Acknowledgement: This paper was first presented at the 9th International Masonry Conference at Guimaraes, Portugal on 7-9 July 2014, and is published by permission of the International Masonry Society (www.masonry.org.uk)

Universidade do Minho
Escola de Engenharia

International Masonry Society

9th International Masonry Conference 2014 in Guimarães

An experimental comparison of hydrated lime and an admixture for masonry mortars

WALKER, PETE[1]; KIOY, STELLA[2]; JOWSEY, AMY[3]

ABSTRACT:. The paper presents the results from an experimental study comparing the use of CL90-S grade hydrated lime with a proprietary air-entraining agent for the production of cement:lime:sand and cement:sand:admixture mortar mixes varying between M2.5 and M10. The study compared fresh (flow table) and hardened (28-day flexural compressive) mortar properties, masonry bond wrench flexural strength and the yield (number of bricks laid for given mortar quantity). Two different mortar sand gradings (fine and medium) were used in the comparison. The cement:lime:sand mortars showed good compliance with expected performance criteria. Air-entrained cement based mortars underperformed in respect of target compressive strength and adhesion values. The high air-entrainment to obtain the target workability increased the yield for the admixture mortars, which was marginally higher than for the lime mortars. Mortar compressive strength improved using the coarser graded sand.

Keywords: *Hydrated lime, masonry mortar, air-entraining admixture*

1 INTRODUCTION

Modern masonry mortars are typically a mixture of fine aggregates (sand) and a blended cement or Portland cement binder. Mix proportions vary depending on performance requirements. Despite the benefits attributed to the inclusion of lime in mortars, including improved workability and movement (reduced need for expansion joints), in recent years' in the UK proprietary air entraining agents have largely displaced the more traditional use of hydrated lime.

This paper presents results from experimental trials undertaken to compare performance of similar mortar mixes prepared using either hydrated lime or a proprietary air-entraining admixture. The aims of the study reported here were more specifically to:

- assess the relation between the traditionally used volume ratios and the obtained, physical mortar characteristics (including compressive strength);
- evaluate the influence of hydrated lime versus admixture (air entrainer) inclusion in masonry mortars on the yield (number of bricks laid for a given quantity of mortar);
- compare the flexural bond strength, as measured using bond wrench method, developed in brickwork using M5 mortars with different mixes.

The experimental work was undertaken at the BRE Centre for Innovative Construction Materials at the University of Bath.

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1) Professor, University of Bath, BRE Centre for Innovative Construction Materials, p.walker@bath.ac.uk
2 PhD student, University of Bath, BRE Centre for Innovative Construction Materials, ab0smk@bath.ac.uk
3) MEng student, University of Bath, Dept. Architecture & Civil Engineering, ahj24@bath.ac.uk

2 EXPERIMENTAL MATERIALS

2.1 Mortar materials

Constituent materials used for the experimental mortars were as follows:

- Sand: Two different bricklaying sands, supplied by Tarmac Mortars UK, denoted here as medium and finely graded were used throughout this study. Despite the different grading the approximate bulk densities were similar at 1523 kg/m^3 and 1491 kg/m^3 for the fine and medium sands respectively.
- Lime: Hydrated lime (CL90-S) manufactured by Lhoist UK (Buxton) was used throughout the study.
- Cement: CEM I-42.5N Portland Cement manufactured by Lafarge Ltd was used throughout the study.
- Additives: A proprietary liquid, air-entraining mortar plasticiser was used throughout the study as detailed below. The additive was a lignin-based surface-active plasticiser marketed to: improve workability and adhesion; minimise cracking; reduce water requirements and improve frost resistance.
- Water: Potable (tap) water was used throughout the mortar preparation.

2.2 Masonry units

Standard format (215 x 102.5 x 65 mm) high density (HD) vertically perforated fired clay facing-bricks were used for the mortar yield study. For the study of bond strength standard format single-frogged high density (HD) fired clay bricks (215 x 102.5 x 65 mm) were used. The three brick series had average total (24-hour immersion) water absorption capacities of: 6.6% (designated low), 7.9% (medium) and 10% (high) respectively.

