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Bond-strength performance of hydraulic lime and natural cement mortared sandstone masonry

S. Barr [a], W.J. McCarter [b,*], B. Suryanto [b]

[a] Engineering Design, Development Services, Falkirk Council, Abbotsford House, Falkirk FK2 7YZ, Scotland, UK
[b] School of Energy, Geoscience, Infrastructure and Society, Heriot Watt University, Edinburgh EH14 4AS, Scotland, UK

HIGHLIGHTS

- Flexural and compressive stress–strain response of NHL and natural cement mortar presented.
- Mortar stiffness correlates with increasing hydraulicity of binder.
- New data presented on the bond strength of mortared sandstone masonry units.
- Influence of pre-wetting time on bond strength of mortared sandstone units presented.
- Sandstone masonry bond strength increases linearly with increasing hydraulicity of binder.

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ABSTRACT

Flexural bond strength is an important performance characteristic of masonry structures yet there is no guidance for lime-mortared stonework in design codes of practice. This study investigates the bond strength of natural hydraulic lime (NHL) and natural cement mortared sandstone masonry. To this end, the flexural bond strength of masonry couplets, built with mortars of three hydraulic strengths and one natural cement and having a water-content adjusted to achieve a similar consistency, was measured with the bond wrench test. Practical mortar compositions and natural curing conditions were used within the experimental programme. Bond strength was found to be directly related to binder hydraulicity and sandstone pre-wetting time – a positive effect in the case of the former and a negative influence in the case of the latter. Pre-wetting time, however, had a greater influence on the feebly hydraulic lime binder (NHL 2) than on the moderately (NHL 3.5) and eminently hydraulic (NHL 5) lime binders. The results presented will assist in improving our knowledge of lime mortared sandstone masonry and in the development of design guidance.

1. Introduction

Lime mortared brickwork and stonework has been used in masonry construction since ancient times. However, the use of lime mortared masonry has been largely displaced since the advent of stronger and faster setting modern Portland cement in the late 19th century. It became evident in the late 20th century that inappropriate use of cement mortars lead to accelerated masonry deterioration [1] which did not occur with lime-mortared masonry due to lime mortar's greater breathability [2]. In addition to its breathability, a lime mortars ability to accommodate movement and its aesthetic appeal has, in recent years, driven a resurgence in its use in masonry, particularly in sandstone masonry construction and conservation projects.

Hydraulic lime mortars, such as Natural Hydraulic Lime (NHL) and natural cement (NC) mortars can set underwater and gain strength by both hydration and carbonation reactions, unlike air-lime mortars which gain strength purely by carbonation. Hydraulic lime mortars are both faster setting and stronger than air-lime mortars but have greater permeability and reduced stiffness in comparison to Portland cement mortars [2]. Despite the advantages of hydraulic lime mortars over cement mortars, their use is inhibited by a lack of published design guidance and performance data. This lack of data also prevents accurate assessments of the considerable quantity of existing masonry structures built from hydraulic lime mortared natural stone. The flexural bond strength of masonry is a particularly important performance characteristic

* Corresponding author. Tel.: +44 131 451 3318; fax: +44 131 451 4617.
E-mail address: w.j.mccarter@hw.ac.uk (W.J. McCarter).

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which plays a significant role in the ability of a masonry structure to resist lateral or eccentric loading.

No specific mention of lime mortars is made in Eurocode 6 [3]. Eurocode 6 (EC6) uses performance based limit state design with mortars being designated according to compressive strength in a standard 1:3 binder:aggregate mix ratio by mass. Within EC6 other strength characteristics, such as masonry shear strength and masonry flexural strength, are derived from the mortar compressive strength. Lime mortars have much lower compressive strength than cement mortar and so for EC6 design, all other lime mortar masonry strength characteristics are automatically designated within or below the lowest category. According to EC6, the masonry flexural strength parallel to the bed joints for a standard mortar with compressive strength under 5 N/mm^2 and natural stone masonry is 0.05 N/mm^2 – a very low value. The UK national annex to EC6 [4] includes no masonry flexural strength data for natural stone masonry or for mortar under 2 N/mm^2 compressive strength.

