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Published version

HETHERINGTON, Steven (2015). A comparative study into the tensile bond strength of the brick mortar interface of Naturally Hydraulic lime and Portland cement mortars. Masonry International, 28 (2), 67-64.

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A COMPARATIVE STUDY INTO THE TENSILE BOND STRENGTH OF THE BRICK MORTAR INTERFACE OF NATURALLY HYDRAULIC LIME AND PORTLAND CEMENT MORTARS

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ABSTRACT
This project was designed to compare and contrast the performance characteristics and properties of a variety of different mortar mixes, with the entire sample set being tested at 28 days. Volume proportioned mortar mixes were produced using both eminently hydraulic lime (NHL5) and Portland cement to give target performance strength specifications of M2, M4 and M6.These target strength specifications are equivalent to traditional volume proportions of 1:3, 1:6 and 1:8.

In each case the mortars were made using a constant mass of sand and the correct proportions of each mortar mix were obtained by varying the mass of binder used. This was designed to give greater control over the water content of each mix.

Bond strength tests were performed on couplets using a direct tensile test, developed at Sheffield Hallam University. The results indicated that Portland cement mortars consistently performed better than the corresponding hydraulic lime mortars in terms of tensile bond strength However, the results also indicated that the higher mix proportion limes did compare favourably with the lower proportioned cement based mortars

KEYWORDS: masonry, tensile bond strength, eminently hydraulic lime (NHL5), Portland cement mortar, comparative study.

1. INTRODUCTION

In recent years the building industry has been encouraged to use hydraulic lime mortars especially in low rise domestic dwellings. This is mainly in response to calls for a more environmentally friendly and sustainable alternative to Portland cement mortars.

Hydraulic limes are produced at lower temperatures than their cement based counterparts and subsequently do not utilise as much fossil fuel in their production reducing the amount of carbon dioxide that is liberated in manufacture.

However, the transition from the use of cement based mortars to lime based mortars has not been fully embraced by the construction industry. This is partly due to a lack of information and confidence surrounding the performance of hydraulic lime mortars and the masonry composite that they produce. This cautious approach can be attributed in some part to the conservative nature of the industry and to the absence of firm, reliable and quantifiable information on the performance of hydraulic limes in comparison to Portland cement. This paper will provide some of the answers to questions surrounding the use and performance of lime mortars.

2. MORTAR PREPARATION

The eminently hydraulic lime (NHL5) and the Portland cement mortar mixes were both produced in accordance with BS 4551:1998. Although this standard has been withdrawn, the mortar mixing procedure it outlines has been found to give an excellent level of replication for the production of mortar mixes and gives a volume of material appropriate to that needed to fabricate the number of test samples required.

The workability of the mixes was tested using the dropping ball test to the procedures set out in BS 4551:2005. This was done to ensure that the workability of each mortar was consistent. This standard states that each "mortar mix prepared in the laboratory should have its consistency adjusted to a penetration of 10+ or - 0.5mm" [1] BS 4551:2005.The workability of each mortar is an important factor and by ensuring that all the mortars have the same workability then direct comparisons can be made between them. Therefore a 10mm penetration using the dropping ball apparatus specified in the standard was used as the bench mark for the workability of all the mortar mixes. This measure of workability correlates with other workability tests and a dropping ball of 10mm offers the same characteristics as a flow table reading of between 160 to 170 mm of flow (BS EN 1015-3). The control of the workability is also enhanced by the use of constant mass sand that is described later.

3. BRICKS

The tensile samples were fabricated using 'engineering' bricks, this term does not exist in the standard but in the uk national annex in BS EN 771 -1:2003 [2]. it states that "The equivalent classifying properties of traditional UK HD high density type clay engineering bricks, and also HD type clay DPC bricks for which only water absorption is the defining limitation, in relation to EN 771-1and perform to BS EN 772-1".[2] The term "engineering brick" is a term that applies to a high density brick with low water absorption and high compressive strength. Therefore 3 perforation wire cut class "B" engineering bricks have been chosen for this study as they are predictable in their performance as far as the initial rate of absorption is concerned. A representative sample of the bricks were used and tested to determine the amount of water that they absorb. This was carried out in accordance with BS.EN 772-11:2011.