2.3 Yield test mortar mixes

Twelve mortar mixes were prepared for the yield study. The mortars were specified by volume proportion, using proportions generally recognised to meet performance levels M2.5, M5 and M10 (Table 1). For consistency at a laboratory scale the mixes were batched by mass, converted from volume fractions using the bulk densities of the materials (Table 2); material volumes were determined from material bulk densities. The total quantity of dry ingredients for all mixes was maintained constant at 125 kg. The plasticiser was used in accordance with the manufacturer's instructions.

The mortar mixes were prepared in the University of Bath's laboratory using a rotating drum mixer. Initially all dry ingredients were mixed together thoroughly before the water was added. The quantity of water added to each mix was controlled by the bricklayers and carefully measured out and recorded (Table 2). Wet mixing was continued for 5 minutes from addition of the water. The mortar was used for no longer than 1½ hours after mixing; no further water was added. The sand was pre-dried to carefully control moisture content. Immediately after mixing, samples of each mortar mix were collected for flow table (in accordance with BS EN 1015-3:1999) and strength testing (in accordance with BS EN 1015-11:1999). The fresh mortar was emptied from the mixing pan into a wheel barrow and weighed before use.

Table 1. Yield test volumetric mortar mix proportions

Mix		CEM I	CL90	Finely graded sand	Medium graded sand
Y1	M2.5	1	2	9	-
Y2	M5	1	1	6	-
Y3	M10	1	½	4½	-
Y4	M2.5	1	2	-	9
Y5	M5	1	1	-	6
Y6	M10	1	½	-	4½
Y7	M2.5	1	-	9	-
Y8	M5	1	-	6	-
Y9	M10	1	-	4½	-
Y10	M2.5	1	2	-	9
Y11	M5	1	1	-	6
Y12	M10	1	½	-	4½

Each mortar mix was sampled and characterised, including the initial spread on the flow-table (measured in accordance with BS EN 1015-3:1999 [1]), density after hardening, 28-day compressive and flexural strengths (measured in accordance with BS EN 1015-11:1999 [2]).

Table 2. Yield test mortar mix proportions by mass

Mix	CEM I	CL90	Finely graded sand	Medium graded sand	Plasticiser	Water	Water: Cement ratio	Water: Binder^{+} ratio
Y1	11.2 kg	9.8 kg	104.0 kg	-	-	31.0 kg	2.77	1.48
Y2	16.3 kg	7.2 kg	101.5 kg	-	-	29.2 kg	1.79	1.24
Y3	21.2 kg	4.7 kg	99.1 kg	-	-	30.0 kg	1.42	1.15
Y4	10.5 kg	9.3 kg	-	105.2 kg	-	19.7 kg	1.88	0.99
Y5	15.4 kg	6.8 kg	-	102.8 kg	-	21.6 kg	1.40	0.97
Y6	20.1 kg	4.4 kg	-	100.5 kg	-	19.6 kg	0.98	0.80
Y7	12.1 kg	-	112.9 kg	-	53 ml	26.9 kg	2.22	2.22
Y8	17.3 kg	-	107.6 kg	-	76 ml	24.5 kg	1.42	1.42
Y9	22.0 kg	-	103.0 kg	-	97 ml	25.9 kg	1.18	1.18
Y10	11.4 kg	-		113.6 kg	50 ml	17.8 kg	1.56	1.56
Y11	16.3 kg	-		108.7 kg	72 ml	16.4 kg	1.01	1.01
Y12	20.8 kg	-		104.2 kg	92 ml	16.4 kg	0.79	0.79

$^{+}$ Combined cement and lime content.

2.4 Bond strength test mortar mixes

Two mixes were prepared using hydrated lime with two further comparable mixes prepared using a proprietary plasticiser additive in place of the lime. The four mortar mixes were prepared to achieve same target compressive strength of 5 N/mm^2 (M5). For each sand-grading (fine and medium) two mixes were prepared, one with hydrated lime and one with plasticiser. Mortar mixes were prepared in accordance with BS EN1052-11 [2], cast in 40 x 40 x 160 mm mortar prism moulds and tested in flexure and compression. For each mortar type, three flexural strength tests and six compressive strength tests were completed. The mixes were prepared in a laboratory bench top drum mixer.

