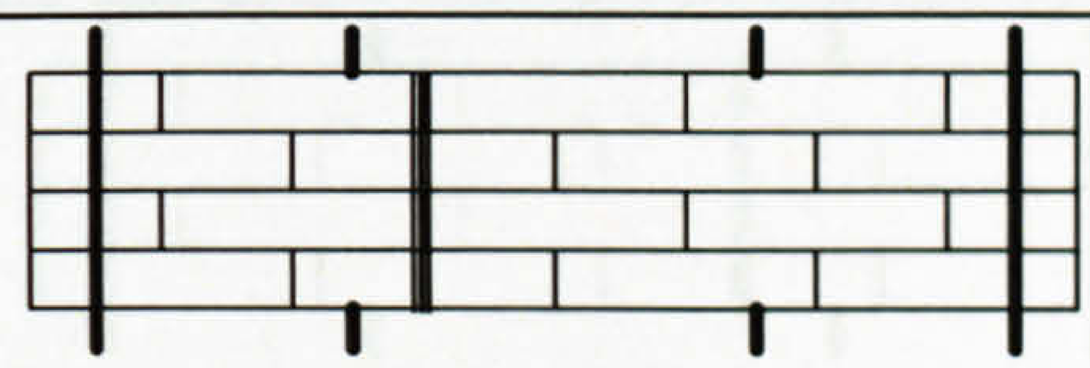
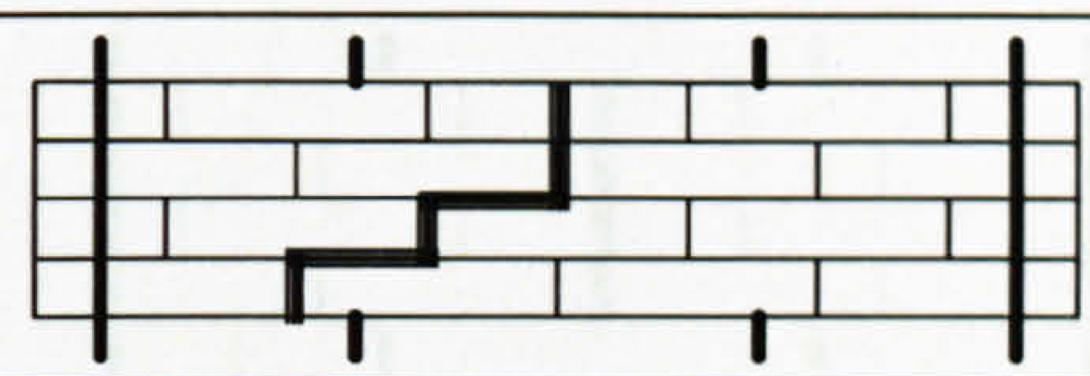
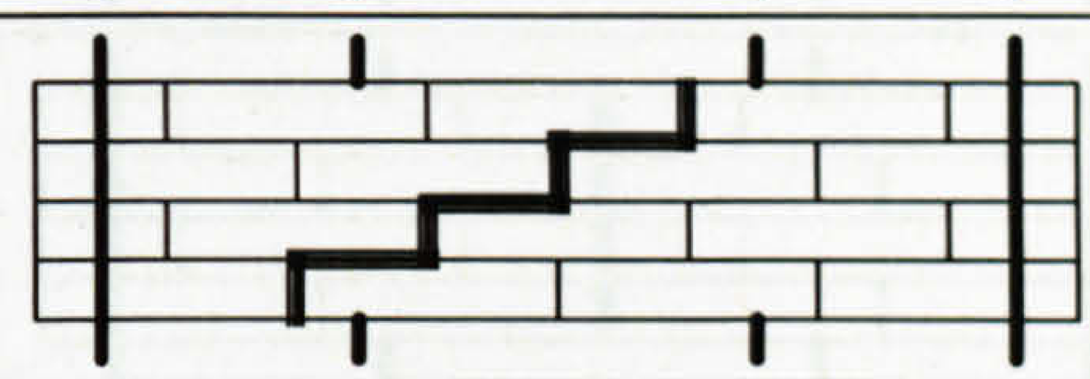
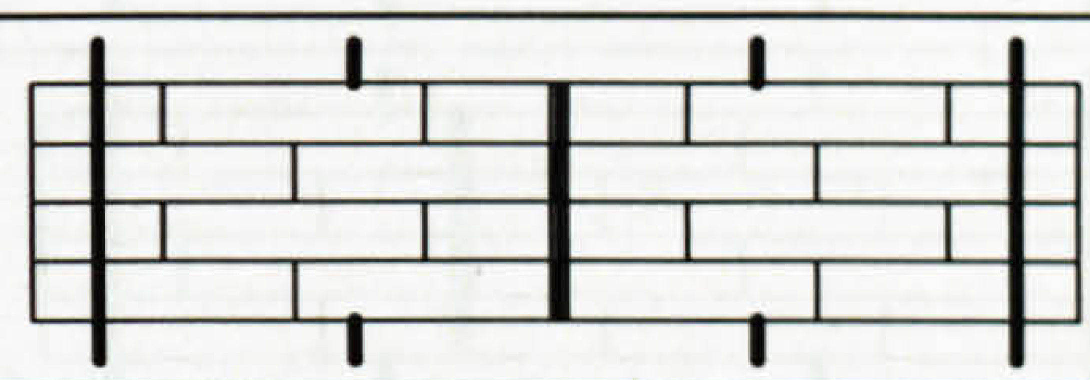
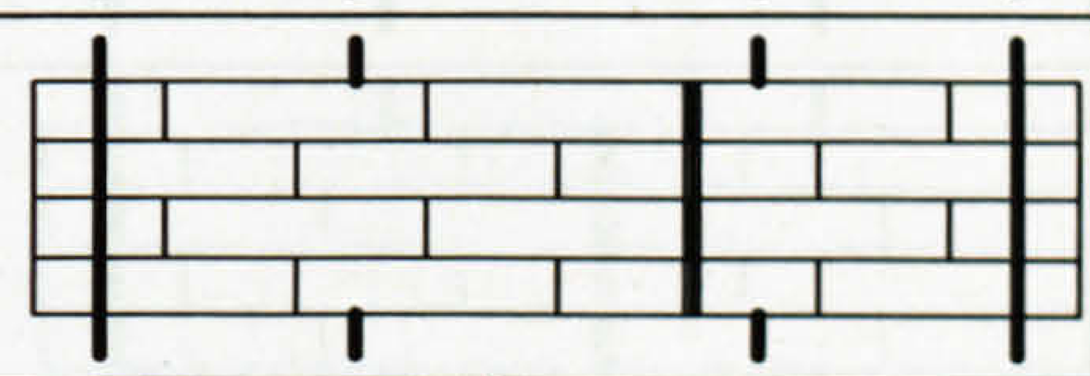
YELLOW BRICK - TLM

B	BUILD DATE		TEST DATE		DAY	7	
	2-Nov-05		9-Nov-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
2111	435	667	668	5.65	5	1168820.3	**0.65**
2112	433	670	670	6.02	6	1173197.9	**0.69**
2113	433	668	667	6.24	5	1168820.3	**0.72**
2114	434	667	667	4.66	4	1167944.8	**0.54**
2115	433	666	666	8.94	7	1166193.8	**1.03**
Yellow		MEAN		6.30	**MEAN**	1168995.4	**0.73**
		STDEV		1.59	**STDEV**	2582.42	**0.19**
		COV		0.25	**COV**	0.00	**0.25**
					CHARACTERISTIC STRENGTH		0.42

P	BUILD DATE		TEST DATE		DAY 7		
	24-Oct-05		31-Oct-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
24101	865	265	265	7.41		464026.0	**1.85**
24102	865	265	265	8.06		464026.0	**2.01**
24103	865	264	264	9.98		462275.0	**2.50**
24104	865	264	265	10.33		463150.5	**2.59**
24105	865	264	265	6.49		463150.5	**1.63**
Yellow		MEAN		8.45	**MEAN**	463325.6	**2.12**
		STDEV		1.65	**STDEV**	732.51	**0.42**
		COV		0.20	**COV**	0.00	**0.20**
					CHARACTERISTIC STRENGTH		1.43

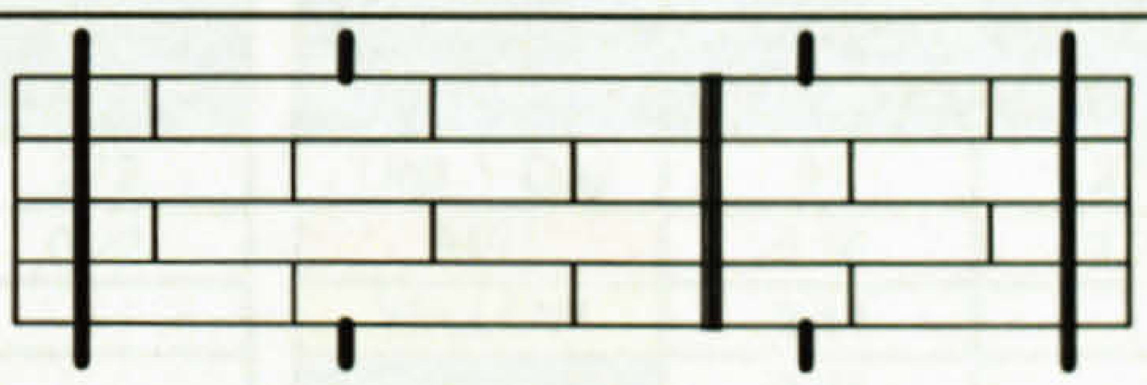
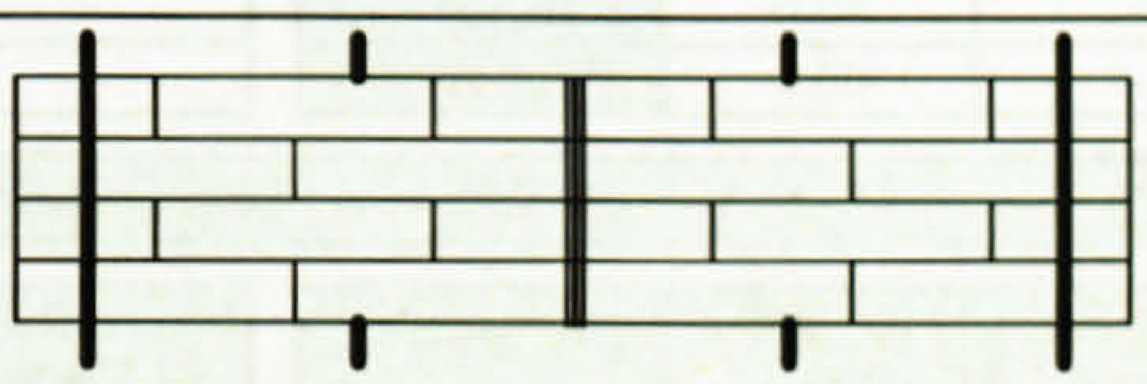
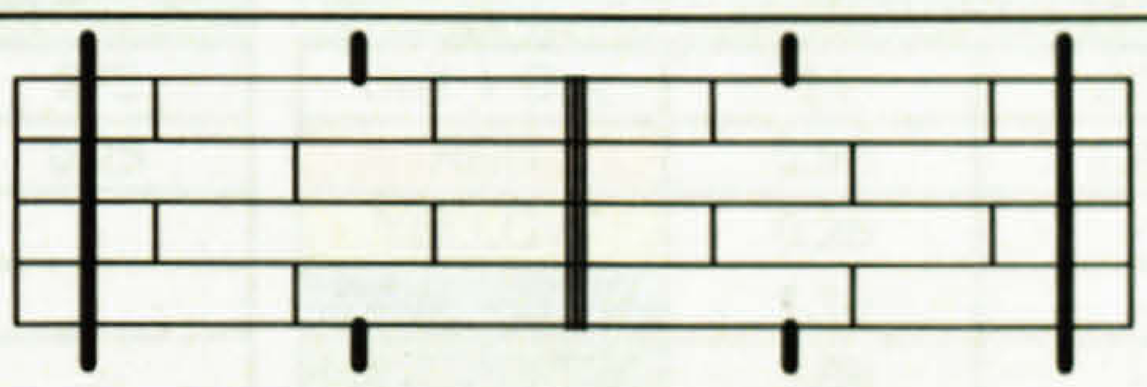
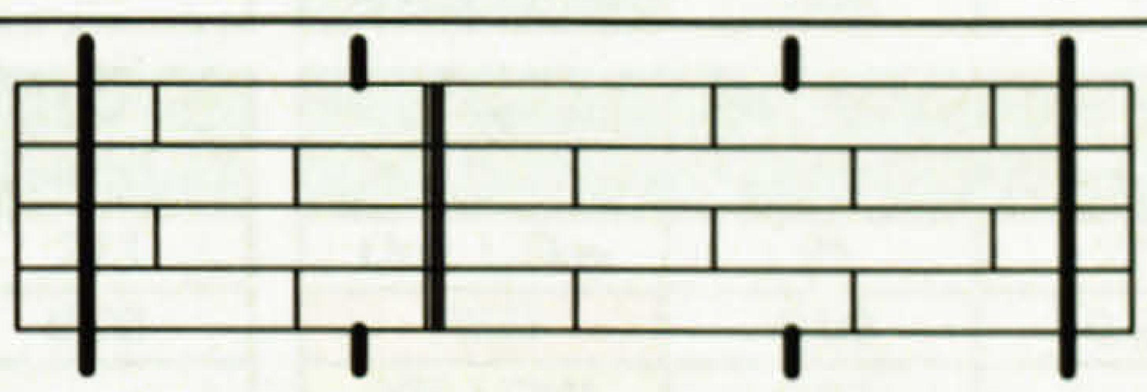
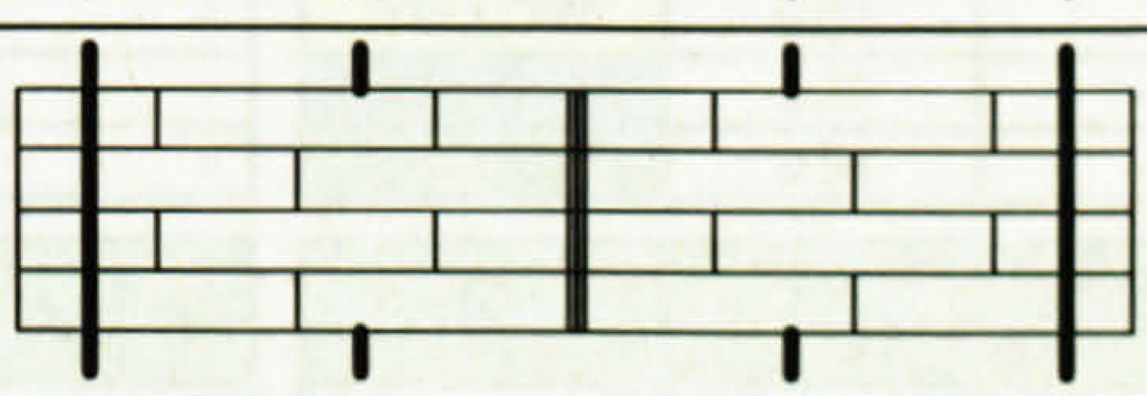
CONCRETE BRICK - TLM