The initial rate of absorption of the bricks being used does play a large part in the overall outcome of the experiment as identified by [3] MARIOROSA et al 2009 "that the most influential characteristic of masonry that needs to be controlled to obtain a good mechanical performance is the water absorption". The test revealed that the average initial rate of absorption for the sample set tested was 0.104 $kg/m^2/min$ with a standard deviation of 0.04 illustrating that the sample set was indeed uniform in its performance as far as the initial rate of suction was concerned

The low initial rate of suction expressed by the bricks would leave more water available in the mortar for hydration of the binder and development of the brick mortar bond. The predictable performance of this masonry unit plays a critical part in the development of the brick / mortar bond strength as any variation within the sample set could adversely affect the experiment due to the excessive de - watering of the mortar and the introduction of another variable.

4. SAND

Overall performance of a mortar is affected by the type of aggregate used. There are a variety of different sources of sand and the importance of choosing the correct sand cannot be overstated. The grain size and shape is also of paramount importance. [4]LANAS et al (2004:2198) state that "an adequate grain size distribution allows the [development] of a high strength in the mortar." With a hydraulic lime mortar a well sorted sharp sand gives the best results [5] NHBC (2008:13) however the use of overly course aggregate reduces mortar strength [4] LANAS et al (2004:2198).This is why the choice of the type of sand is important along with the fact that sand is volumetrically the largest proportion of any mortar and has an impact on the amount of water required to reach a target mix consistency. Work by [6] DE-SHUTTER, & POPPE (2004:517) also highlighted the impact sand has on the rheological and mechanical properties of mortar.

There are a number of British and European standards that cover the use of sands for building purposes and they suggest the correct grain size and distribution based on a grading envelope. [7] BS 1200; 1976 p.5 states that there are two main types of sand classified based on a sieve analysis as types G and S. The sand used in this experiment conformed to this standard and was a type S sand and is a typical example of the type of

sand used in everyday domestic house construction.
The sand is known to excerpt a controlling influence on the water demand and rheology of the mortar and by maintaining a set mass of sand and varying the amount of binder in each mortar mix a reduction and elimination of variables between each mix can be achieved. The advantage of this is that "the use of a constant mass of sand for comparative investigations concentrates upon maintaining the source and quality of the sand as a constant." [8] Seaton (2004:89). As sand makes up the largest proportion of any mortar by controlling the mass of sand used more control is provided over the amount of water required and subsequently the workability of the mortar.

5. CALCULATION OF MIX PROPORTIONS USING CONSTANT MASS SAND

The use of a mortar mix that is proportioned using a constant mass of sand gives a greater degree of control over the amount of water needed to obtain a set workability. Indeed "the presence of a constant mass sand design means that any additional water requirement is uniquely dependent on the amount of binder" [8] (Seaton 2004 p113). As the amount of binder used is small in comparison to the sand the influence exerted by the binder on water demand is low and therefore more controllable throughout the experiment.
The procedure used to calculate the mix proportions was done using a container of a known volume. The container was filled a number of times with sand, cement and lime to obtain an average mass of each material for that given volume. Table 1 shows the average masses produced by this process. These proportions equate to traditional volume/gauged mixes and would give mortar mixes that would be produced in any small to medium sized building operation that is batching and utilising mortar on site. However, while the mix proportions specified for use in this investigation are in general use due consideration was given to the standards where [9] BS EN 998-2 :2010 states that "for prescribed mortars the mix proportions by volume or by weight of all the constituents shall be declared by the manufacturer" as displayed in Table 1. Although the mass of hydraulic lime used in each case is lower than that of the cement this is simply due to the different densities of the binders. The volume of the different binders used still equates to the relative mix proportions stated.