To ensure that the mixes were of equivalent compressive strengths preliminary tests were undertaken to determine appropriate mix proportions. The workability of each mortar mix was set at a flow table result of 175mm ± 5mm. The total quantity of all ingredients for all mixes was maintained constant at 2 kg. Initially mixes for the lime mortars, in both medium and fine sand were carried out for 1:1:6 (cement:lime:sand). Strength tests were undertaken at 7 days rather than 28 days due to time constraints. The final mix proportions chosen are outlined in Table 3.

Table 3. Bond strength volumetric mortar mix proportions

Mix	CEM I	CL90	Fine sand	Medium Sand	7 day compressive strength (N/mm^2)
B1	1	1	6	-	4.5
B2	1	1	-	6	5.5
B3	1	-	5	-	6.3
B4	1	-	-	5.25	6.0

For construction of the bond wrench wall tests, the total quantity of all ingredients for all mixes was maintained constant at around 40 kg, as shown in Table 4. The plasticiser was used in accordance with the manufacturer's instructions.

Table 4. Bond strength mortar mix proportions (by mass (kg))

Mix	CEM I	CL90	Fine sand	Medium Sand	Water
B1	4.4	2.0	27.6	-	6.1
B2	4.3	1.9	-	26.7	7.1
B3	6.0	-	29.5	-	4.6
B4	5.4	-	-	29.7	5.0

3 EXPERIMENTAL METHODOLOGY

3.1 Yield tests

A team of two experienced UK based bricklayers were asked to lay as many bricks as possible for each mortar mix prepared. The bricks were laid indoors on the floor of the university's structures laboratory. The standard format bricks were laid in stretcher (running) bond in walls measuring 12 bricks long (approximately 2690 mm) and 102.5 mm thick. Materials were batched and weighed before and after mixing. The bricklayers were instructed to lay as many bricks as possible, including half bricks, until the mortar was used up. Mortar bed and perpend joints were laid full but the brick perforations were not to be filled. On completion the number of bricks and wall dimensions were recorded before disposal. The yield test trials were undertaken in period 2012-2013.

3.2 Bond strength tests

Brickwork stack bonded prisms were built using three different fired clay bricks, designated for this study, relatively, as high, medium and low water absorption. The brickwork specimens for bond wrench testing were prepared according to the standard BS EN1052-5:2005 [3]. The mortar mixes were scaled up from the initial test mixes of 2kg to a total wet mix quantity of 40kg. For each of the mortar mixes nine prism specimens were prepared, flow table readings were taken and an air content test also carried out. The larger mortar mixes were prepared in large rotating drum mixer. The test prisms were built by an experienced bricklayer. Following curing in ambient laboratory conditions, flexural bond strengths were measured 28 days after construction. The bond wrench tests were conducted in 2013.

4 EXPERIMENTAL RESULTS

4.1 Yield test mortar properties

The fresh and hardened properties of the mortars from the yield tests are reported in Table 5.

Table 5. Yield test mortar properties

Mortar Mix	Flow Table value (mm)	Mortar Density (kg/m^3)	28day Compressive strength (N/mm^2)		28 day Flexural strength (N/mm^2)	
			Average[a]	Range	Average[b]	Range
Y1	168	1637	2.1	1.9 - 2.3	0.79	0.76 - 0.81
Y2	174	1678	6.2	5.7 - 6.6	1.89	1.86 - 1.91
Y3	180	1714	10.3	9.6 - 11.2	2.57	2.18 - 2.97
Y4	162	1519	4.6	4.2 - 4.9	1.36	1.17 - 1.51
Y5	186	1523	7.2	7.0 - 7.4	2.11	2.05 - 2.14
Y6	174	1550	9.8	9.1 - 10.2	2.51	2.22 - 2.64
Y7	151	1501	1.5	1.4 - 1.7	0.69	0.67 - 0.71
Y8	171	1438	3.6	3.0 - 3.9	1.37	1.22 - 1.38
Y9	176	1491	8.2	7.8 - 8.7	2.53	2.38 - 2.52
Y10	171	1405	2.3	2.0 - 2.7	1.07	1.04 - 1.14
Y11	167	1470	5.6	5.2 - 6.0	1.34	1.00 - 1.61
Y12	162	1506	9.2	8.5 - 10.2	2.58	2.46 - 2.65