B	BUILD DATE		TEST DATE		DAY	7	
	3-Nov-05		10-Nov-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height		Reading			
2x10	mm	L	R	kN		mm³	N/mm²
3111	433	668	667	13.24	5	1168820.3	**1.53**
3112	435	664	666	12.87	5	1164442.7	**1.49**
3113	436	671	671	10.43	5	1174949.0	**1.20**
3114	434	665	665	9.83	5	1164442.7	**1.14**
3115	433	671	671	15.25	6	1174949.0	**1.75**
Concrete		MEAN		12.32	**MEAN**	1169520.7	**1.42**
		STDEV		2.21	**STDEV**	5267.70	**0.25**
		COV		0.18	**COV**	0.00	**0.18**
					CHARACTERISTIC STRENGTH		1.01

P	BUILD DATE		TEST DATE		DAY	7	
	24-Oct-05		31-Oct-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm³	N/mm²
24101	864	265	265	14.25		464026.0	**3.56**
24102	865	265	265	10.69		464026.0	**2.67**
24103	865	265	264	11.2		463150.5	**2.81**
24104	865	264	265	15.63		463150.5	**3.91**
24105	864	262	263	16.2		459648.4	**4.09**
Concrete		MEAN		13.59	**MEAN**	462800.3	**3.41**
		STDEV		2.53	**STDEV**	1815.52	**0.64**
		COV		0.19	**COV**	0.00	**0.19**
					CHARACTERISTIC STRENGTH		2.36

AIRCRETE BRICK - TLM

B	BUILD DATE		TEST DATE		DAY 7		
	24-Oct-05		31-Oct-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
24101	434	669	669	3.50	4	1171446.9	**0.40**
24102	432	670	670	2.55	5	1173197.9	**0.29**
24103	433	670	670	3.57	5	1173197.9	**0.41**
24104	434	671	671	1.58	3	1174949.0	**0.18**
24105	434	668	668	2.05	4	1169695.8	**0.24**
Aircrete	MEAN			2.65	**MEAN**	1172497.5	**0.31**
	STDEV			0.88	**STDEV**	1996.49	**0.10**
	COV			0.33	**COV**	0.00	**0.33**
					CHARACTERISTIC STRENGTH		0.14

P	BUILD DATE		TEST DATE		DAY 7		
	24-Oct-05		31-Oct-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
24101	856	260	260	2.62		455270.8	**0.67**
24102	855	260	260	3.06		455270.8	**0.78**
24103	855	260	265	2.97		459648.4	**0.75**
24104	855	260	264	3.36		458772.9	**0.85**
24105	854	260	267	2.42		461399.5	**0.61**
Aircrete	MEAN			2.89	**MEAN**	458072.5	**0.73**
	STDEV			0.37	**STDEV**	2726.79	**0.09**
	COV			0.13	**COV**	0.01	**0.13**
					CHARACTERISTIC STRENGTH		0.58

Appendix E.2 – Natural Hydraulic Lime

SUMMARY SHEET

NATURAL HYDRAULIC LIME - WALLETTES

TEST DATA

B	MEAN FAILURE STRENGTH	
Unit \ Day	91	273
RED	2.10	2.47
YELLOW	0.48	-
CONCRETE	10.98	-
AIRCRETE	0.45	-

P	MEAN FAILURE STRENGTH	
Unit \ Day	91	273
RED	4.06	5.24
YELLOW	1.11	-
CONCRETE	5.04	-
AIRCRETE	7.33	-

B	STDEV FAILURE STRENGTH	
Unit \ Day	91	273
RED	0.29	0.56
YELLOW	0.17	-
CONCRETE	1.19	-
AIRCRETE	0.08	-

P	STDEV FAILURE STRENGTH	
Unit \ Day	91	273
RED	0.39	1.06
YELLOW	0.12	-
CONCRETE	1.23	-
AIRCRETE	2.17	-

B	COV FAILURE STRENGTH	
Unit \ Day	91	273
RED	0.14	0.23
YELLOW	0.34	-
CONCRETE	0.11	-
AIRCRETE	0.17	-

P	COV FAILURE STRENGTH	
Unit \ Day	91	273
RED	0.10	0.20
YELLOW	0.11	-
CONCRETE	0.24	-
AIRCRETE	0.30	-

WALLETTE DATA ANALYSIS

B	MEAN FLEXURAL STRENGTH	
Unit \ Day	91	273
RED	0.22	0.25
YELLOW	0.05	-
CONCRETE	1.13	-
AIRCRETE	0.46	-

P	MEAN FLEXURAL STRENGTH	
Unit \ Day	91	273
RED	0.93	1.20
YELLOW	0.25	-
CONCRETE	1.16	-
AIRCRETE	1.86	-

B	STDEV FLEXURAL STRENGTH	
Unit \ Day	91	273
RED	0.03	0.06
YELLOW	0.02	-
CONCRETE	0.12	-
AIRCRETE	0.08	-

P	STDEV FLEXURAL STRENGTH	
Unit \ Day	91	273
RED	0.09	0.24
YELLOW	0.03	-
CONCRETE	0.29	-
AIRCRETE	0.54	-

B	COV FLEXURAL STRENGTH	
Unit \ Day	91	273
RED	0.14	0.23
YELLOW	0.34	-
CONCRETE	0.11	-
AIRCRETE	0.17	-

P	COV FLEXURAL STRENGTH	
Unit \ Day	91	273
RED	0.09	0.20
YELLOW	0.11	-
CONCRETE	0.25	-
AIRCRETE	0.29	-

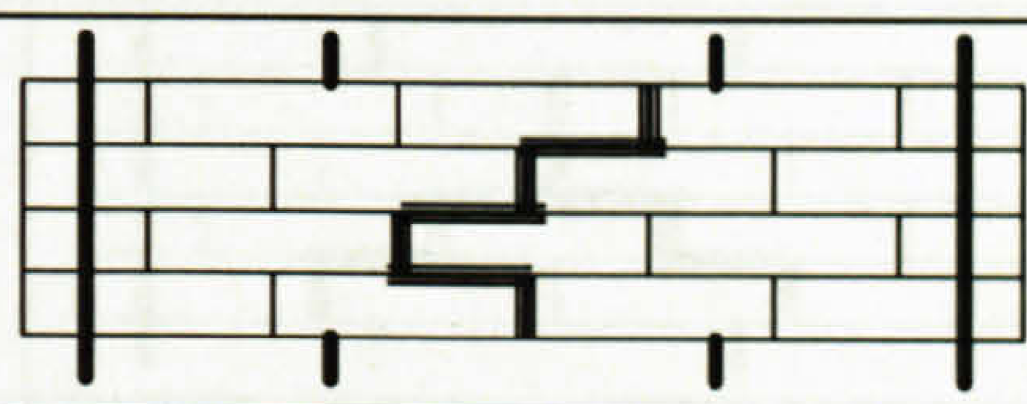
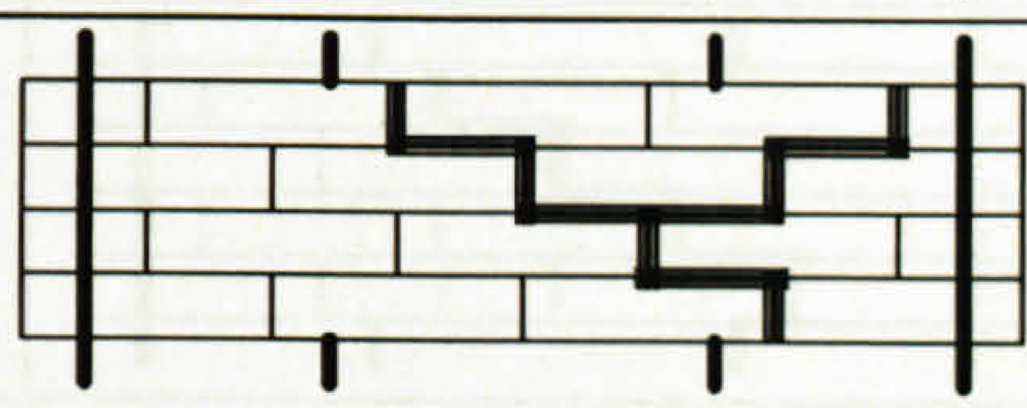
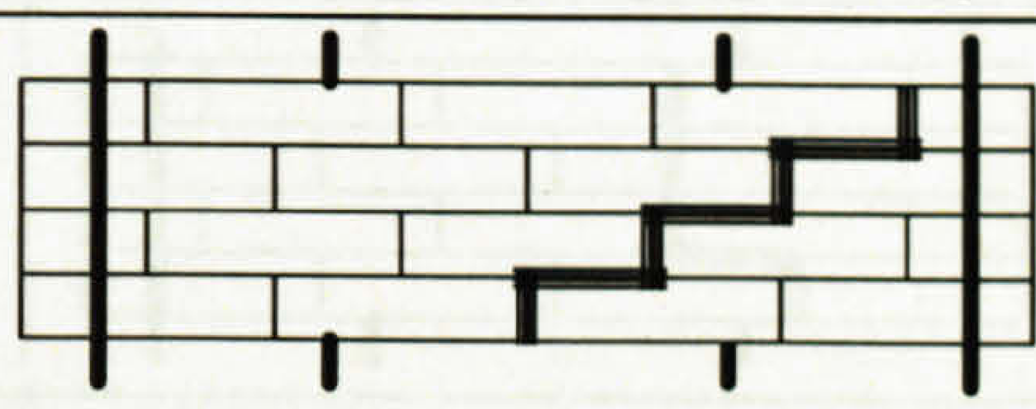
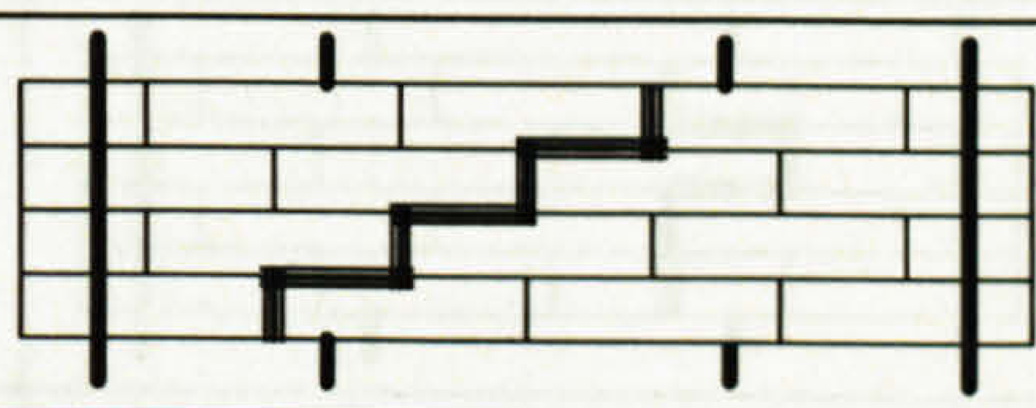
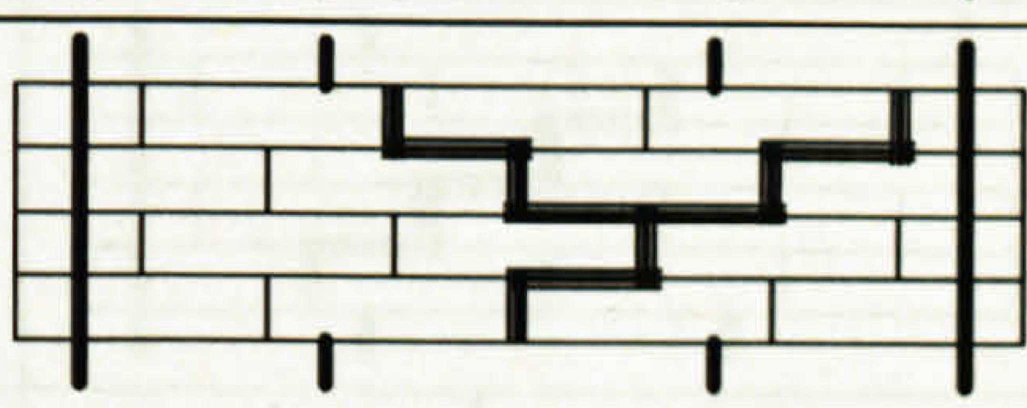
CHARACTERISTICS