6. SAMPLE MANUFACTURE

This was done using a couplet making jig. The jig was employed to a method described by [10] TAYLOR-FIRTH. A (1990:60) "where the preparation of test specimen couplets [controls the] workmanship required to make the joint yet at the same time [is] a reasonable simulation of bricklaying practice." This ensured that all the test samples were made to a reliable and consistent standard, eliminating any operator error that may occur during their manufacture and reducing unwanted variables due to workmanship. This way of preparing the samples is not a standard procedure and there are alternative methods. For example, in [11] BS EN 1052-5:2005 guidance is given on the manufacture of a stack bonded column where "the unit shall be laid so that the thickness of the joint is as specified, the masonry unit shall be checked for linear alignment." The column is then surcharged with a stress between 2 and 5 $x10^{-3}$N/mm2. Both methods are subject to the variability of workmanship which in turn will influence the performance of the samples. However, the manufacturing rig that is described by Taylor Firth A is designed to control the manufacturing procedure and subsequently reduces the effect that workmanship has on the preparation of the samples. This method of sample preparation has several advantages. A large sample population can be produced with a good degree of repeatability in a short timescale. Each sample is independent so there is less likelihood of the whole sample set being disturbed at an early age thus affecting the overall performance of the samples. As the samples are produced in a relatively short period of time there is less opportunity for the

mortar sample to deteriorate. This ensures that the performance of the samples made later on in the sample preparation period are less likely to be affected by deterioration of the mortar.
The sample manufacturing sequence is displayed in figure 1 'A to D'. Figure 1'A' shows the two couplet making rigs and figure 1 'B' shows how a gauged 15mm deep bed of mortar is initially applied to the lower brick. The brick and mortar are then moved to the second rig that is shown in figure 1'C', where two 10mm bars are placed either side of the mortar prior to the top brick being applied to the mortar with a sliding downward pressure. The upper brick cannot be pushed down on to the mortar as the mortar exerts some hydraulic pressure making it hard to meet the required mortar depth of 10mm. When this has been done the two 10mm bars are removed. Care has to be taken at this point not to disturb the joint as although the brick has just been "laid" a rudimentary bond will have developed. The completed couplet can then be removed from the rig as illustrated in figure 'D' prior to being placed in a moist air curing chamber.

7. PROPERTIES OF THE HARDENED MORTAR

A series of cubes and prisms were produced as specified by the British standard BS 4551:1998. They were subsequently tested in accordance with this standard to the prescribed test method. The mortar cubes were subject to compressive loading while the prisms were subject to three point bending (modulus of rupture).
The samples were moist air cured along with the couplets to ensure that they had experienced the same conditioning and curing that the mortar within the couplets had been subjected to. These samples would provide an indication of the reliability and performance of each mix design and the results can be seen graphically represented in figures 2 and 3. Both the cubes and prisms express similar trends, with the 1:3 cement binder mortar displaying higher compressive and flexural strength than the rest of the samples and the 1:3 lime mortar displaying similar properties to the 1:8 cement mortar [12].(HETHERINGTON 2014 p.276).

8. THE WATER ABSORPTION AND POROSITY OF THE MORTARS

It is stated that lime mortars exhibit a more "breathable" nature than their cement based counterparts and that "naturally hydraulic lime mortars have surprisingly high permeability [and] water vapour permeability rates" [13] (J.SCHORK 2012 p.7). Subsequently the increased porosity allows water in both vapour and liquid form to freely move into and from the masonry and this is why lime mortars are deemed to be more sympathetic to the surrounding materials. A series of tests was carried out to confirm the porosity and water absorption of each sample set with samples taken from the prism samples that had been tested to find the flexural strengths of the respective mortars. The procedure adopted for testing the mortar samples was based on a top pan weighing method where the initial dry mass of each sample is taken. The calculation of water absorption was based on the formula given in BS EN 772-21 (2011). However, the procedure adopted for conditioning the samples was done by vacuum saturation and calculating the apparent porosity was based on results obtained from a top pan weighing technique.
The results clearly show that the lime based mortars have a more open porous structure than their corresponding cement based counterparts as can be seen in table 2 [12] (HETHERINGTON 2014 p.276).
However, some degree of commonality is expressed between the 1:3 lime based mortar and the 1:8 cement based mortar. They appear to have similar water absorption and apparent porosity and this is also reflected in the compressive and flexural strengths. In addition the 1:8 lime based mortar did not differ greatly from the 1:6 lime mortar. This is due in part to the friable nature of the 1.8 mortar which showed signs of distress when subjected to the test procedure.

