FLEXURAL BOND STRENGTH DEVELOPMENT OF BRICKWORK USING NATURAL HYDRAULIC LIME (NHL) MORTAR

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SUMMARY

This paper presents results from an ongoing experimental study on flexural bond strength of brickwork built using natural hydraulic lime (NHL) mortars. Flexural bond strengths were determined by bond wrench testing stack-bonded prisms in accordance with BS 1052-5:2005. Experimental parameters studied have included brick water absorption properties, lime mortar binder/sand ratio, lime grade, and sand grading. Both mortar strength and bond wrench strength increased with age, lime content and increasing lime grade. Coarser-graded sand developed higher strength mortar. Brick water absorption characteristics had a significant influence on bond strength.

INTRODUCTION

Over the past decade the use of hydraulic lime mortars in the UK for both new masonry work and restoration work has increased significantly. Benefits of lime mortars, over cement mortars, include greater tolerance of movements, higher water vapour permeability, improved aesthetics, and potentially lower embodied CO_2. Current UK structural design codes (BS 5628, 2005; BS EN 1996, 2005) do not provide design data for lime mortared masonry. Though some recent research has been completed investigating the properties of hydraulic lime mortars (Allen et al. 2003; Lanas et al. 2004), there is a scarcity of data on the mechanical properties of lime mortared masonry.

The initial rate of strength development and the final strength of lime mortars are generally accepted to be lower than cement mortars. However, in replacing cement, lime mortars are now often used in applications, such as cavity walls, much thinner than traditionally used. Masonry must develop sufficient flexural bond strength to resist lateral loads as well as eccentric vertical loads.

This paper presents bond strength test results, determined by bond wrench test in accordance with BS EN 1052-5 (2005), of brickwork prisms using three different bricks and six different natural hydraulic lime (NHL) mortar mixes. These are compared with the performance of a weak cement lime mortar. The development of bond strength and lime mortar strength with age are presented for a range of mortars and bricks. The results presented here are part of a three-year study into the structural properties of hydraulic lime mortared brickwork.

EXPERIMENTAL PROGRAMME

The experimental programme has comprised tests on brick properties, NHL mortar properties and flexural bond strength using the bond wrench method. The experimental parameters studied include:

- Brick initial rate of absorption, total water absorption and sorptivity (designated low, medium and high suction bricks);
- Brick moisture content at laying;
- Lime mortar mix proportions (1:2, 1:2.25 and 1:2.5 lime: sand (by volume));
- Hydraulic lime grade (NHL2 and NHL3.5);
- Mortar sand grading (fine, medium and coarsely graded sand).

Control baseline materials for comparison were designated as the 1:2.25 lime (NHL 3.5): medium graded sand mortar combined with the medium suction bricks. Performance of the lime mortars and brickwork are compared with a 1:3:12 cement:hydrated-lime:sand mortar and brickwork prism specimens. The mortars and brickwork prisms were tested at different ages. The baseline mortar and prisms were tested at 14, 28, 56, 91 and 365 days. Other mortars and brick prisms were tested mainly after 28 and 91 days.

Materials

Extruded three-hole perforated clay bricks, supplied by Ibstock Brick Ltd, with nominal dimensions 215×102.5×65 mm, were used throughout the study. The properties of the bricks used are summarised in Table 1.

Table 1. Properties of Bricks

Brand name	Staffordshire Slate Blue Smooth	Berkeley Red Multi	Hardwicke Welbeck Autumn Antique
Report designation	Low suction	Medium suction	High suction
Net dry density (kg/m^3)	2209	2127	1685
Proportion of holes	18%	17%	17%
Nominal compressive strength (N/mm^2)	75	55	40
Water absorption (%) Average (of 10 tests): Coefficient of Variation:	 2.3 14.9%	 5.1 6.9%	 16.0 5.0%
IRA (kg/m^2.min) Average (of 10 tests): Coefficient of Variation:	 0.1 35.0%	 1.3 7.3%	 2.4 8.9%
Sorptivity (mm.min$^{-1/2}$) Average (of 3 tests):	 0.02	 0.40	 2.08

Castle Cement Ltd NHLs (grades NHL2 and NHL3.5) were used throughout the study. Lafarge Blue Circle Portland cement and Lhoist UK CL 90 grade hydrated lime were used for the 1:3:12 mortars. The grading curves of mortar (silica) sands are shown in Figure 1. The

medium graded sand (brand name ‘Binnegar’) sand was used for most lime mortar mixes and the cement:lime:sand mortar. For comparison coarse graded (‘Allerton Park’) and fine graded (‘Yellow Pit’) sands were also used.