B	CHARACTERISTIC STRENGTH	
Unit \ Day	91	273
RED	0.17	0.16
YELLOW	0.02	-
CONCRETE	0.93	-
AIRCRETE	0.33	-

P	CHARACTERISTIC STRENGTH	
Unit \ Day	91	273
RED	0.78	0.80
YELLOW	0.21	-
CONCRETE	0.68	-
AIRCRETE	0.96	-

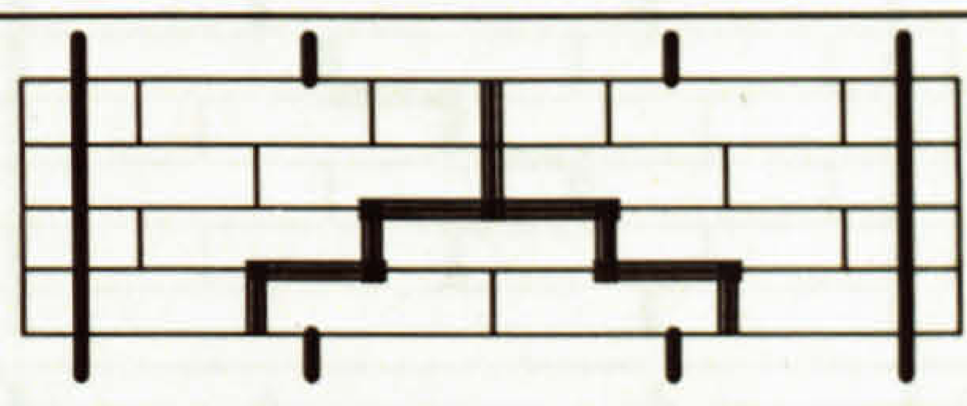
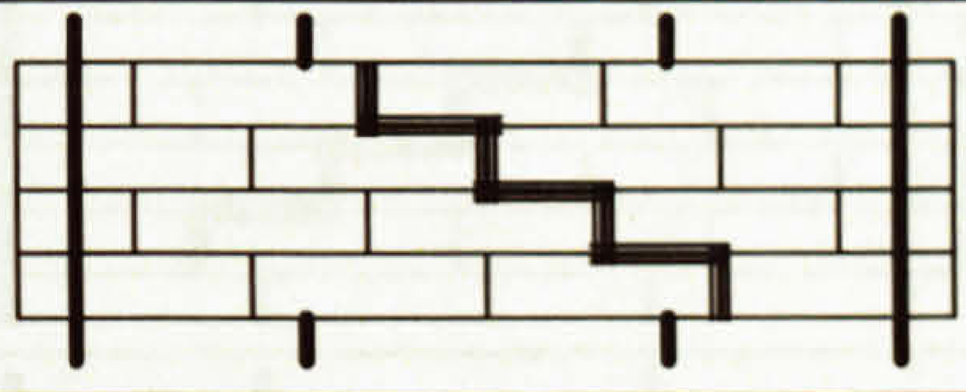
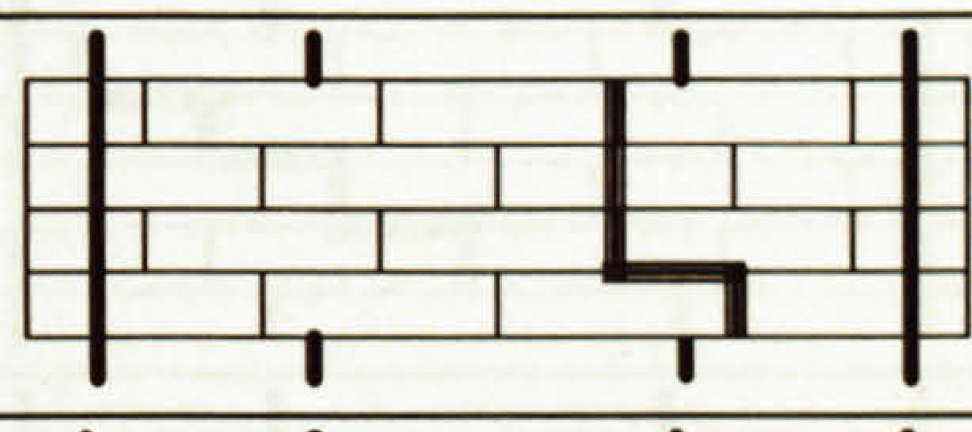
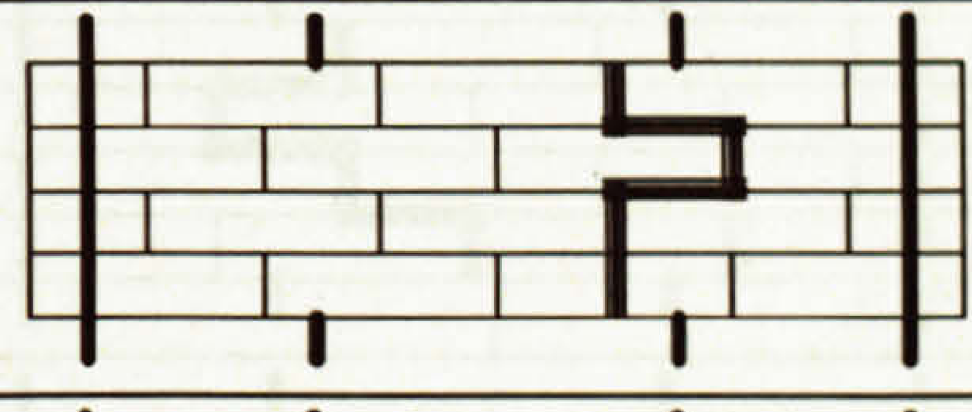
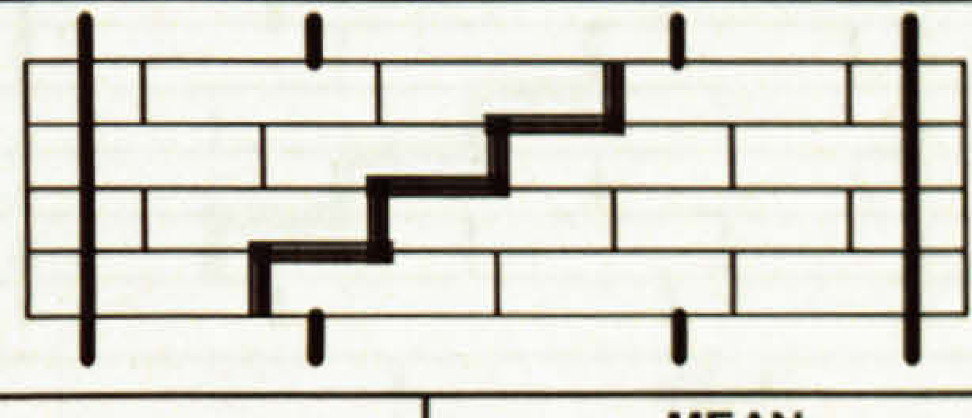
RED BRICK - NHL

B	BUILD DATE		TEST DATE		DAY 91		
	02 August 2005		01 November 2005		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
281	438	745	745	1.80	5	1304526.0	**0.19**
282	439	745	745	1.95	8	1304526.0	**0.20**
283	436	744	744	2.32	6	1302775.0	**0.24**
284	440	745	745	2.49	5	1304526.0	**0.26**
285	438	740	740	1.96	5	1295770.8	**0.20**
Red		MEAN		2.10	**MEAN**	1302424.8	**0.22**
		STDEV		0.29	**STDEV**	3796.17	**0.03**
		COV		0.14	**COV**	0.00	**0.14**
					CHARACTERISTIC STRENGTH		0.17

P	BUILD DATE		TEST DATE		DAY 91		
	01 August 2005		31 October 2005		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
181	880	290	290	3.58		507802.1	**0.82**
182	885	289	289	3.84		506051.0	**0.88**
183	890	290	290	4.39		507802.1	**1.00**
184	880	290	290	4.51		507802.1	**1.03**
185	890	289	289	3.98		506051.0	**0.91**
Red		MEAN		4.06	**MEAN**	507101.7	**0.93**
		STDEV		0.39	**STDEV**	959.09	**0.09**
		COV		0.10	**COV**	0.00	**0.09**
					CHARACTERISTIC STRENGTH		0.78

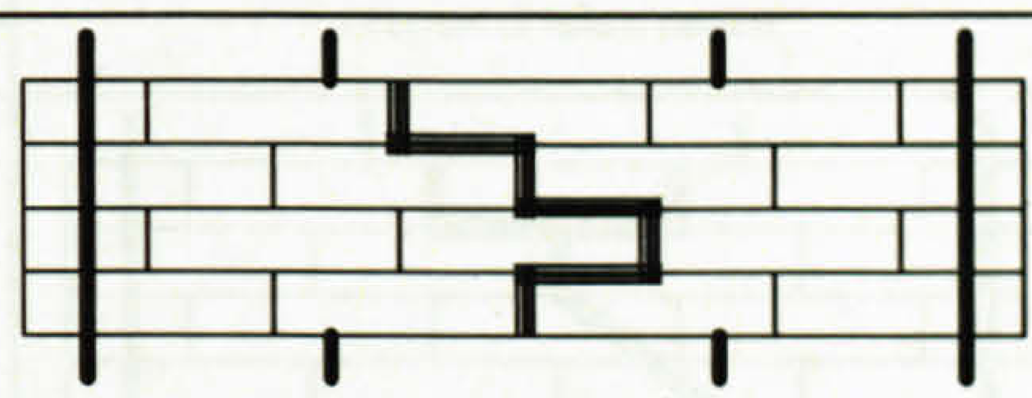
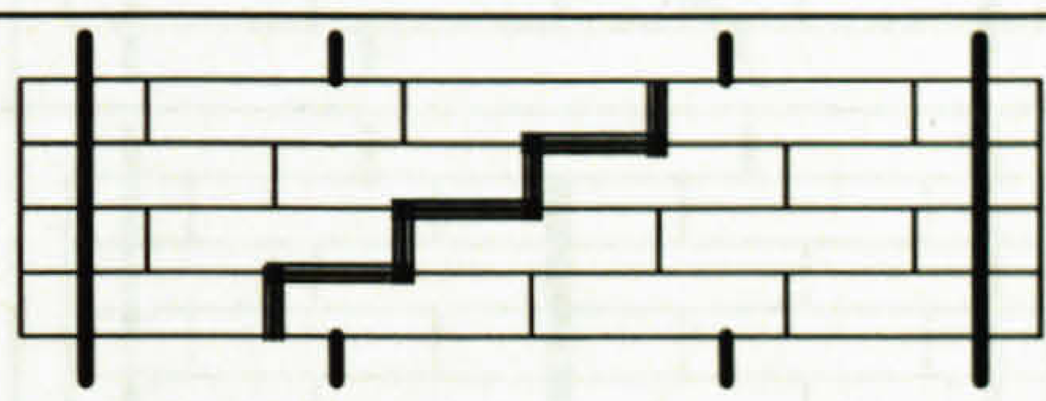
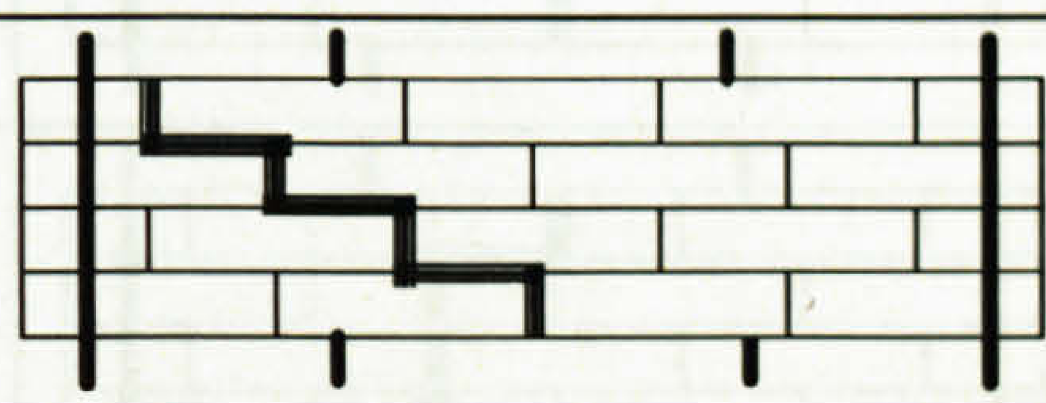
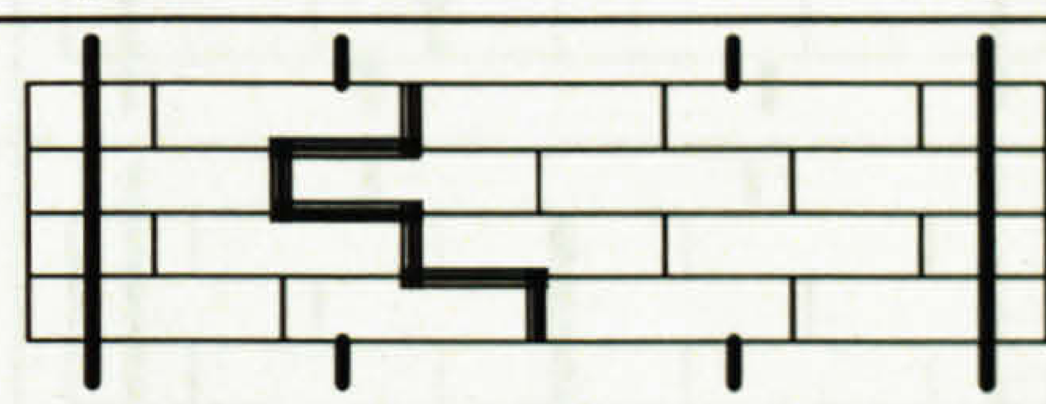
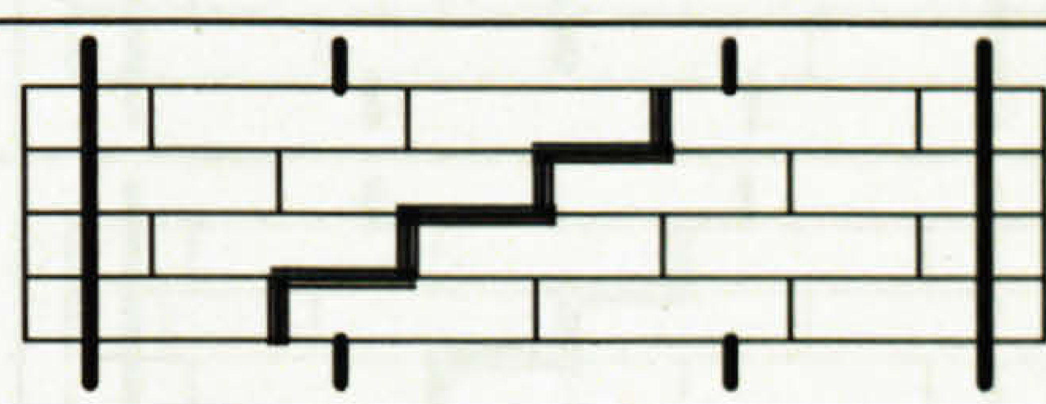
RED BRICK - NHL

B	BUILD DATE		TEST DATE		273	DAY	
	15 August 2005		15 May 2006		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	(mm)	L	R	(kN)		mm^3	N/mm^2
281	439	743	743	2.00	4	1301024.0	**0.21**
282	438	750	750	1.76	5	1313281.3	**0.18**
283	439	748	750	2.67	5	1311530.2	**0.27**
284	440	745	746	3.09	7	1305401.6	**0.32**
285	438	745	745	2.82	4	1304526.0	**0.29**
Red		MEAN		2.47	**MEAN**	1307152.6	**0.25**
		STDEV		0.56	**STDEV**	5105.12	**0.06**
		COV		0.23	**COV**	0.00	**0.23**
					CHARACTERISTIC STRENGTH		0.16