9. TENSILE TEST APPARATUS

The tensile test apparatus developed at Sheffield Hallam University and also known as the 'SHU' test is a direct tensile test comprised of two cradles designed to test a pre-formed couplet sample illustrated in figure 4. It is designed to provide a more characteristic and repeatable indication of the brick mortar bond strength. This in turn allows for a more "detailed study of the various factors affecting the brick mortar interface to be analysed in greater depth." [10] (TAYLOR-FIRTH & TAYLOR 1990:2).

The case for any direct tensile test is compelling as "the application and use of masonry bond strength tests that rely on a lever arm or bending mechanism are less likely to give a characteristic value for bond strength than a direct tensile test." [14] KALAF (2005:726).

10. TEST RESULTS

The photographs in figures 5 and 6 show the respective samples after failure illustrating the type of failure exhibited by each sample set. The test rig is designed to pull the top brick and the mortar away from the lower brick. The photographs illustrate that the samples did not all fail in the same predetermined way but in a variety of ways. A number of samples failed through the mortar and others failed at the top brick mortar interface. However, all of the failure mechanisms shown in figures 5 and 6 would be deemed acceptable and viable if the same criteria for a successful failure were applied from BS EN 1052-5:2005. That is that the failures took place at either the upper or lower brick mortar interface or through the mortar.

The bond strength results are calculated by taking the maximum load at failure in Newtons divided by the gross mortar to brick contact area measured in mm^2.

The 1:8 lime mortar exhibits a bond strength that is on average 44% less than that of the samples made with a 1:8 cement binder. Both sample sets show some signs of variation with the hydraulic lime samples exhibiting less variability than the cement based binder .The 1:6 lime mortar again exhibits lower bond strength than that of the cement binder in this case on average 46% less and the variability of the sample sets show that the hydraulic lime exhibits significantly less variability than that of the cement based binder.

The 1:3 lime mortar mix exhibits a lower bond strength than that of the 1:3 cement binder (in this case 41%) and the variability of the two sample sets exhibit the same trend as exhibited by the other mortars namely that the hydraulic lime samples show significantly less variability in their performance.

The tensile bond strength results for each sample set were analysed and compared across each mortar designation. A statistical analysis of the results using the 't' test indicated, with a 95% level of confidence, that the results were significantly different when compared to the 1:8 lime and cement mortars. This trend was repeated for both the 1:6 mortar mixes and the 1:3 mortar mixes. Further cross analysis of the results highlighted that this was also the case when comparing the 1:6 cement mortars with the 1:3 lime mortars where a significant difference was found. However, when the results of the test performed on the 1:8 cement mortar samples were compared with the 1:3 lime mortar samples no significant difference was found.

While it is evident that the lime mortars exhibit a considerable reduction in tensile bond strength compared to the cement based mortars there is evidence that there is some overlap and subsequent commonality between the 1:6 and 1:8 cement mortars and the 1:3 lime mortars. A statistical analysis comparing the 1:8 cement mortars and the 1:3 lime mortars illustrated no significant difference between these two mortar types.

This could be used as evidence that the higher proportioned lime mortars may be used to replace the lower proportioned cement based mortars.

11. DISCUSSION

The bond strength results shown in table 3 and the graphical representation in figure 7 demonstrate a gradual reduction in bond strength from the stronger 1:3 cement based mortar to the 1:8 cement based mortar. This is a clear and well defined trend with the variation in each sample set providing some overlap with the next mortar set. For example, some overlap in bond strength exists between the 1:3 cement mortar and the 1:6 cement mortar and this trend appears to extend throughout the whole sample set. The graph in figure 7 shows an overlap in the bond strengths between the 1:6 and 1:8 cement based mortars and the 1:3 lime based mortars. This indicates that a 1:3 lime based mortar could indeed serve as a replacement for a 1:8 cement based mortar with a large degree of confidence in terms of its bond strength capabilities. If the flexural and compressive strengths are taken into account this further re enforces the point as the 1:8 cement based mortar has a similar flexural and compressive strength to the 1:3 lime based mortar. The water absorption and porosity results are again similar with the 1:8 cement mortar expressing comparable properties to the 1:3 lime based mortar.