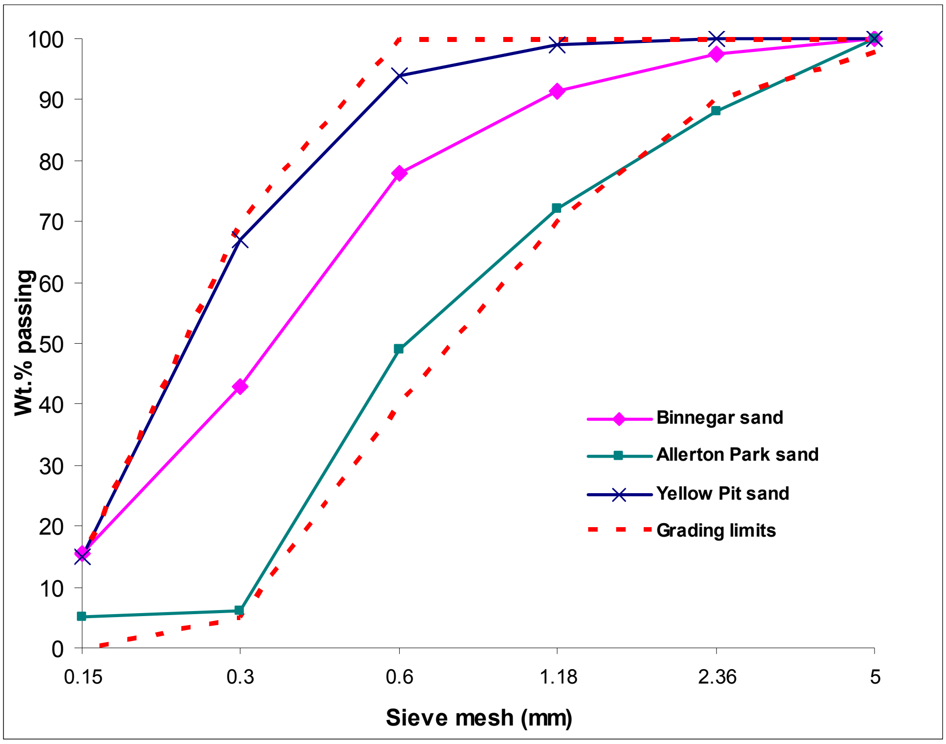

Figure 1. Grain Size Distribution of Sands

Mortar mixes

Table 2 outlines the experimental mortar mix compositions. The constituent material ratios are, following convention, by volume. However, for experimental mixing materials were batched by mass using material bulk densities. The mortar workability was controlled initially by an experienced bricklayer, and thereafter reproduced by careful batching of materials. The water content of the mortar was adjusted to suit the brick suction properties, reduced for the low suction bricks (water:lime ratio 1.40; flow value 160) and increased for the high suction bricks (water:lime ratio 1.48; flow value 173). The flow values for the mortars were determined in accordance with BS EN 1015-3:1999. The 1:3:12 cement:hydrated-lime:sand included in the study used Binnegar sand (water:cement ratio 2.48; flow value 177).

The water requirements of the lime mortar mixes increased with sand content to achieve comparable flow. The lower grade lime (NHL2) required more water than the higher grade mix. As sand fineness increased the water content also increased. These observations were all in line with expectations.

Table 2. Hydraulic Lime Mortar Mix Details

Lime	Sand	Mix proportions (by volume)	Water:lime ratio	Flow value
NHL 3.5	'Binnegar'	1:2	1.40	172
		1:2.25	1.49	169
		1:2.5	1.69	172
	'Allerton Park'	1:2.25	1.43	137
	'Yellow Pit'	1:2.25	1.55	156
NHL 2	'Binnegar'	1:2.25	1.58	165

Manufacture, curing and testing of specimens

The mortars were mixed in a rotating drum mixer. Initially dry materials were combined and thereafter water was carefully added and mixing continued for 10 minutes in total. The cement mortars were used at this point; however the hydraulic lime mortars were left to stand (under cover) for 50 minutes before briefly re-mixing and use. Cement mortars were used for 1½ hours before discarding, whilst the lime mortars were used for up to four hours.

Four-brick high stack-bonded prisms were adopted for the determination of flexural bond strength using the bond wrench method. All bricks were air-dried under laboratory conditions before use. To study the influence of brick moisture content, units were prepared in sealed plastic bags to the required moisture contents (3.7%, 7.8%, 11.8% and 15.6%) three-days in advance of construction. All mortar joint thicknesses were maintained at a nominal 10 mm. At the same time of building the brick prisms, three 40×40×160 mm^3 mortar prisms, for each mortar test series, were cast in steel moulds (in accordance with BS EN 1015-11:1999). Immediately following construction, the brick and mortar specimens were covered in plastic for up to seven days. Thereafter they were stored in a climate room maintained at $20^oC\pm2^oC$ and RH 65%±5% with ambient CO_2 levels until testing.