[a] – average of 6 tests
[b] – average of 3 tests

The water quantity in each mortar mix was controlled by the bricklayers. This had proven to be a reliable means of achieving consistent workability in previous work. In this trial the flow table workability varied between 151 mm (mix Y7) and 186 mm (mix Y5). The mixes were prepared in this order and so mix Y7 was the first mix using the plasticiser. The bricklayers commented that mix Y7 was ‘too stiff’, but addition of further water was not permitted once mixing had been completed. Mix Y5 was the wettest mix; the bricklayers commented that it was ‘too creamy’ (too wet). The average flow table value for the hydrated lime mixes was 174 mm and 166 mm for the plasticiser mixes.

The mortar densities were determined by weighing and measuring the strength test prisms. The most significant variation in density is noted in mixes Y1-Y3, which were significantly denser than the remaining nine mixes. Sand grading may be reason for this result although this trend is not reflected in the plasticised mixes.

The 28-day strength performance of the mixes is given in Table 3. Five of the mixes met the desired compressive strength performance requirements, with a further three marginally below the desired performance. Most notably mortar mixes Y7-Y9 were significantly below the strength performance levels required. The tests were conducted at short notice and so trial mixes were not prepared prior to wall construction. Without exception the change from CL90-S to plasticiser has impaired compressive strength of the mortars, although this deterioration in performance is not reflected in the flexural strength tests. The reduction in compressive strength varied between 6% and as much as 50% (on average just under 29%). There is also notable difference in performance as a result of sand use. The ‘coarser’ sand mixes (Y4-Y6 and Y10-Y12) are generally stronger than the corresponding mixes using the ‘finer’ sand; this is in accordance with expectations.

Almost all cement:lime based recipes correspond to the traditional accepted correlations with the compressive strength. The admixture using recipes all underperform and would require a higher cement dosage to obtain the tabulated values.

4.2 Bond strength mortar properties

The bond strength test mortar samples were tested at 7, 14 and 28 days. The flexural and compressive strength test results, together with flow table spread and air content, are shown in Table 6 below.

Table 6. Compressive strengths, air content and flow values of the mortars

Mix	Flow value (mm)	Air content (%)	7 day (N/mm^2)	14 day (N/mm^2)	28 day (N/mm^2)
B1	174	10.4	4.5	4.7	5.5
B2	175	4.6	5.5	5.8	5.9
B3	165	20.0	9.4	10.6	11.7
B4	171	18.5	9.6	11.4	11.8

There is a significant difference between the expected compressive strength values for the plasticiser mortar mixes for the brickwork prisms compared to the earlier mortar tests reported in Table 3. The distinct increase in compressive strength for both plasticiser mortar mixes is attributed to the difference in mixers used and the longer mixing times.

4.3 Mortar yield wall construction results

The number of bricks laid, together with the quantity of mortar and final wall dimensions are presented in Table 7. On average the mass of fresh mortar available for bricklaying is around 4% lower than the total quantities presented in Table 2. This is due to use of material in mortar prism and flow table tests and the loss of material on the sides of the mixer pan.