The results obtained from the tensile test method or “SHU” test and sample preparation method do offer a degree of control and level of repeatability illustrating definite trends and expressing relatively low coefficients of variation (Table 4) compared to other bond strength tests. The results also suggest that the method employed in the fabrication of the samples is a robust, reliable and repeatable process and that the test systems employed are sensitive enough to identify the differences within the sample sets. This can be illustrated by closer examination of the coefficient of variation for each set of results. The average coefficient of variation (CoV) for all the tensile results was 19.5% as illustrated in table 6. This is an improvement on the coefficient of variation stated by [8] Seaton (2004:146) at 24% but higher than the 12% stated by [10] Taylor Firth & Taylor (1990).

The variability between the different binder types may be due in part to the water retentively of the hydraulic binder as stated by [15] PAVIA & HANLEY (2008:p.921) However, in all cases the tensile results are supported by the cube and prism strengths which mirror the findings of the bond strength and are displayed graphically in figures 1 and 2.

It is also argued that lime is more flexible and that “lime mortars behave as if they are flexible……. are slower hardening and remain more flexible than cement sand mortars” [16] (British Lime Association 2011).The advantage of this is that lime based mortars can adapt to early movement. However, when considering the 28 day flexural strength the results in the graph in figure 3 illustrate that a 1:8 cement sand mortar expresses similar flexural strength to the 1:3 lime mortar. The results appear to indicate that the properties of a 1:8 cement based mortar are similar to that of a 1:3 NHL5 lime mortar.

12. CONCLUSIONS

Consideration of the experimental test method has shown that the method of sample preparation and testing using the S.H.U bond strength provides a robust and repeatable set of results that express low coefficients of variation. It could be argued that masonry will never, or very rarely, be put into tension and therefore a direct tensile test is not a viable test to use. However, the results expressed in this paper illustrate the ability of this test procedure to differentiate between different types of mortars and their bond strength characteristics. The test apparatus and sample manufacturing techniques, including the use of constant mass sand, provide a reliable and repeatable indicator of the likely in service performance of the masonry composite. The tests also indicate that hydraulic lime mortars can provide an alternative to cement based mortars as far as bond strength is concerned for certain applications. However, larger volumes of hydraulic lime binders are required to give the same level of performance in comparison to their cement based counterparts. Alternatively equivalent masses of binders should be employed. This is in effect what probably happens on site where a bag of hydraulic lime 25kg is added to 3 bags of sand where a 25kg bag of hydraulic lime is larger than a 25kg bag of cement .The test results do indicate that a 1:3 hydraulic lime binder has a comparable set of characteristics to a 1:8 and to some degree a 1:6 cement mortar mix.

Although this research is not primarily concerned with the relative sustainable merits of the two binders highlighted it would be wrong not to in part address this issue as this is one of the reasons for the re-introduction of lime as a building material.

Lime is a more environmentally friendly alternative to cement as its production releases far less carbon dioxide. However, if a greater volume of hydraulic lime is required to obtain the same performance as a cement based binder then it could be argued that another sustainable option may be to reduce the amount of the cement used in mortars. In effect thought should be given to the use of cement based mortar mixes that could be considered "lean" or "weaker."

The benefits would be a mortar that is more environmentally friendly but would maintain some of the high performance characteristics.