P	BUILD DATE		TEST DATE		273	DAY	
	15 August 2005		15 May 2006		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
1581	880	291	290	6.43		508677.6	**1.47**
1582	890	289	289	5.71		506051.0	**1.31**
1583	880	291	292	5.82		510428.6	**1.32**
1584	885	291	291	4.02		509553.1	**0.92**
1585	880	290	290	4.23		507802.1	**0.97**
Red		MEAN		5.24	**MEAN**	508502.5	**1.20**
		STDEV		1.06	**STDEV**	1684.10	**0.24**
		COV		0.20	**COV**	0.00	**0.20**
					CHARACTERISTIC STRENGTH		0.80

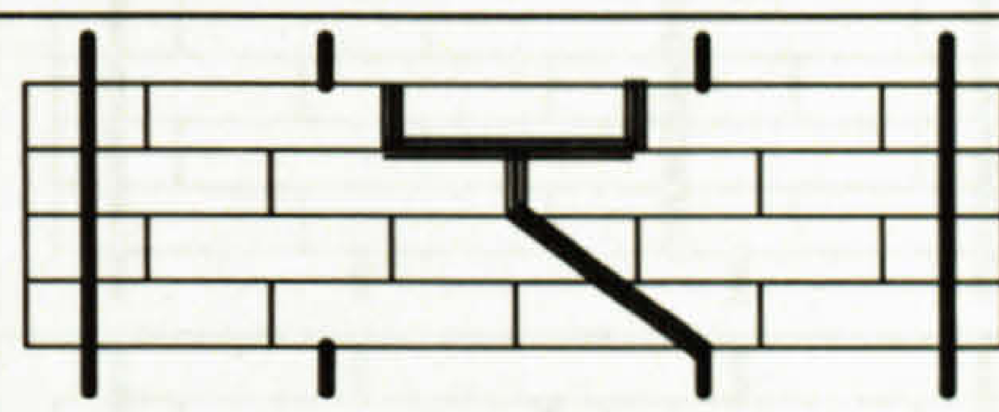
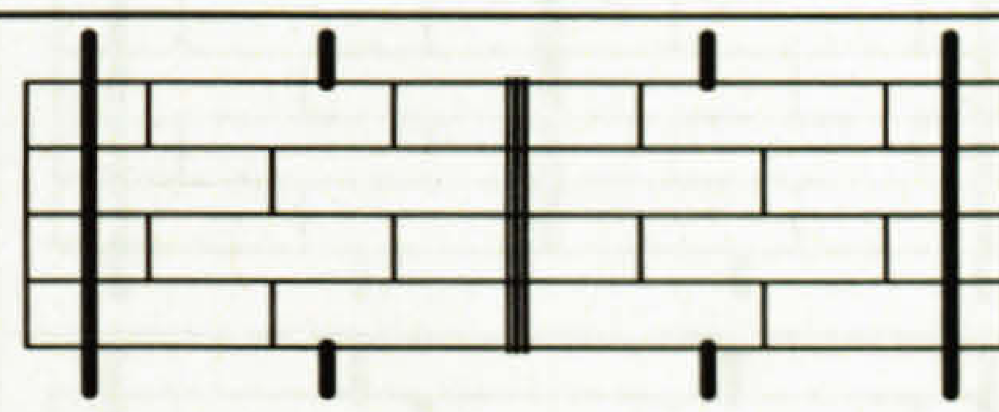
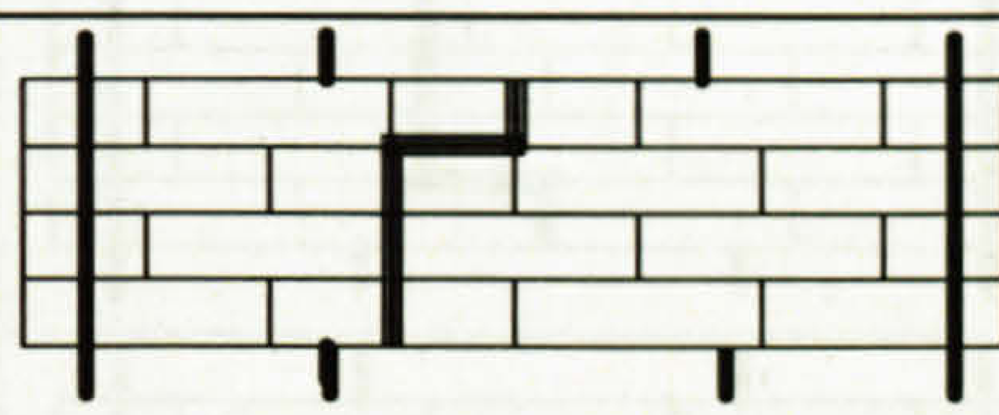
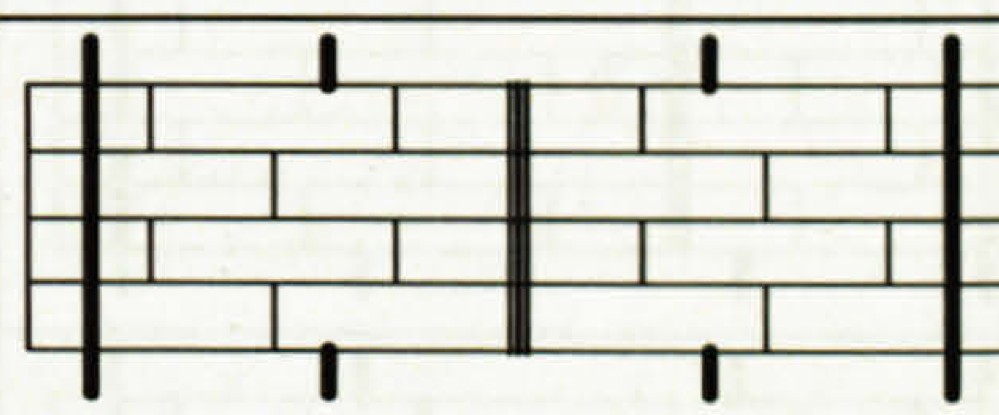
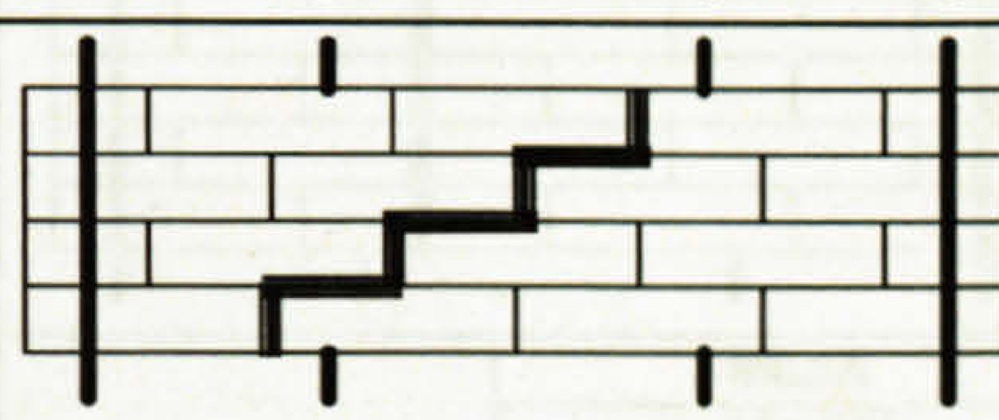
YELLOW BRICK - NHL

B	BUILD DATE		TEST DATE		DAY 91		
	16 August 2005		15 November 2005		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
1681	440	743	743	0.35	5	1301024.0	**0.04**
1682	440	750	750	0.44	4	1313281.3	**0.05**
1683	440	748	748	0.39	5	1309779.2	**0.04**
1684	440	745	745	0.47	4	1304526.0	**0.05**
1685	440	750	750	0.77	6	1313281.3	**0.08**
Yellow		MEAN		0.48	**MEAN**	1308378.3	**0.05**
		STDEV		0.17	**STDEV**	5453.59	**0.02**
		COV		0.34	**COV**	0.00	**0.34**
					CHARACTERISTIC STRENGTH		0.02

P	BUILD DATE		TEST DATE		DAY 91		
	01 August 2005		31 October 2005		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
2771	880	290	290	0.93		507802.1	**0.21**
2772	880	284	285	1.06		498171.4	**0.25**
2773	880	285	285	1.15		499046.9	**0.27**
2774	880	290	290	1.16		507802.1	**0.26**
2775	880	290	290	1.24		507802.1	**0.28**
Yellow		MEAN		1.11	**MEAN**	504124.9	**0.25**
		STDEV		0.12	**STDEV**	5044.70	**0.03**
		COV		0.11	**COV**	0.01	**0.11**
					CHARACTERISTIC STRENGTH		0.21

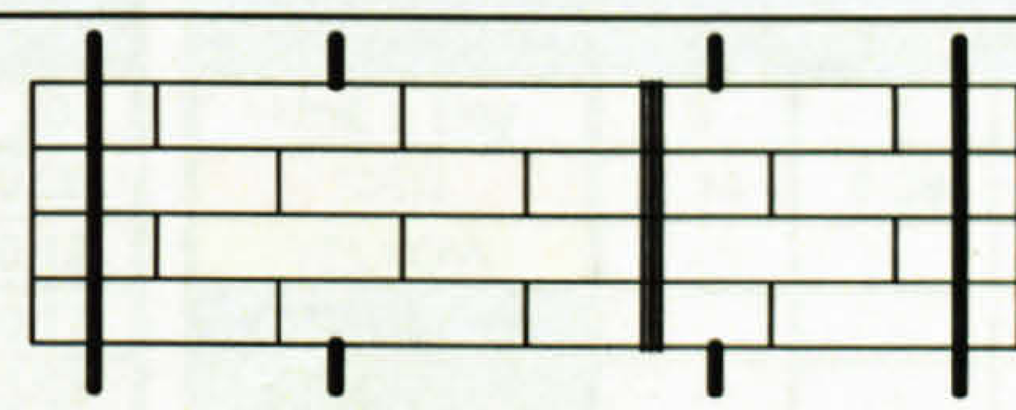
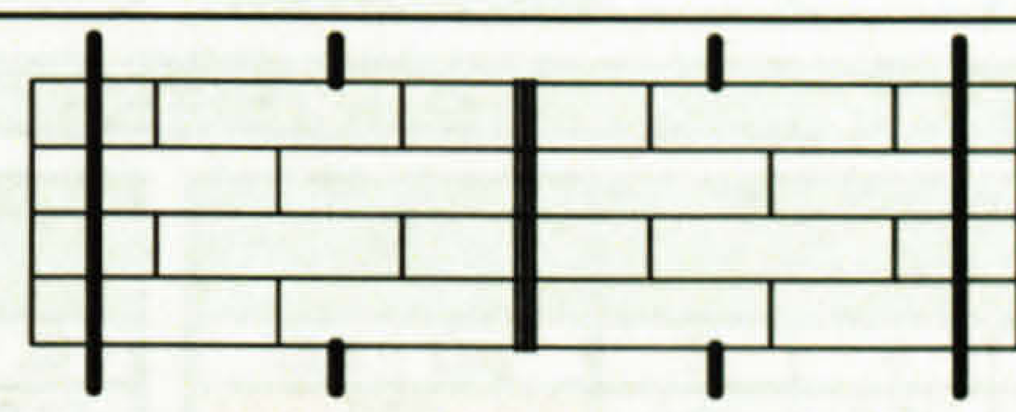
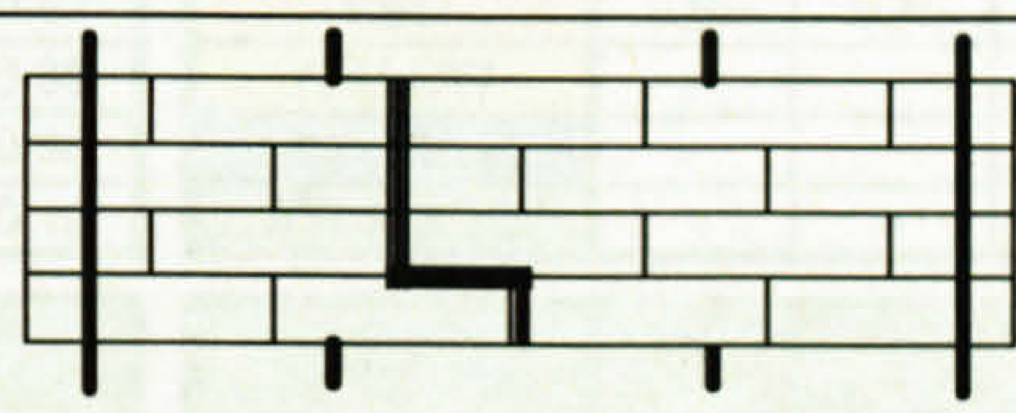
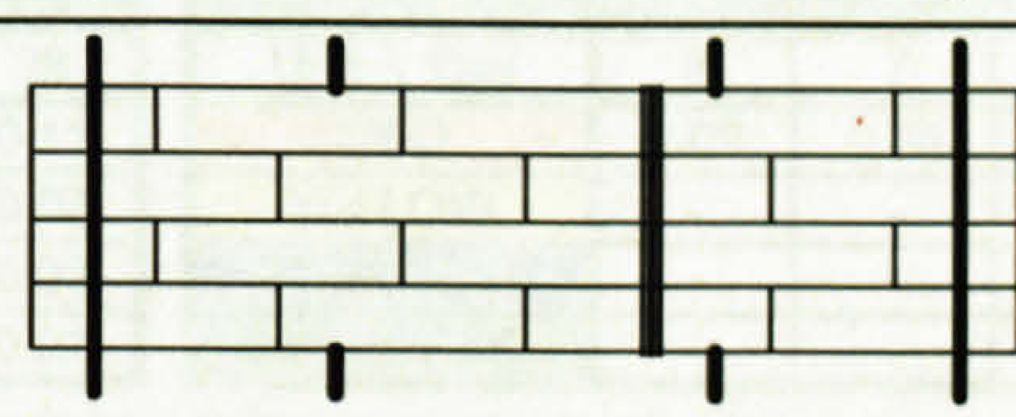
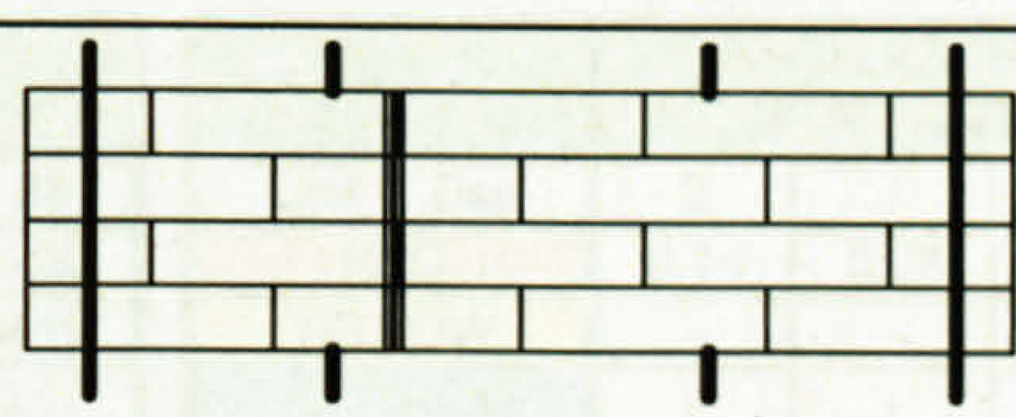
CONCRETE BRICK - NHL