Bond wrench strength of brick prisms was determined at different ages in accordance with BS EN 1052-5:2005. For each combination of brick and mortar, four prisms were built and tested, giving 12 joints for each test series. The corresponding hardened mortar properties were determined on the same day. The flexural and compressive strengths of mortar were tested in accordance with BS EN 1015-11:1999. For each batch of mortar, three prisms and six half-prisms were tested for each age to determine the flexural and compressive strength values respectively.

MORTAR STRENGTH TEST RESULTS AND DISCUSSION

Test results for the experimental mortars are summarized in Table 3. All mixes have been tested up to 91 days, with the exception of the baseline 1:2.25 (NHL3.5:Binnegar sand) mortar that has also been tested at 365 days. In reflection of the slower strength development of lime mortars testing at 91 days has become the accepted equivalent of 28 days strength for cement mortars. The lime mortar compressive strengths at 91 days varied, depending on mix proportions, lime grade and sand grading, between 0.76 and 1.52 N/mm^2. By comparison the

28 day strength of the 1:3:12 mortar was 1.00 N/mm^2. Sand grading had the greatest influence on mortar compressive strength. The coarser graded Allerton Park sand mortar developed significantly higher compressive strength, compared to the baseline mix, though the flexural strength of the coarse sand mortar was, by 91 days, lower. The use of the finer 'Yellow Pit' sand impaired both flexural and compressive mortar strengths.

In all cases mortar flexural and compressive strengths increased with age. Strength development is derived from the hydraulic set and the slower process of carbonation, which is generally more important to lime mortars. Rate of carbonation depends on atmospheric CO_2 levels, temperature and relative humidity levels. Between 14 and 91 days the strength development of the 1:2.25 baseline and the 1:3:12 cement:lime:sand mortars are very similar, although very early age strengths were not recorded. At 91 days the 1:2.25 mortar attained 97% of its one-year compressive strength. By 28 days the lime mortars attained between 56% and 71% of their 91 days strengths.

Table 3. NHL Mortar Flexural and Compressive Strengths
(40 x 40 x 160 mm specimens)

	Age (days)	Flexural strength (N/mm^2)	Compressive strength (N/mm^2)
1:2	28	0.36	0.68
	91	0.40	1.20
1:2.25	14	0.30	0.53
	28	0.33	0.60
	56	0.37	0.85
	91	0.45	0.95
	365	0.49	0.98
1:2.5	28	0.32	0.55
	91	0.36	0.78
1:2.25 (NHL 2)	28	0.28	0.54
	91	0.40	0.97
1:2.25 (coarse sand)	28	0.34	1.13
	91	0.34	1.52
1:2.25 (fine sand)	28	0.27	0.50
	91	0.27	0.76
1:3:12	14	0.34	0.72
	28	0.34	1.00
	91	0.40	1.19

BOND WRENCH TEST RESULTS AND DISCUSSION

Bond wrench test results are summarised in Tables 4 and 5 below. The characteristic 91 day bond strengths (5 % fractile value) for the NHL3.5 mortars, with the medium suction brick, varied between 0.25 and 0.45 N/mm^2, depending on mix proportions and sand grading. The coefficient of variation for the bond tests, using low and medium suction bricks, generally fell between 13% and 18% (overall range 5%-23%). However, for the high suction bricks there was much greater variation in performance (coefficient of variation around 45%).

In bond wrench testing, three distinctive failure modes were observed. The most common failure was 'interface failure', which occurred along the contact surfaces between the brick bed face and mortar bed joint. All low and high water absorption brick prisms failed in this way. The second failure mode was 'mortar failure', in which mortar adhered to both bricks either side of the test joint, and the mortar joint split apart in flexure. This was also commonly observed, especially in the older, and generally stronger, prism tests. Finally, the combination of both interface failure and mortar failure occurred in a small number of cases.

The experimental bond strengths, as reported in Table 4, increased with age up to 91 or 365 days. To date the most complete bond strength development data are for the 1:2.25 baseline mortar. Up to 91 days the rate of bond strength development was comparable with the rate of mortar strength development with age. By 14 days the average bond strength had attained 0.21 N/mm^2 (46% of the 91 day value). By comparison the mortar at 14 days had achieved between 56% and 67% of their 91 day strength. At 28 days the average bond had attained 65% whilst mortar had reached 63-73% of the 91 day strength. Between 91 and 365 days the bond strength increased by a further 41% although there was little improvement in mortar strength over this time. Continued carbonation of the mortar joint is the most likely primary mechanism for this continued improvement in bond strength.