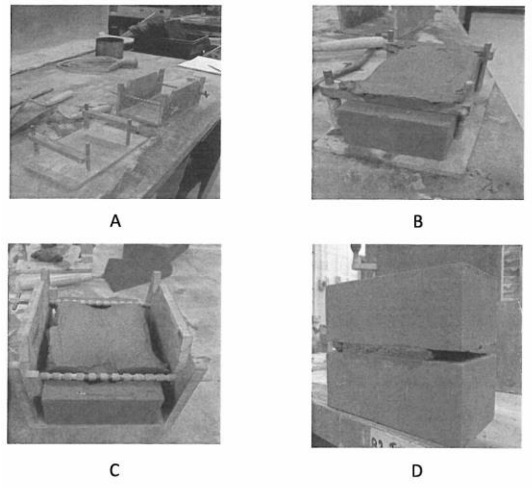

Figure 1 A, B, C, D Sequence of manufacture of the brick couplets

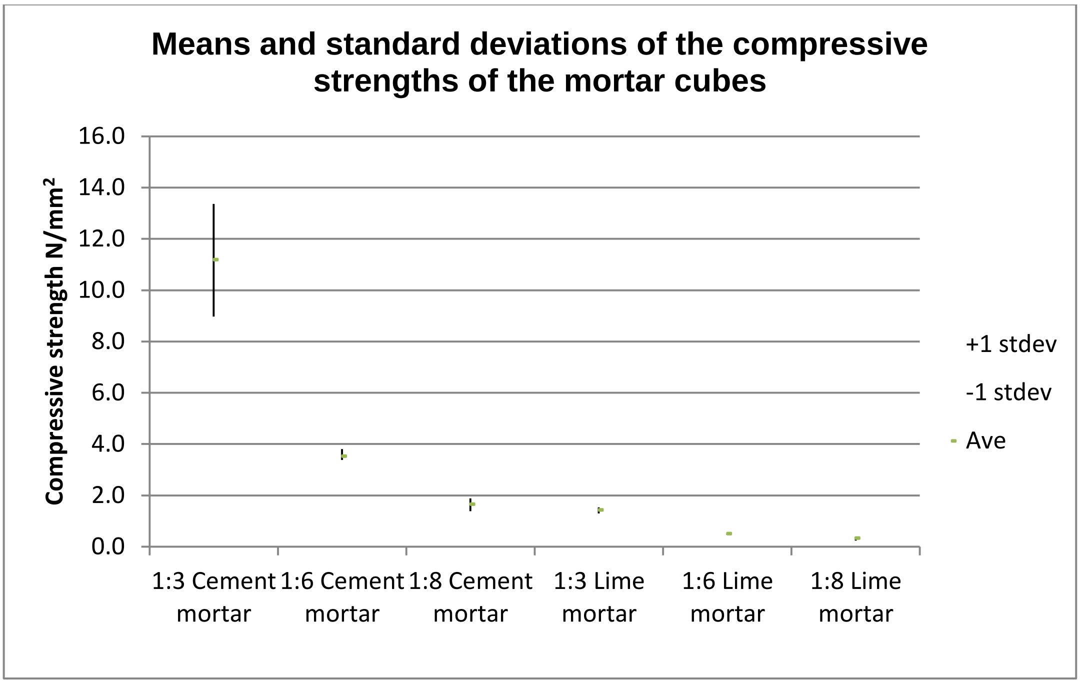

Figure 2 Means and standard deviations of the compressive strengths of the mortar cubes (HETHERINGTON.S 2014 p.281)