B	BUILD DATE	TEST DATE		DAY	91		
	04 August 2005	03 November 2005		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength	
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm³	N/mm²
481	440	744	743	9.7	5	1301899.5	**1.01**
482	440	742	741	10.9	4	1298397.4	**1.13**
483	440	745	745	12.7	5	1304526.0	**1.31**
484	440	750	750	11.5	4	1313281.3	**1.18**
485	440	750	750	10.1	6	1313281.3	**1.04**
Concrete		MEAN		10.98	**MEAN**	1306277.1	**1.13**
		STDEV		1.19	**STDEV**	6753.44	**0.12**
		COV		0.11	**COV**	0.01	**0.11**
					CHARACTERISTIC STRENGTH		0.93

P	BUILD DATE	TEST DATE		DAY	91		
	03 August 2005	02 November 2005			FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm³	N/mm²
2771	880	290	290	5.60		507802.1	**1.28**
2772	880	285	285	6.90		499046.9	**1.60**
2773	880	288	288	3.74		504300.0	**0.86**
2774	880	290	290	4.50		507802.1	**1.03**
2775	880	291	291	4.46		509553.1	**1.02**
Concrete		MEAN		5.04	**MEAN**	505700.8	**1.16**
		STDEV		1.23	**STDEV**	4180.55	**0.29**
		COV		0.24	**COV**	0.01	**0.25**
					CHARACTERISTIC STRENGTH		0.68

AIRCRETE BRICK - NHL

B	BUILD DATE		TEST DATE		DAY	91	
	10 August 2005		09 November 2005		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
1081	434	74.3	74.3	0.53	5	130102.4	**0.55**
1082	432	75.0	75.0	0.38	4	131328.1	**0.39**
1083	433	74.8	75.0	0.54	5	131153.0	**0.56**
1084	434	74.5	74.6	0.41	4	130540.2	**0.42**
1085	434	74.5	74.5	0.39	6	130452.6	**0.40**
Aircrete		MEAN		0.45	**MEAN**	130715.3	**0.46**
		STDEV		0.08	**STDEV**	510.51	**0.08**
		COV		0.17	**COV**	0.00	**0.17**
					CHARACTERISTIC STRENGTH		0.33

P	BUILD DATE		TEST DATE		DAY 91		
	09 August 2005		08 November 2005		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
981	856	260	260	3.85		455270.8	**0.98**
982	855	260	260	6.94		455270.8	**1.77**
983	855	260	265	9.23		459648.4	**2.33**
984	855	260	264	9.03		458772.9	**2.28**
985	854	260	267	7.62		461399.5	**1.92**
Aircrete		MEAN		7.33	**MEAN**	458072.5	**1.86**
		STDEV		2.17	**STDEV**	2726.79	**0.54**
		COV		0.30	**COV**	0.01	**0.29**
					CHARACTERISTIC STRENGTH		0.96

Appendix E.3 – Ordinary Portland Cement Mortar

SUMMARY SHEET

ORDINARY PORTLAND CEMENT - WALLETTES

TEST DATA

B	MEAN FAILURE STRENGTH		
Unit \ Day	3	7	28
RED	1.05	1.48	5.53
YELLOW	-	-	3.72
CONCRETE	-	-	3.23
AIRCRETE	-	-	1.81

P	MEAN FAILURE STRENGTH		
Unit \ Day	3	7	28
RED	2.92	3.32	5.33
YELLOW	-	-	4.37
CONCRETE	-	-	3.30
AIRCRETE	-	-	2.19

B	STDEV FAILURE STRENGTH		
Unit \ Day	3	7	28
RED	0.17	0.49	1.12
YELLOW	-	-	0.70
CONCRETE	-	-	0.54
AIRCRETE	-	-	0.15

P	STDEV FAILURE STRENGTH		
Unit \ Day	3	7	28
RED	0.40	0.26	0.41
YELLOW	-	-	0.32
CONCRETE	-	-	0.27
AIRCRETE	-	-	0.38

B	COV FAILURE STRENGTH		
Unit \ Day	3	7	28
RED	0.16	0.33	0.20
YELLOW	-	-	0.19
CONCRETE	-	-	0.17
AIRCRETE	-	-	0.08

P	COV FAILURE STRENGTH		
Unit \ Day	3	7	28
RED	0.14	0.08	0.08
YELLOW	-	-	0.07
CONCRETE	-	-	0.08
AIRCRETE	-	-	0.17

WALLETTE DATA ANALYSIS

B	MEAN FLEXURAL STRENGTH		
Unit \ Day	3	7	28
RED	0.11	0.15	0.57
YELLOW	-	-	0.39
CONCRETE	-	-	0.33
AIRCRETE	-	-	0.19

P	MEAN FLEXURAL STRENGTH		
Unit \ Day	3	7	28
RED	0.66	0.75	1.21
YELLOW	-	-	0.99
CONCRETE	-	-	0.75
AIRCRETE	-	-	0.50

B	STDEV FLEXURAL STRENGTH		
Unit \ Day	3	7	28
RED	0.02	0.05	0.11
YELLOW	-	-	0.07
CONCRETE	-	-	0.06
AIRCRETE	-	-	0.02

P	STDEV FLEXURAL STRENGTH		
Unit \ Day	3	7	28
RED	0.09	0.06	0.10
YELLOW	-	-	0.08
CONCRETE	-	-	0.06
AIRCRETE	-	-	0.09

B	COV FLEXURAL STRENGTH		
Unit \ Day	3	7	28
RED	0.16	0.33	0.20
YELLOW	-	-	0.19
CONCRETE	-	-	0.17
AIRCRETE	-	-	0.08

P	COV FLEXURAL STRENGTH		
Unit \ Day	3	7	28
RED	0.14	0.08	0.08
YELLOW	-	-	0.08
CONCRETE	-	-	0.06
AIRCRETE	-	-	0.17

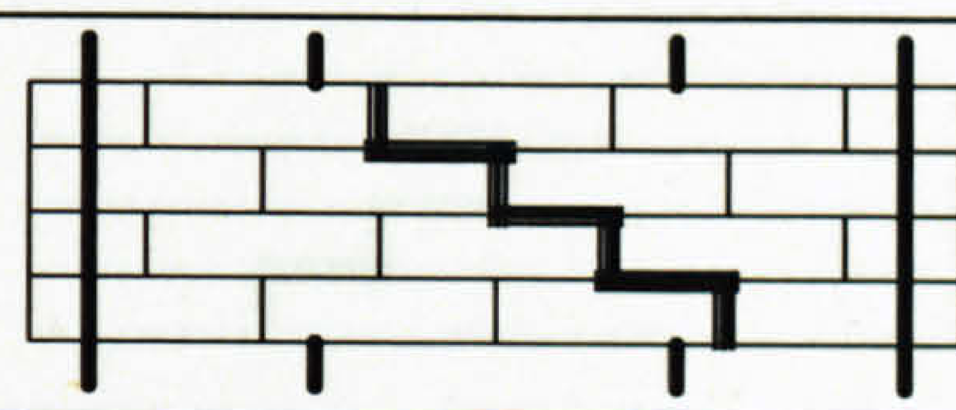
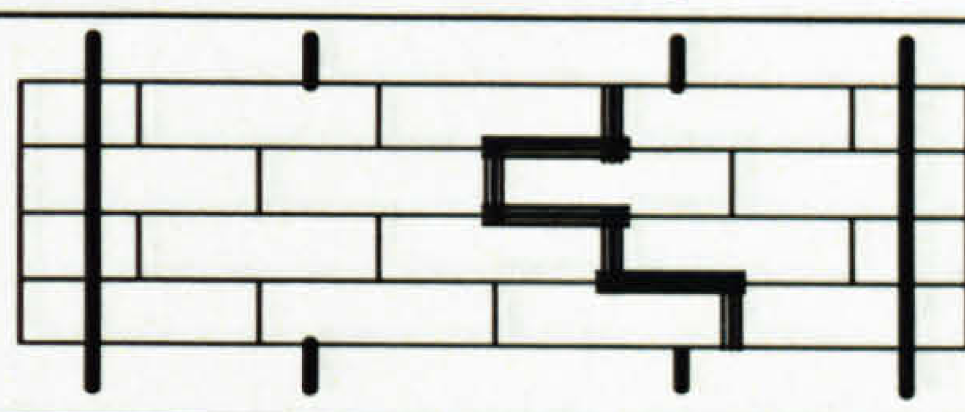
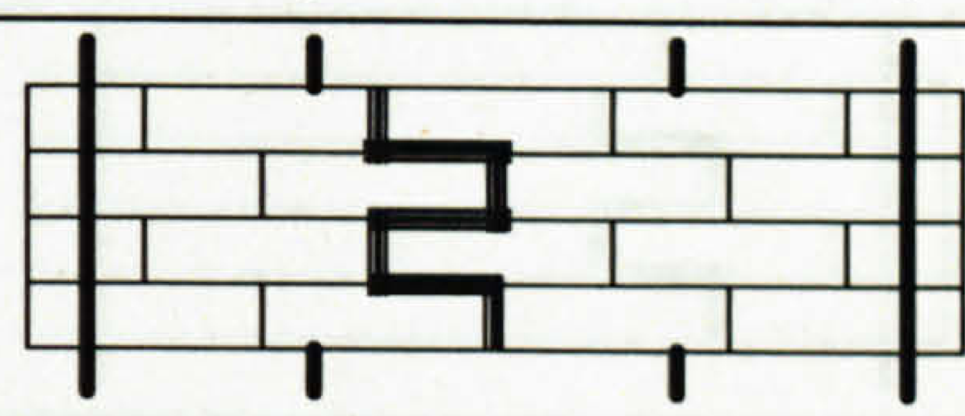
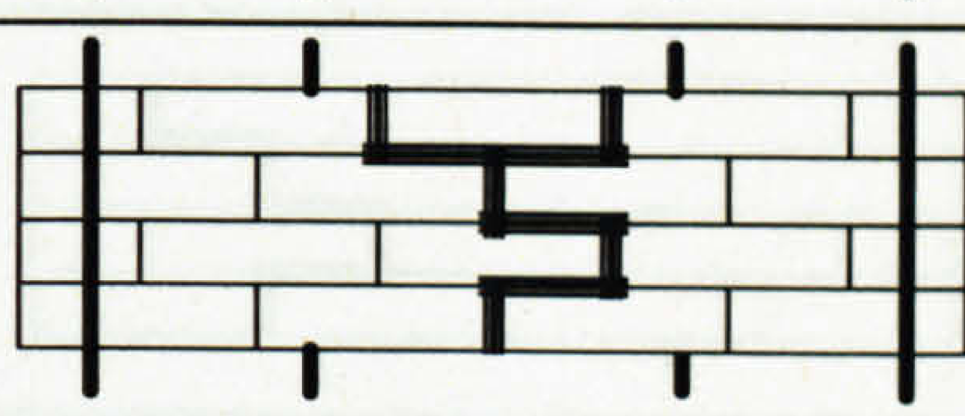
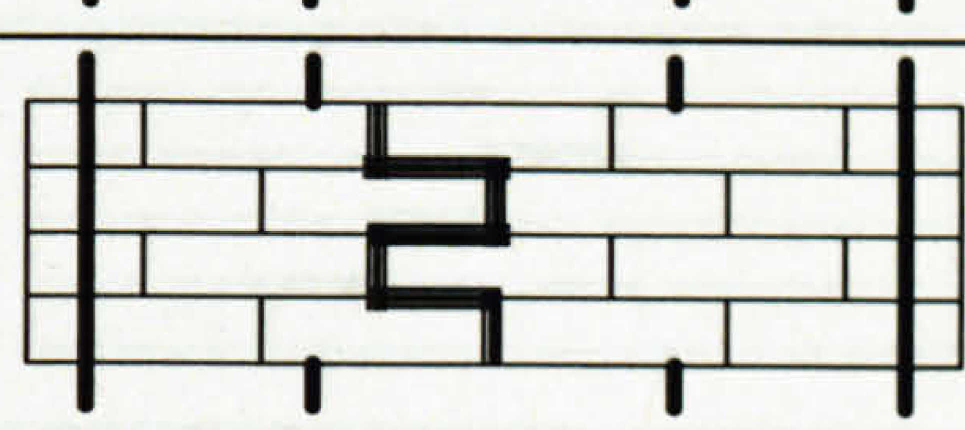
CHARACTERISTICS