Varying mortar mix proportions, lime grade and sand grading have had a significant influence on the bond development between brick and mortar. The NHL3.5, medium graded sand,1:2, 1:2.25 and 1:2.5 mortars all developed similar bond strengths at 28 days. The influence of lime content has become apparent at 91 days. As lime binder content increased, the bond strength increased. As expected a change in lime grade to NHL2 reduced the bond strength. Though using coarsely-graded sand increased mortar strength, the bond strengths of the Binnegar and Allerton Park sand mortars are similar. Using finer sand has been detrimental to bond strength.

The strength properties of the 1:2.25 baseline lime mortar and 1:3:12 cement mortar were very similar between 14 and 91 days. However, the average bond strengths of the cement mortar are between 63% and 96% higher than the lime mortar bond strengths at ages up to 91 days.

Influence of brick suction

Brick suction has a significant influence on bond development. The bond wrench strengths of both low and high suction bricks were both very low (Table 5). A number of joints failed before testing (indicated in Table 5). These joint 'tests' have been excluded from the results as their actual strength is unknown; however, taking their strength as zero would not be appropriate. The true full sample average and characteristic strengths are therefore, as a result of premature failure, likely to be lower than those reported in Table 5. All joints failed along

Table 4. Bond Strength using varied Mortars
(Medium Suction Bricks)

	Age (day)	Average strength (N/mm^2)	CV (%)	Range (N/mm^2)	95% characteristic strength (N/mm^2)
1:2	28	0.34	18.4	0.30-0.40	0.22
	91	0.61	15.1	0.43-0.75	0.45
1:2.25	14	0.21	10.6	0.18-0.25	0.17
	28	0.30	18.5	0.21-0.42	0.21
	56	0.40	19.5	0.23-0.46	0.25
	91	0.46	12.2	0.36-0.52	0.36
	365	0.65	5.2	0.59-0.70	0.59
1:2.5	28	0.28	13.9	0.23-0.34	0.22
	91	0.38	11.1	0.30-0.47	0.31
NHL 2	28	0.24	22.2	0.15-0.34	0.15
	91	0.29	18.0	0.22-0.39	0.21
Allerton Park sand	28	0.29	13.5	0.23-0.35	0.22
	91	0.42	8.8	0.34-0.48	0.34
Yellow Pit sand	28	0.23	21.0	0.15-0.32	0.15
	91	0.37	17.1	0.26-0.52	0.25
1:3:12	14	0.35	18.9	0.24-0.46	0.24
	28	0.49	15.4	0.40-0.61	0.37
	91	0.90	23.0	0.62-1.27	0.56

Table 5. Bond Wrench Strength Using Different Water Absorption Bricks

Brick type	Age (day)	No. of test specimen*	Mean strength (N/mm^2)	CV (%)	Range (N/mm^2)	Characteristic strength (N/mm^2)
Low suction	14	8	0.08	23.36	0.04-0.10	0.05
	28	10	0.16	15.90	0.12-0.20	0.12
	56	10	0.18	15.73	0.13-0.23	0.13
	91	12	0.23	14.18	0.18-0.28	0.15
High suction	14	8	0.09	45.72	0.02-0.16	0.03
	28	7	0.10	45.48	0.05-0.18	0.04
	56	12	0.18	41.58	0.05-0.31	0.06
	91	9	0.09	52.77	0.05-0.12	0.03

*Number of test joints less than 12 due to premature failure when handling.

the interface between the mortar and brick. However, the weak bonds developed using these bricks are due to different reasons. In the low suction bricks the mortar does not develop good bond due to poor dewatering and transport of mortar agents into the brick surface (Sugo et al, 2001). In contrast the high suction bricks prevent adequate hydration of lime binder.

The influence of brick suction has been further explored by investigating the influence of moisture content at laying of the high suction brick. Samples of the high suction bricks were prepared to the following moisture contents before laying: 3.7%, 7.8%, 11.8%, and 15.6%. The IRA values were measured for different brick moisture contents. The relationship between moisture content and IRA is linear (Figure 2); the influence of brick moisture content on sorptivity is not available at the time of reporting.