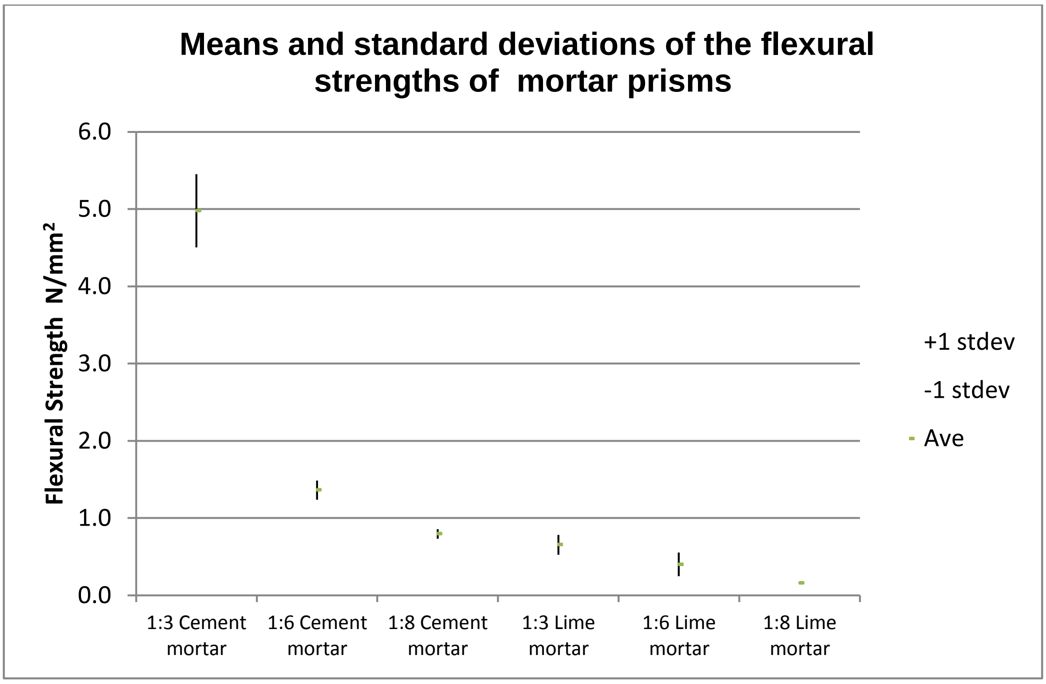

Figure 3 Means and standard deviations of the flexural strengths of the mortar prisms (HETHERINGTON.S 2014 p 281)