B	CHARACTERISTIC STRENGTH		
Unit \ Day	3	7	28
RED	0.08	0.07	0.39
YELLOW	-	-	0.27
CONCRETE	-	-	0.24
AIRCRETE	-	-	0.16

P	CHARACTERISTIC STRENGTH		
Unit \ Day	3	7	28
RED	0.51	0.65	1.05
YELLOW	-	-	0.86
CONCRETE	-	-	0.65
AIRCRETE	-	-	0.35

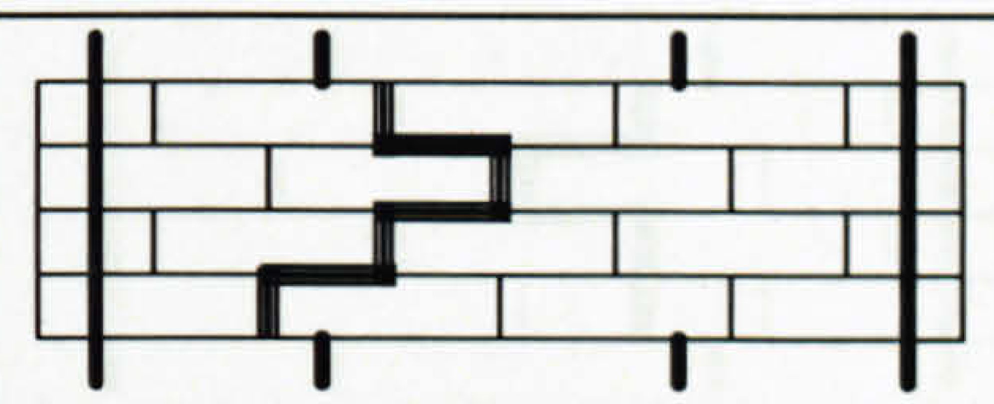
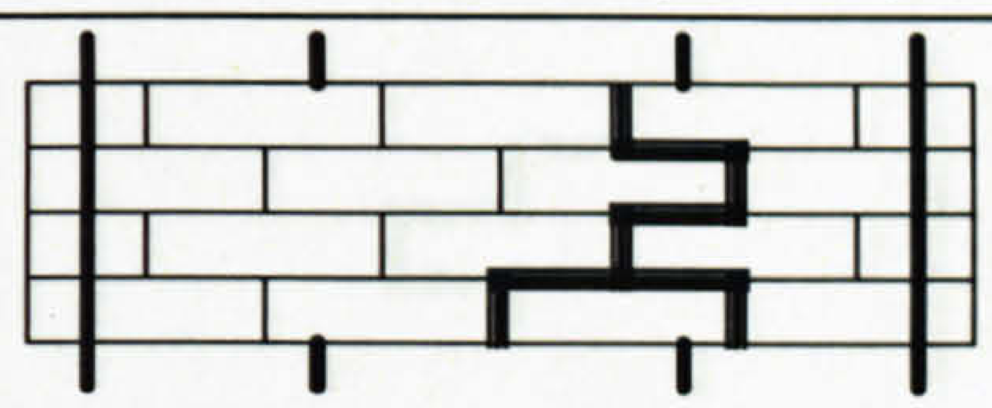
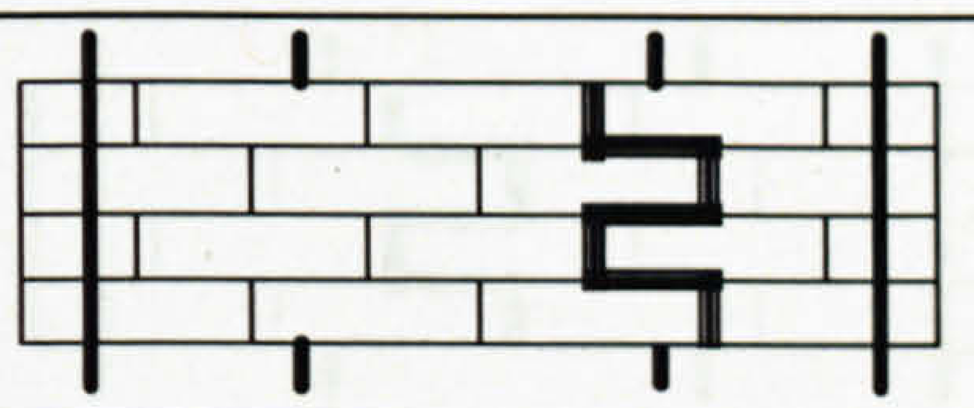
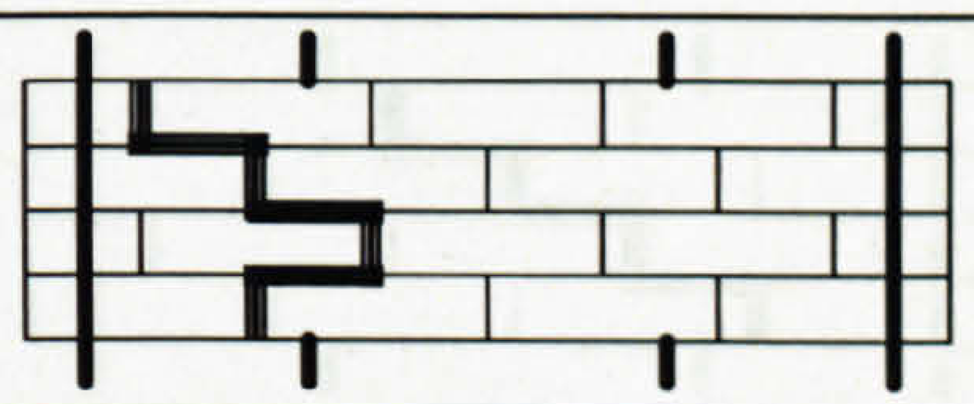
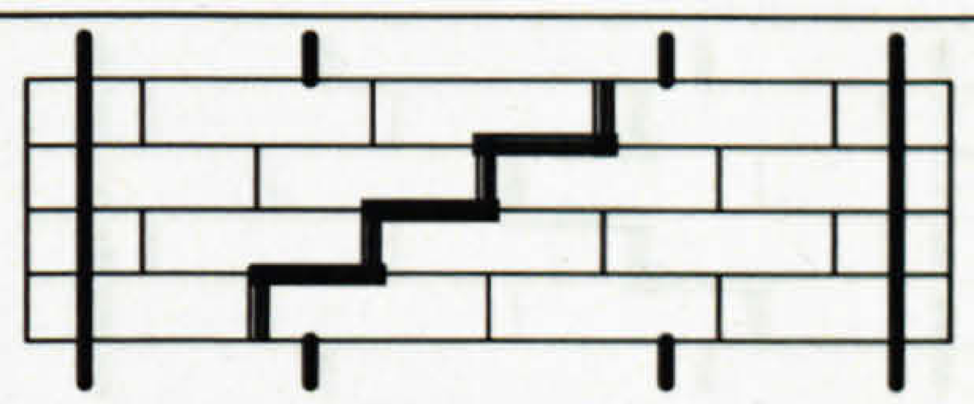
RED BRICK - OPCiii

B	BUILD DATE		TEST DATE		DAY	3	
	27 June 2005		30 June 2005		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
2761	442	748	748	1.09	6	1309779.2	**0.11**
2762	444	746	746	0.99	4	1306277.1	**0.10**
2763	440	745	745	1.00	4	1304526.0	**0.10**
2764	440	742	742	1.32	5	1299272.9	**0.14**
2765	440	740	740	0.87	3	1295770.8	**0.09**
Red		MEAN		1.05	**MEAN**	1303125.2	**0.11**
		STDEV		0.17	**STDEV**	5592.38	**0.02**
		COV		0.16	**COV**	0.00	**0.16**
					CHARACTERISTIC STRENGTH		0.08

P	BUILD DATE		TEST DATE		DAY 3		
	27 June 2005		30 June 2005		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
2761	890	293	293	3.28		513055.2	**0.74**
2762	890	293	291	2.52		511304.2	**0.57**
2763	890	290	290	3.24		507802.1	**0.74**
2764	890	293	292	3.12		512179.7	**0.71**
2765	890	293	290	2.45		510428.6	**0.56**
Red		MEAN		2.92	MEAN	510954.0	**0.66**
		STDEV		0.40	STDEV	2015.60	**0.09**
		COV		0.14	COV	0.00	**0.14**
					CHARACTERISTIC STRENGTH		0.51

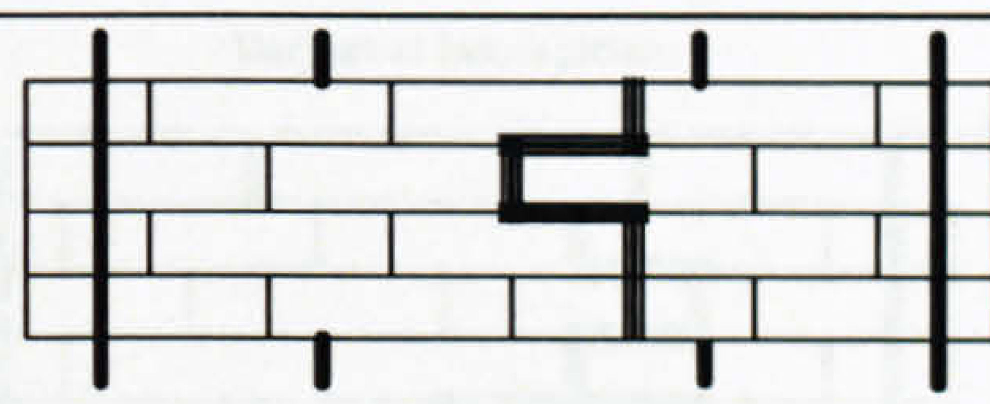
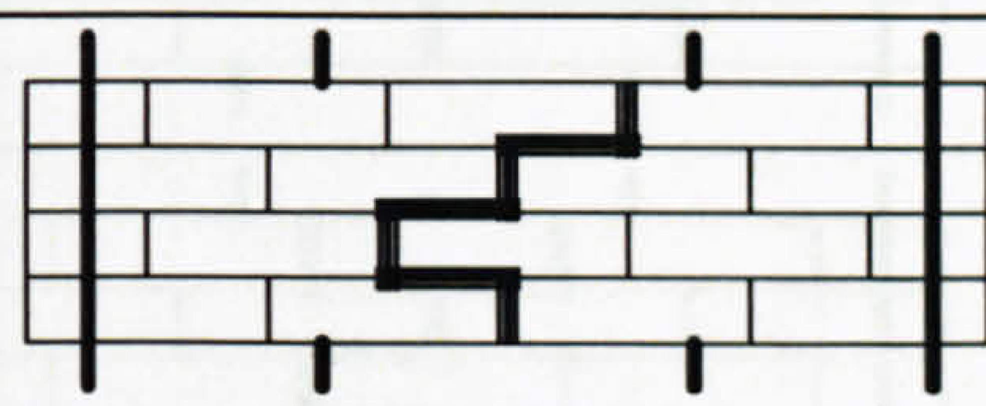
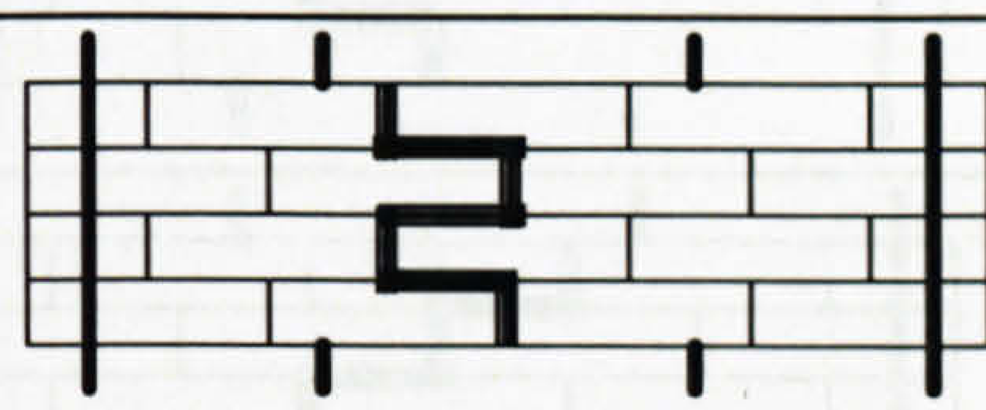
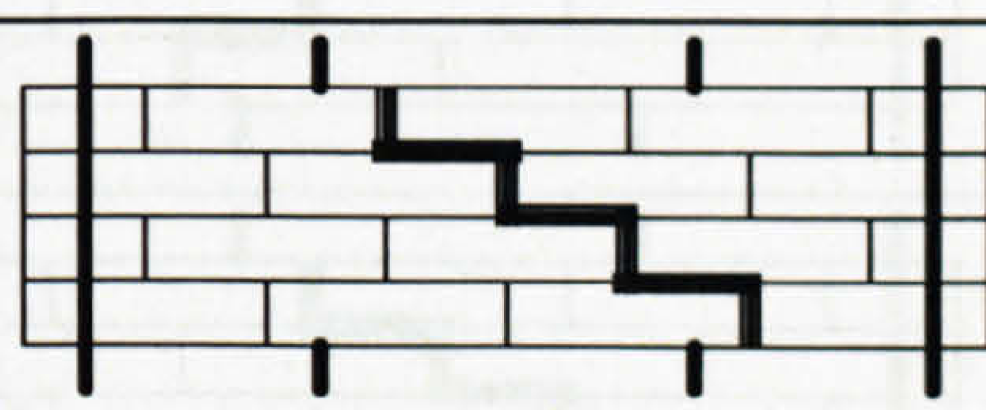
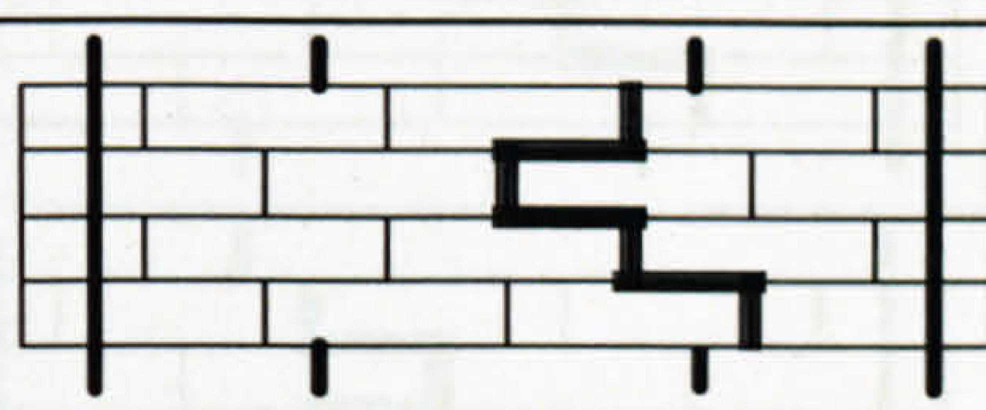
RED BRICK - OPCiii