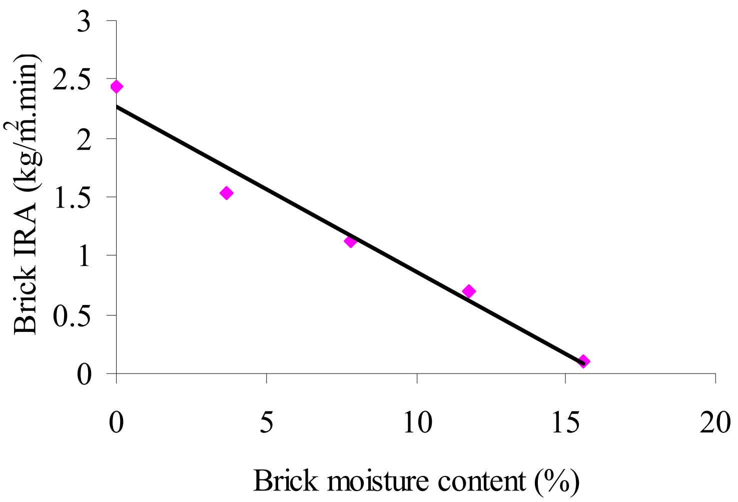

Figure 2. Relationship between Brick Moisture Content and IRA

The relationship between brick moisture content is unclear (Figure 5). The average and characteristic strength trends for each moisture content data set are shown. Though bond strengths have improved for brick moisture contents 3.7% and 7.8%, compared to oven dry, there is a drop in strength at 11.8% before an apparent recovery at 15.6% (saturated). With an increased data set and different moisture contents, the trend would be clearer of course. It is possible that that overall bond strength is relatively uninfluenced by brick moisture content in this case. Further experiments are planned to investigate this behaviour and so no firm conclusions regarding brick moisture content should be drawn from the tests completed to date.

SUMMARY AND CONCLUSIONS

This paper has presented initial findings from an ongoing investigation of bond strength in brickwork using hydraulic lime mortars. Based on tests completed to date the following conclusions have been made:

- The flexural and compressive strengths of NHL mortars are generally lower than commonly used cement:lime:sand mortars. The strengths of NHL mortars are similar to 1:3:12 cement mortar.

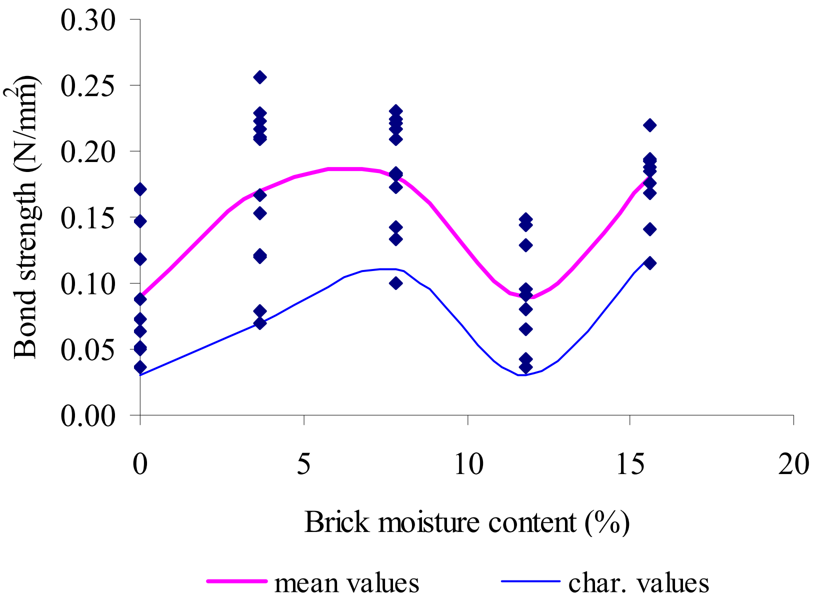

Figure 3. Influence of Brick Moisture Content on Bond Strength

- NHL mortars gain strength with age. Mortars develop a significant proportion of their final strength at early age (up to 14 days). Mortar strength at 91 days appears to be a good approximation of its final (one-year) strength.
- NHL mortars increase strength with lime content and lime grade. Coarse-graded sand helps the mortar to develop higher strength compared to a medium-graded sand, whilst fine-graded sand impairs the mortar strength development.
- Cement:lime:sand mortar developed higher bond strength in brickwork than similar strength NHL mortars.
- The bond strengths using NHL mortars in brickwork increase with age (up to 91 days), lime content and lime grade. Coarse and medium graded sand mortars develop similar bond strengths, which are higher than fine-graded sand mortars.
- As with cement mortars, brick suction has a significant influence on bond development. Low and high suction bricks develop much lower and more varied bond strength than medium range suction bricks.

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