Table 7. Wall test data

Mortar mix	Mass of fresh mortar (kg)	Total number of bricks laid	Total number of courses laid	Wall dimensions		Mass of fresh mortar per brick (kg)	Number of bricks laid per 100 kg of dry materials
				Height (mm)	Length (mm)		
Y1	149	158.5	13.21	1055	2694	0.94	133
Y2	148	158.0	13.17	1052	2701	0.94	132
Y3	148	156.0	13.00	977	2697	0.95	131
Y4	138	168.5	14.04	1124	2693	0.82	141
Y5	141	170.5	14.21	1126	2694	0.83	142
Y6	139	168.5	14.04	1126	2693	0.82	140
Y7	147	172.5	14.38	1130	2696	0.85	143
Y8	144	174.5	14.54	1128	2696	0.82	145
Y9	143	174.5	14.54	1126	2696	0.82	147
Y10	137	176.5	14.71	1126	2691	0.78	147
Y11	136	176.5	14.71	1126	2698	0.77	147
Y12*	104	135.5	11.29	904	2696	0.77	147

* Smaller quantities are due to a shortage of bricks.

The wall dimensions are very consistent. The average depth of each course, over the twelve walls, varied between 75.1 mm and 75.4 mm. Variations in the wall dimensions, caused by variations in the quality of work, is therefore unlikely to be a significant reason for variation in brick usage. The walls are shown in Figure 1 below.

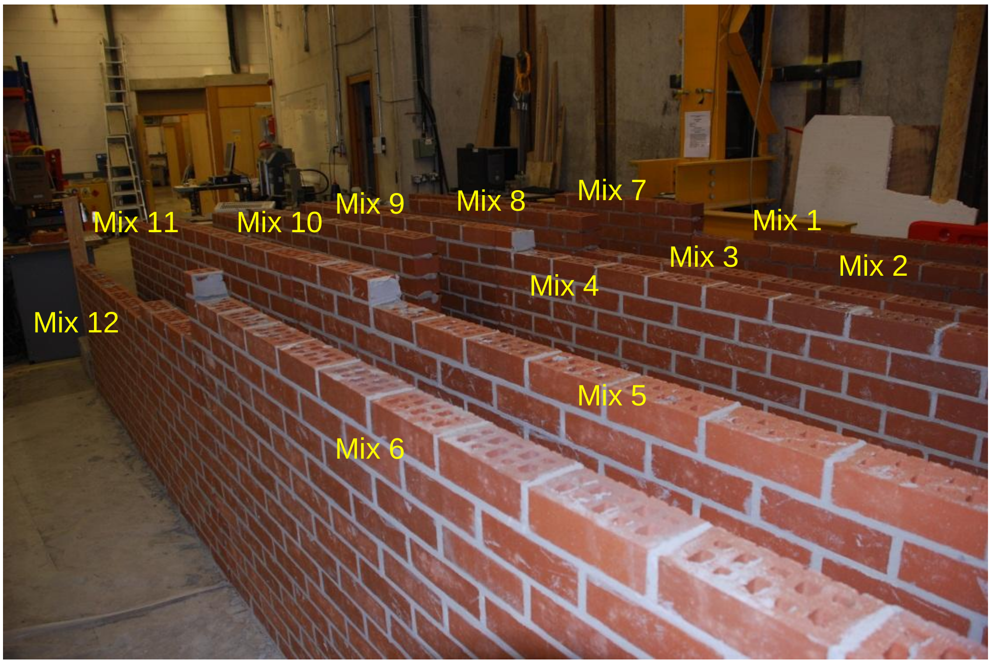

Figure 1. Test walls

The quantity of fresh mortar used per brick and the number of bricks laid per 100 kg of dry mortar material (sand, cement and lime) are both presented in Table 7. These figures do not account for small quantities of mortar lost (wasted) during bricklaying, but as this would normally occur the figures are considered valid. The output (number of bricks laid) is notably lower in mixes Y1-Y3, especially compared to mixes Y4-Y6. This may be attributed to the higher density of mixes Y1-Y3; the increased brick output for the later mixes is in direct proportion to the change (decrease) in mortar density (with the volume of mortar used in the walls remaining constant). Less dense mortars will lay a higher number of bricks.

The bricklayers were asked for their feedback. Apart from comments already given above concerning workability (related to water content), the bricklayers stated a preference for the plasticiser containing mortars, citing improved workability and the ease of cleaning tools on completion of working. However, it should be noted that bricklayers used in this work have common practice with admixtures and no experience with the use of lime containing mortars.