B	BUILD DATE		TEST DATE		DAY	7		
	24 June 2005		01 July 2005		Bond Failure at Number of Joints counting from the Top		Z	Flexural Strength
WALL	Width	Height (mm)		Reading				
2x10	mm	L	R	kN			mm³	N/mm²
2461	440	742	742	1.95	4		1299272.9	**0.20**
2462	440	740	740	1.06	3		1295770.8	**0.11**
2463	440	740	740	1.37	7		1295770.8	**0.14**
2464	440	740	740	2.05	5		1295770.8	**0.21**
2465	440	750	748	0.99	4		1311530.2	**0.10**
Red		MEAN		1.48	MEAN		1299623.1	**0.15**
		STDEV		0.49	STDEV		6826.82	**0.05**
		COV		0.33	COV		0.01	**0.33**
					CHARACTERISTIC STRENGTH			0.07

P	BUILD DATE		TEST DATE		DAY 7		
	23 June 2005		30 June 2005		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm³	N/mm²
2361	890	290	292	3.56		509553.1	**0.81**
2362	890	295	290	3.65		512179.7	**0.83**
2363	890	294	294	3.14		514806.3	**0.71**
2364	890	295	295	3.09		516557.3	**0.69**
2365	890	293	293	3.15		513055.2	**0.71**
Red		MEAN		3.32	**MEAN**	513230.3	**0.75**
		STDEV		0.26	**STDEV**	2655.59	**0.06**
		COV		0.08	**COV**	0.01	**0.08**
					CHARACTERISTIC STRENGTH		0.65

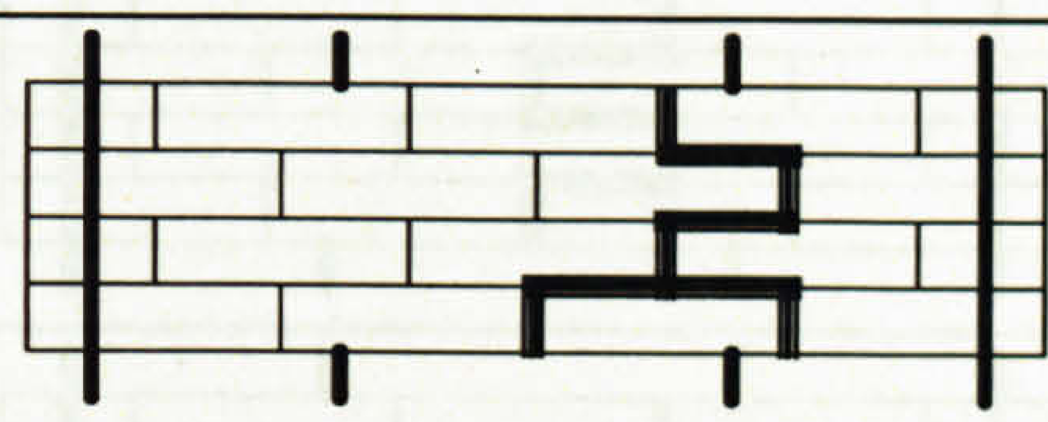
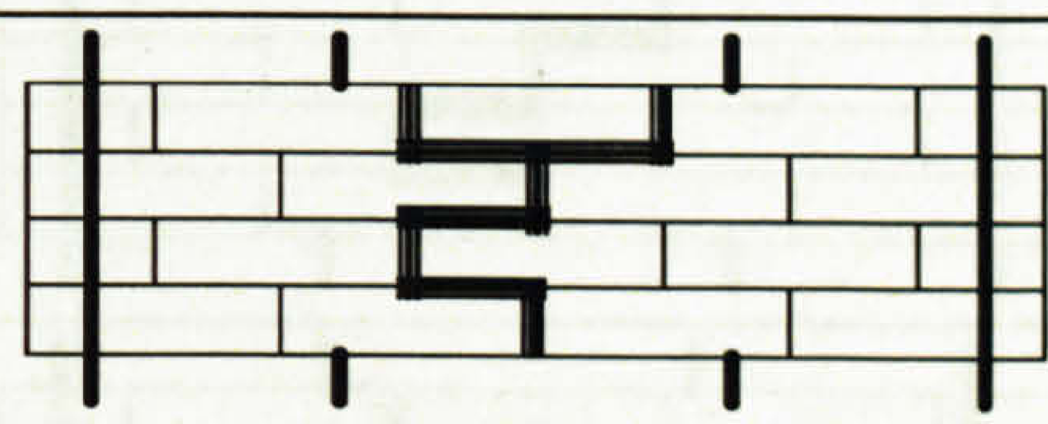
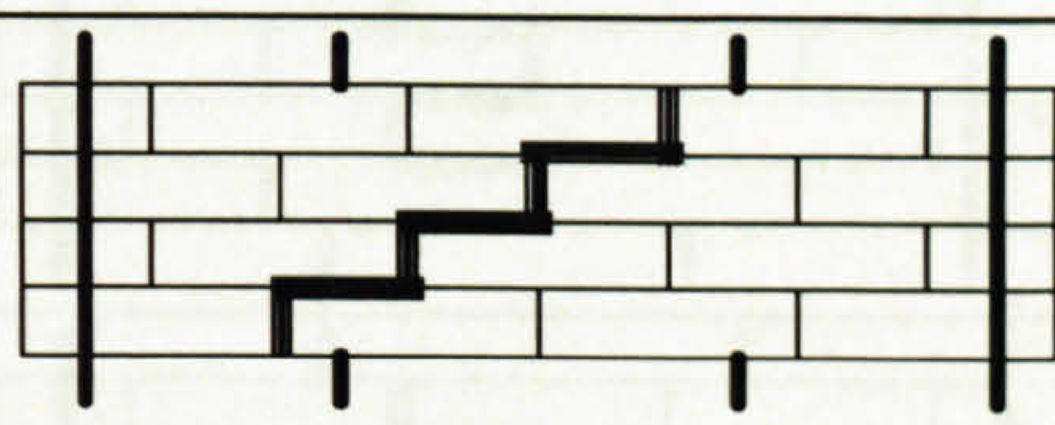
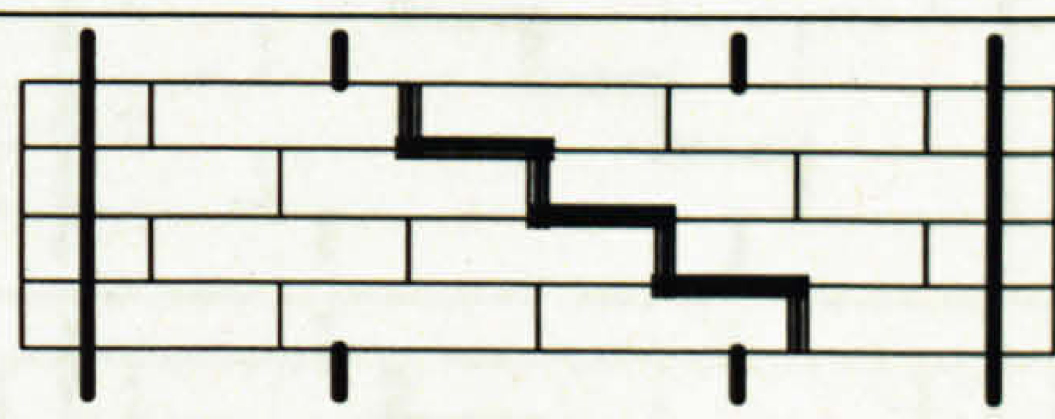
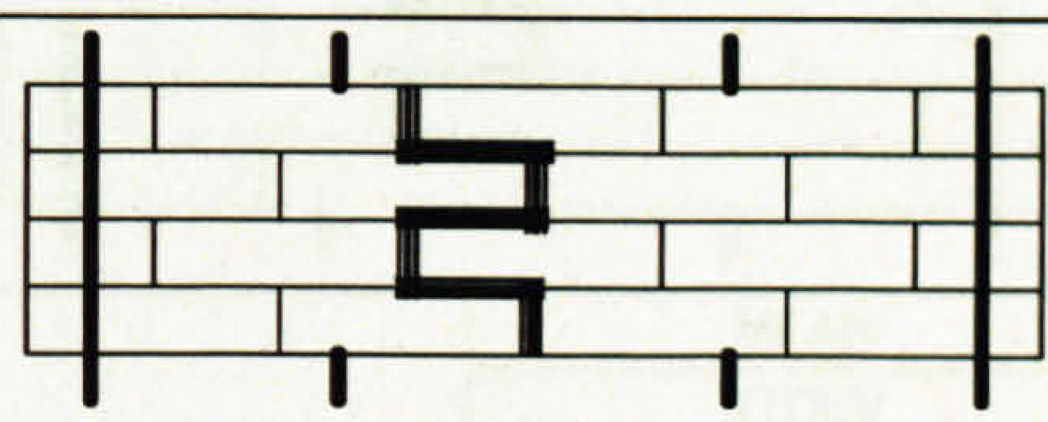
RED BRICK - OPCiii

B	BUILD DATE	TEST DATE			DAY	28	
	15 June 2005	13 July 2005			Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm³	N/mm²
1561	440	742	742	6.50	5	1299272.9	**0.68**
1562	440	740	740	4.59	2	1295770.8	**0.48**
1563	440	740	740	4.54	3	1295770.8	**0.47**
1564	440	740	740	5.08	3	1295770.8	**0.53**
1565	440	750	748	6.96	5	1311530.2	**0.72**
Red		MEAN		5.53	**MEAN**	1299623.1	**0.57**
		STDEV		1.12	**STDEV**	6826.82	**0.11**
		COV		0.20	**COV**	0.01	**0.20**
					CHARACTERISTIC STRENGTH		0.39

P	BUILD DATE	TEST DATE			DAY 28		
	15 June 2005	13 July 2005			FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm³	N/mm²
1561	890	290	290	5.55		507802.1	**1.27**
1562	890	293	290	5.86		510428.6	**1.33**
1563	890	295	295	4.78		516557.3	**1.07**
1564	890	295	295	5.34		516557.3	**1.20**
1565	890	290	290	5.13		507802.1	**1.17**
Red		MEAN		5.33	**MEAN**	511829.5	**1.21**
		STDEV		0.41	**STDEV**	4447.09	**0.10**
		COV		0.08	**COV**	0.01	**0.08**
					CHARACTERISTIC STRENGTH		1.05

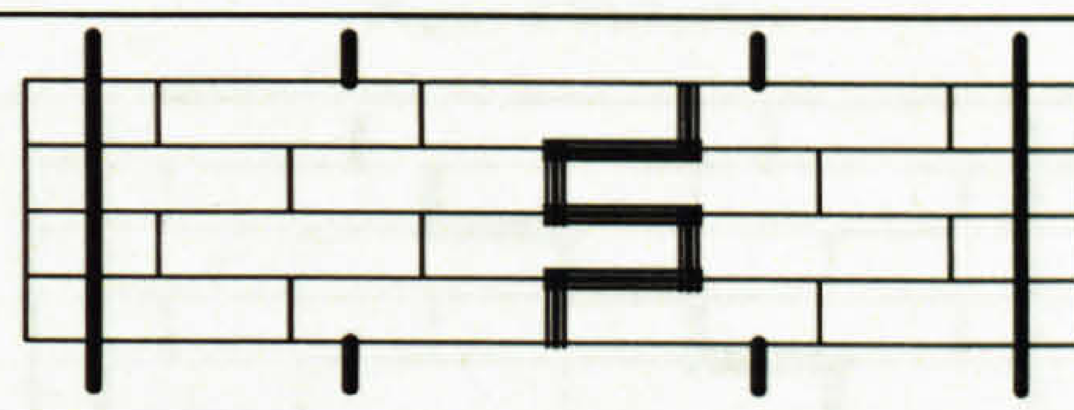
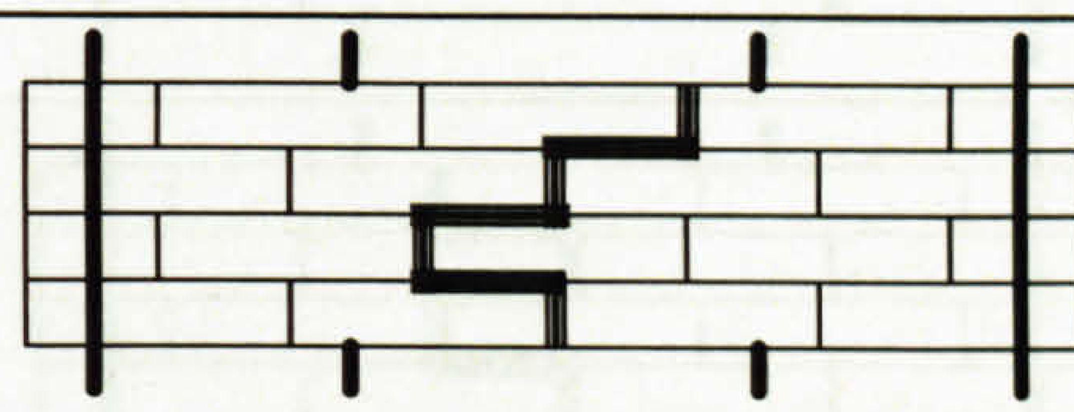
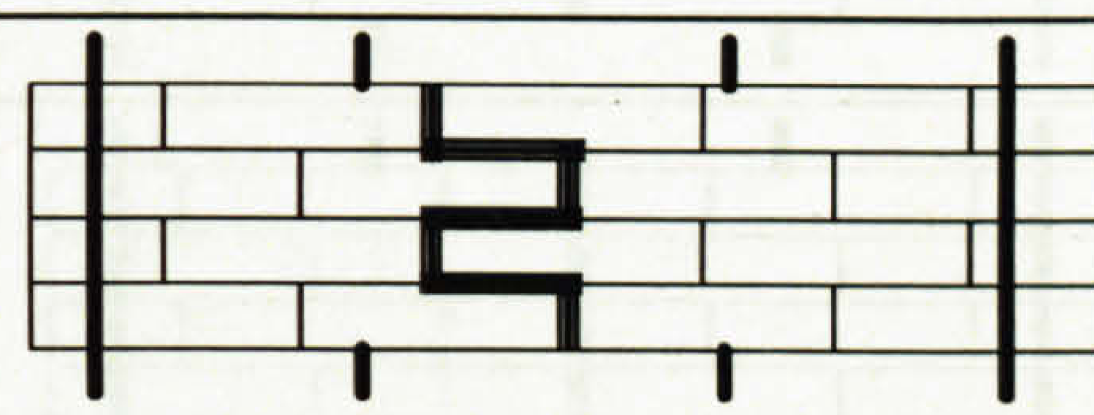
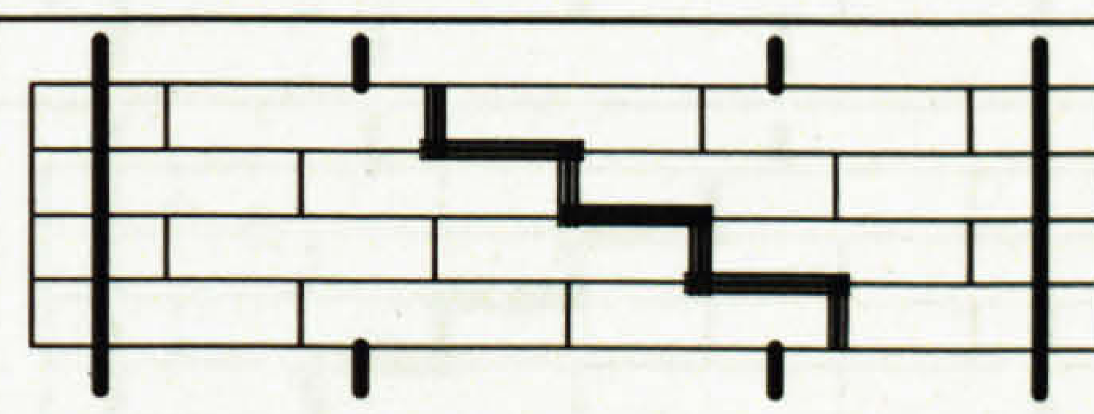
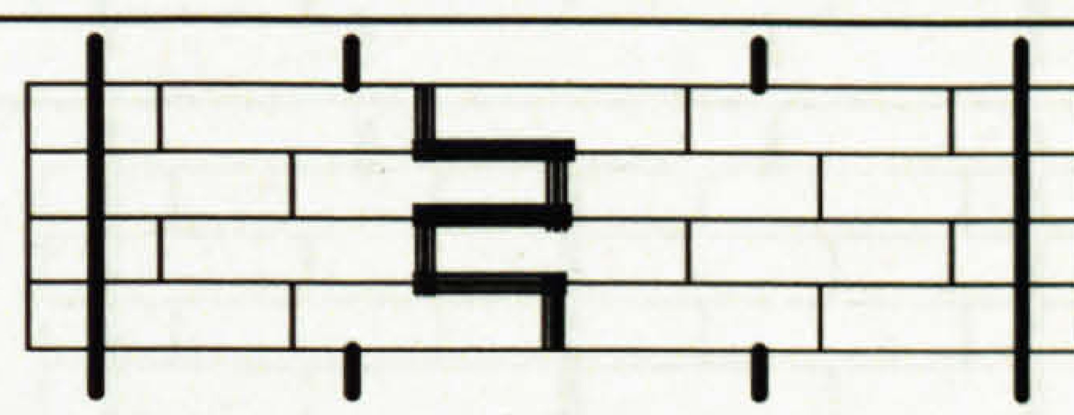
YELLOW BRICK - OPCiii