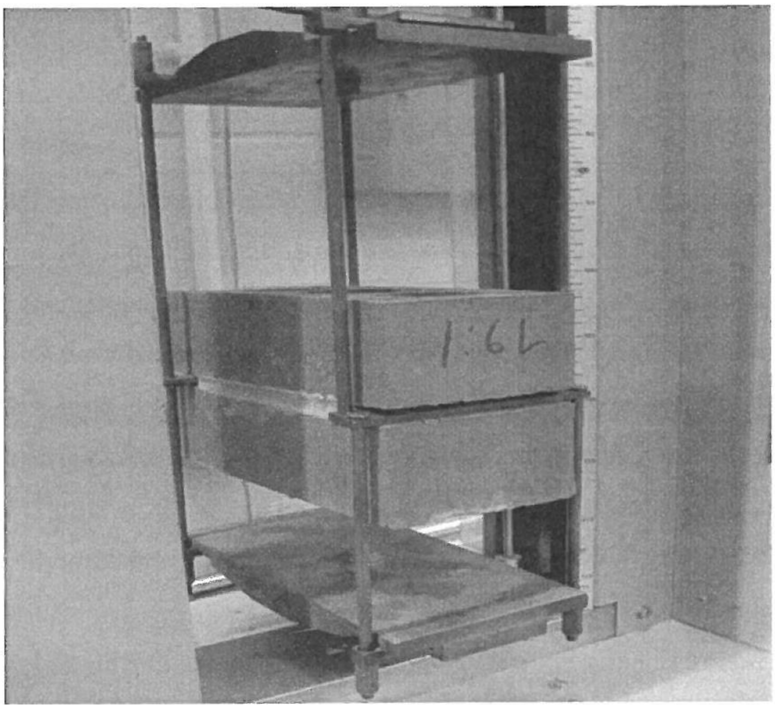

Figure 4 Tensile bond strength test rig

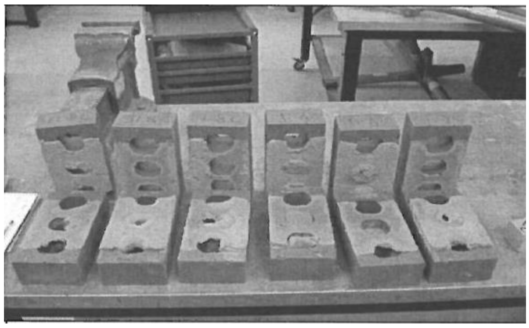

Figure 5 and Figure 6 1:8 lime mortar and 1:8 cement mortar samples

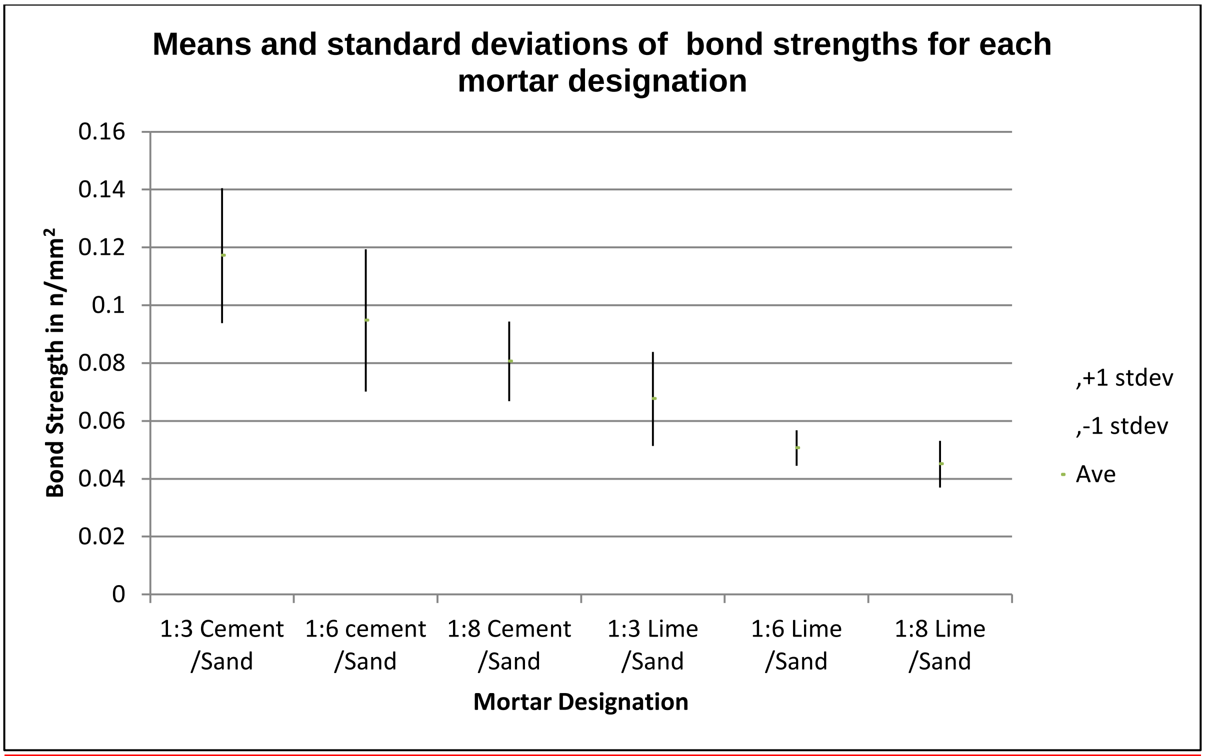

Figure 7 Means and standard deviations of the tensile bond strength results

Table 1
Mortar mix proportions and masses

	Cement Mixes			Lime Mixes	
Mix Specification	Sand (g)	Cement (g		Sand(g)	Lime(g)
1:3	4570.8g	1331.64g		4570.8g	929.18g
1:6	4507.8g	665.82g		4570.8g	464.59g
1:8	4507.8g	499g		4570.8g	348.4g

Table 2
Porosity and water absorption of mortar (HETHERINGTON.S 2014.p282)

Porosity and water absorption						
	1.3c	1:6c	1:8c	1:3 L	1:6L	1:8L
% Apparent Porosity	35.38	37.38	38.20	38.50	40.14	40.30
%Water Absorption	21.29	23.35	24.20	24.11	25.68	25.88

Table 3
Summary of bond strength results

	Average bond strength N/mm^2	Standard deviation	% Coefficient of variation
1:8 Lime /Sand	0.045	0.008	17.9
1:8 Cement /Sand	0.081	0.014	17.1
1:6 Lime /Sand	0.051	0.006	12.13
1:6 cement /Sand	0.095	0.025	25.95
1:3 Lime /Sand	0.068	0.016	12.13
1:3 Cement /Sand	0.117	0.023	19.9

Table 4
Coefficient of variation of the bond strength results

Coefficient of variation for the bond strength tests	
Mix Designation	% Coefficient of Variation
1:3 Cement/ Sand	19.90
1:6 Cement/ Sand	25.95
1:8 Cement/ Sand	17.10
1:3 Lime / Sand	24.00
1:6 Lime / Sand	12.13
1:8 Lime / Sand	17.90
Ave	19.50

Acknowledgements

Journal of Building Survey, Appraisal & Valuation Volume 3 Number 3 London, Henry Stewart Publications

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