4.4 Flexural bond strengths

The 28-day flexural bond strengths are presented for each of three bricks and four mortar mixes in Table 8. The failure modes were consistently along the interface between the brick and mortar joints, as shown in Figure 2.

Table 8. Average and characteristic bond strengths (N/mm^2)

Brick Water Absorption	1:1:6 (cement:lime:sand)				Plasticised mortars			
	Fine sand		Medium sand		Fine sand		Medium sand	
	Ave.	Charac.	Ave.	Charac.	Ave.	Charac.	Ave.	Charac.
10.0%	0.52	0.12	0.22	0.05	0.13	0.11	0.09	0.05
7.9%	0.81	0.40	0.74	0.47	0.37	0.09	0.25	0.08
6.6%	1.52	1.01	1.02	0.58	0.49	0.37	0.29	0.10

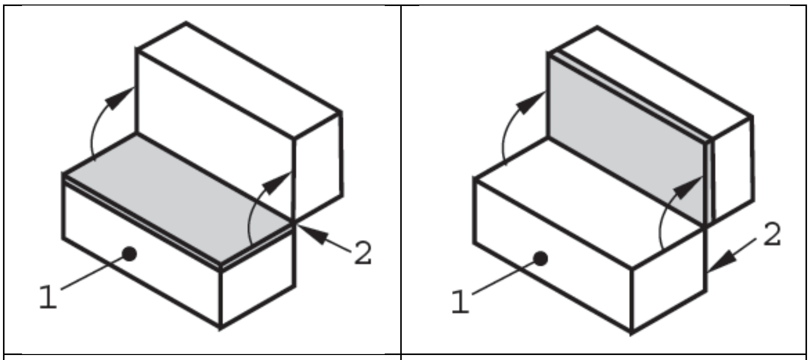

Figure 2: Failure mechanisms (taken from BS EN 1052-5:2005 [3])

Although the plasticised mortars had significantly greater compressive strengths than the equivalent cement:lime mortars, the later consistently provide significantly greater flexural bond strengths for all three brick types and both sand gradings.

The choice of sand grading and brick type has a significant impact on the overall bond strength. The finely graded sand mortars generally achieved higher bond strengths than the medium sand mortars.

The absorption of the brick used also greatly influenced the bond strength. As brick water absorption increased the bond strength reduced. This is a well-known effect caused by the dewatering effects of the bricks.

5 CONCLUSIONS

Following the experimental work outlined above the following conclusions have been made:

- There was a slight improvement in yield using the plasticiser containing mortar mixes. This has been explained by the reduction in mortar density as a result of air entrainment.
- The cement:lime based mortars showed good compliance with the traditionally accepted performance criteria (volume proportions versus mortar strength class).
- Strength performance of the mortars containing air-entraining plasticisers was sensitive to mixing method employed. Significantly lower strengths were achieved using laboratory scale bench top mixers compared to larger scale pan mixer.
- In the yield test series, all mixes using air-entrainer admixture underperformed and did not obtain the tabulated strength values.
- Mortar compressive strength performance and yield generally improved when using the more coarsely graded sand.
- Although in the bond strength test series the plasticiser mortars had significantly greater compressive strengths than the equivalent cement:lime mortars, the later consistently provide significantly greater flexural bond strengths for all three brick types and both sand gradings.
- The choice of sand grading and brick type has a significant impact on the overall bond strength. The finely graded sand mortars generally achieved higher bond strengths than the medium sand mortars.
- The absorption of the brick used also greatly influenced the bond strength. As brick water absorption increased the bond strength reduced. This is a well-known effect caused by the dewatering effects of the bricks.

ACKNOWLEDGEMENTS

The support and contribution from the following organisations and people in this work is acknowledged: Sophie Hayward, David Williams and Neil Price (University of Bath); Mike Haynes (Lhoist UK); Richard Givens (Lafarge Tarmac Lime & Powders); Frederik Verhelst (Lhoist); SC Bricklaying Contractors Ltd.

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