B	BUILD DATE		TEST DATE		DAY 28		
	15 June 2005		13 July 2005				
WALL	Width	Height (mm)		Reading	Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
2x10	mm	L	R	kN		mm^3	N/mm^2
1761	440	745	745	3.24	5	1304526.0	0.34
1762	440	742	742	3.50	5	1299272.9	0.36
1763	440	746	745	2.98	4	1305401.6	0.31
1764	440	745	745	4.21	3	1304526.0	0.44
1765	440	746	746	4.67	3	1306277.1	0.48
Yellow	MEAN			3.72	MEAN	1304000.7	0.39
	STDEV			0.70	STDEV	2740.81	0.07
	COV			0.19	COV	0.00	0.19
					CHARACTERISTIC STRENGTH		0.27

P	BUILD DATE		TEST DATE		DAY 28		
	17 June 2005		15 July 2005		FAILURE MODE		
WALL	Width	Height (mm)		Reading	Diagram of failure pattern	Z	Flexural Strength
4x4	mm	L	R	kN		mm^3	N/mm^2
1561	890	290	294	4.19		511304.2	0.95
1562	890	290	290	4.94		507802.1	1.13
1563	890	295	293	4.16		514806.3	0.94
1564	890	295	294	4.34		515681.8	0.98
1565	890	290	291	4.23		508677.6	0.96
Yellow	MEAN			4.37	MEAN	511654.4	0.99
	STDEV			0.32	STDEV	3534.76	0.08
	COV			0.07	COV	0.01	0.08
					CHARACTERISTIC STRENGTH		0.86

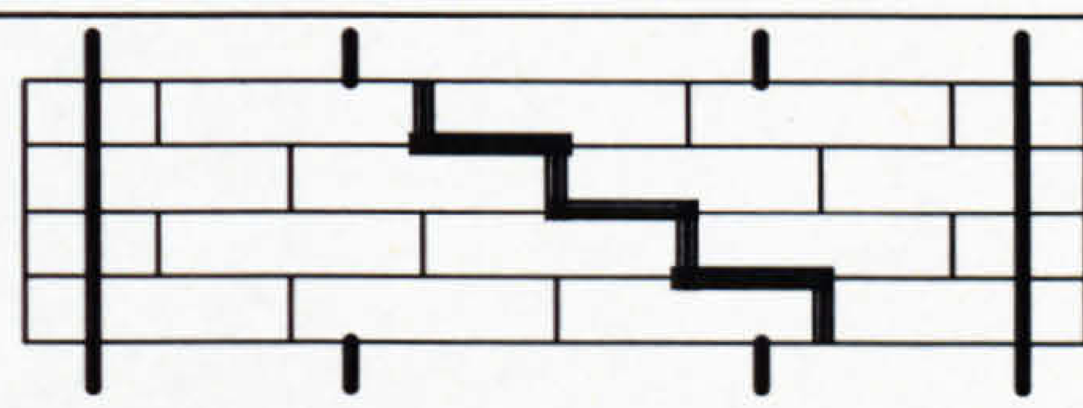
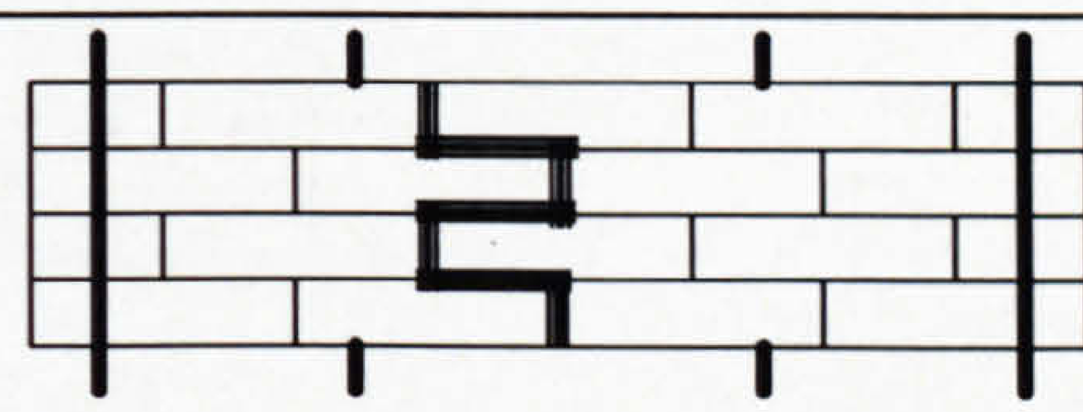
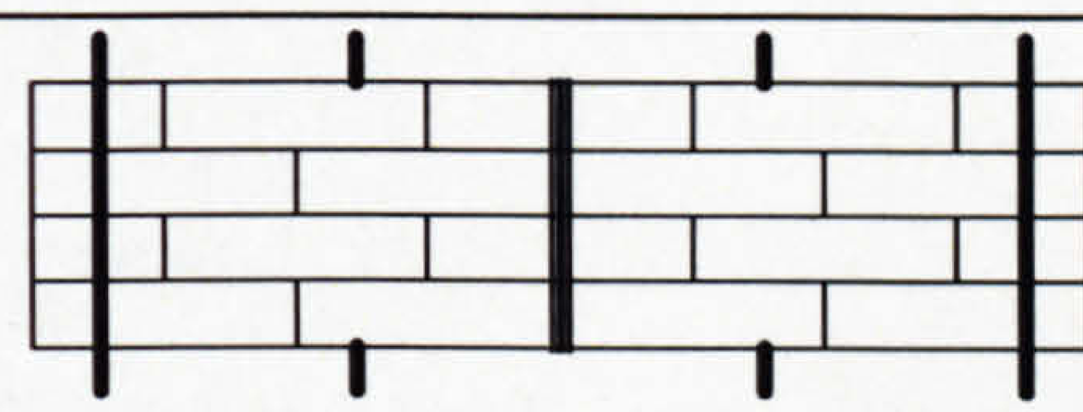
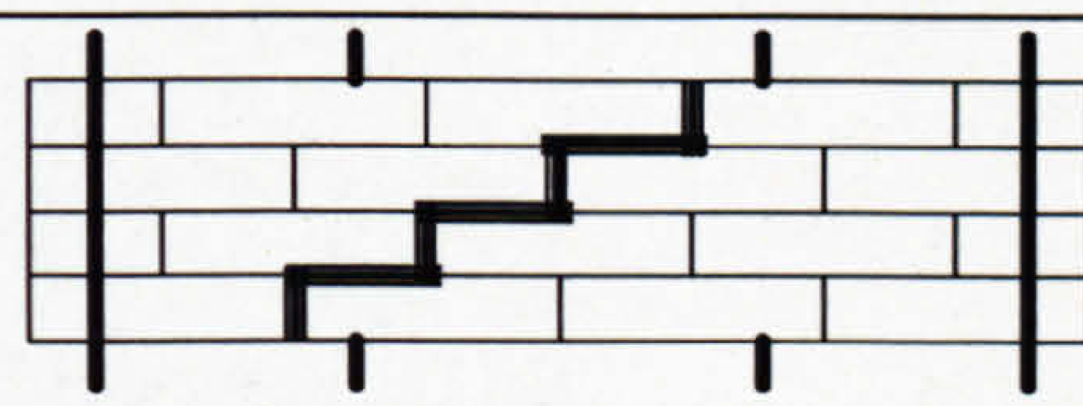
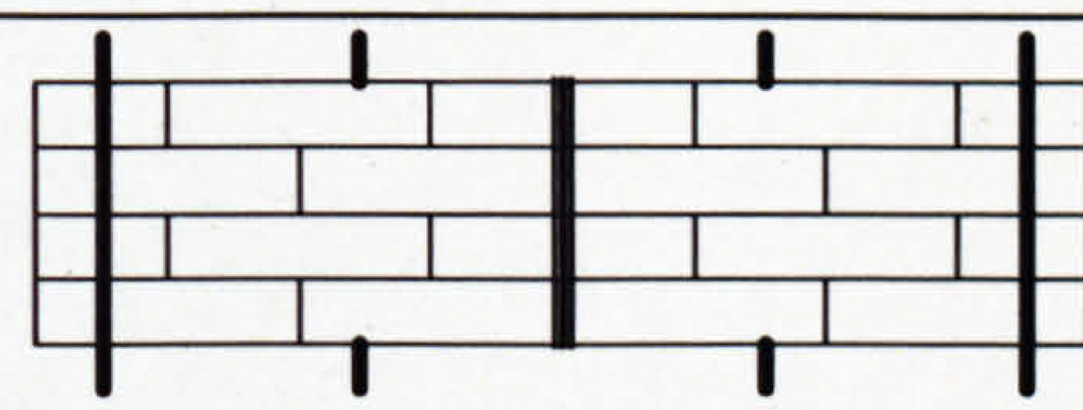
CONCRETE BRICK - OPCiii

B	BUILD DATE		TEST DATE		DAY	28	
	24-Sep-05		22-Oct-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
2491	440	744	744	2.86	5	1302775.0	0.30
2492	440	745	744	3.82	5	1303650.5	0.40
2493	440	740	740	2.75	4	1295770.8	0.29
2494	440	745	745	2.89	3	1304526.0	0.30
2495	440	745	745	3.81	3	1304526.0	0.39
Concrete		MEAN		3.23	MEAN	1302249.7	0.33
		STDEV		0.54	STDEV	3693.83	0.06
		COV		0.17	COV	0.00	0.17
					CHARACTERISTIC STRENGTH		0.24

P	BUILD DATE		TEST DATE		DAY 28		
	23-Sep-05		21-Oct-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
2391	890	290	294	3.23		511304.2	0.73
2392	890	290	290	3.54		507802.1	0.81
2393	890	295	293	2.98		514806.3	0.67
2394	890	295	294	3.62		515681.8	0.81
2395	890	290	291	3.12		508677.6	0.71
Concrete		MEAN		3.30	MEAN	511654.4	0.75
		STDEV		0.27	STDEV	3534.76	0.06
		COV		0.08	COV	0.01	0.08
					CHARACTERISTIC STRENGTH		0.65

AIRCRETE BRICK - OPCiii

B	BUILD DATE		TEST DATE		DAY 28		
	17-Aug-05		14-Sep-05		Bond Failure at Number of Joints counting from the Top	Z	Flexural Strength
WALL	Width	Height (mm)		Reading			
2x10	mm	L	R	kN		mm^3	N/mm^2
1781	440	745	745	1.81	5	1304526.0	0.19
1782	440	740	740	1.91	5	1295770.8	0.20
1783	440	743	745	1.57	3	1302775.0	0.16
1784	440	745	745	1.95	4	1304526.0	0.20
1785	440	745	745	1.83	3	1304526.0	0.19
Aircrete		MEAN		1.81	MEAN	1302424.8	0.19
		STDEV		0.15	STDEV	3796.17	0.02
		COV		0.08	COV	0.00	0.08
					CHARACTERISTIC STRENGTH		0.16

P	BUILD DATE		TEST DATE		DAY 28		
	23-Sep-05		21-Oct-05		FAILURE MODE	Z	Flexural Strength
WALL	Width	Height (mm)		Reading	Diagram of failure pattern		
4x4	mm	L	R	kN		mm^3	N/mm^2
2391	890	290	294	1.92		511304.2	0.44
2392	890	290	290	1.98		507802.1	0.45
2393	890	295	293	2.61		514806.3	0.59
2394	890	295	294	1.84		515681.8	0.41
2395	890	290	291	2.59		508677.6	0.59
Aircrete		MEAN		2.19	MEAN	511654.4	0.50
		STDEV		0.38	STDEV	3534.76	0.09
		COV		0.17	COV	0.01	0.17
					CHARACTERISTIC STRENGTH		0.35