There has been increasing academic interest in the flexural strength of lime-mortared masonry, likely driven by an increasing awareness of the benefits of lime mortared masonry and general paucity of bond strength data. Work has, in the main, focussed on modern clay bricks of various types. For example, Zhou et al [5] tested clay bricks (perforated and unperforated) of various absorptivity with hydraulic limes mortars of various hydraulicities and mix ratios for curing periods up to 91 days. Not all configurations were tested and experiments focussed on a NHL 3.5 mortar in a 1:2.25 mix ratio by volume (1:6.62 by mass) using dry clay bricks with initial rate of absorption ranging from 0.1 to 2.4 kg/(m^2 min). For a NHL 3.5 mortar in a 1:2.25 mix ratio by volume, mean values of masonry flexural strength (based on the bond-wernch test) were found to range from 0.09 N/mm^2 for the highest suction brick to 0.49 N/mm^2 for a medium suction brick. The highest value of masonry flexural strength was found to be 0.63 N/mm^2 for a NHL 5 mortar in a 1:2.25 mix ratio by volume with a medium suction brick. Pavia and Hanley [6] also tested clay bricks which were pre-wetted to control suction using lime mortars of various hydraulicity and flow in a 1:2.5 mix ratio (by mass) for a curing period of 28-days. For a NHL 3.5 mortar mean values of masonry flexural strength were found to range from 0.20 N/mm^2 for a low-flow mortar to 0.61 N/mm^2 for a high-flow mortar. Mean values of masonry flexural strength for NHL 2 and NHL 5 mortars ranged between these values and generally increased with greater mortar hydraulicity and flow. Costigan and Pavia [7] tested dry, medium suction, frogged clay bricks with hydraulic lime mortars of varying hydraulicity in a 1:3 mix ratio (by mass) for a range of curing periods. For a curing period of 28-days, mean values of masonry flexural strength were approximately 0.11 N/mm^2 for NHL 2 mortar, 0.16 N/mm^2 for NHL 3.5 and 0.15 N/mm^2 for NHL 5 mortar. For a curing period of 6-months, mean values of masonry flexural strength had increased and were, approximately, 0.19 N/mm^2 for NHL 2 mortar, 0.40 N/mm^2 for NHL 3.5 and 0.37 N/mm^2 for NHL 5 mortar.

Lawrence et al [8] identified critical brick-surface pore sizes that govern bond strength. It was found that calcium silicate crystals can penetrate pores under 1 μm whereas calcium hydroxide crystals can only penetrate pore sizes above 1 μm. It was concluded that bond strength of hydraulic lime mortars would improve with greater proportion of brick-surface pore sizes under 1 μm. Other related studies on mortars include those Hendrickx et al [9] investigating the early water transport between two mortars of different water retention – a lime-mortar and a cement-mortar – and two bricks of different absorption rates – an extruded clay brick and a moulded clay brick. Both mortar water retention and block absorption rate influence the amount of residual water remaining in the mortar and it was concluded that the effect of mortar water retention on water transport is greater than the brick absorption rate. Aggregate texture, size and grading all influence the workability, compressive and flexural strength of mortar [10–13] which will, in turn, effect bond strength.

It should be noted that previous studies have used lime mortars with clay bricks as the block material. In practice, however, there is a much greater need for natural stone to be paired with hydraulic lime mortar due to stone being generally more susceptible to deterioration caused by cement mortar. This study aims to characterise the flexural bond strength of hydraulic lime mortared sandstone blocks and to determine the correlation between masonry flexural strength, mortar bed-joint strength and block absorption (pre-wetting time). Prompt natural cement mortar is also investigated; in addition, mortar mix ratios commonly used in practice (batched by volume) are employed together with natural curing conditions that would be experienced on site. Regarding pre-wetting, studies on clay bricks have shown that pre-wetting can have either a positive or negative effect on the interfacial bond [14,15], therefore it was also the intention of this study to clarify this matter for sandstone blocks.

2. Experimental programme

2.1. Materials

Cullalo stone, a fine-grained grey sandstone from the Cullaloe quarry in Fife (Scotland), was supplied in brick-sized dimensions i.e. 215 × 102.5 × 65 mm [16]. The physical properties of the sandstone blocks (as supplied by the manufacturer) were: compressive strength – 50 MPa; tensile strength – 5 MPa; porosity – 15% and total absorption – 5%. The coefficient of water absorption due to capillary action, as detailed in BS EN 772-11:2011 [17], is not a mandatory test for suppliers to report, however, this was determined within the experimental programme detailed below.

St. Astier NHL grades 2, 3.5 and 5 and a Vicat Prompt natural cement (NC), with a premixed 0.6% citric acid additive to retard the set of NC, were used throughout. Compositional data for the St. Astier and NC binders are summarised in Table 1 [18,19]. A well-graded building sand (2 mm maximum particle size) was used reflecting common site practice.

2.2. Mix proportions and initial flow

Mortars were pre-bagged in a 1:2 lime:aggregate mix ratio by volume (not mass) as commonly used in practice. The consistency of the mortar mix was assessed by measurement of the initial flow in accordance with BS EN1015-3:1999 [20]. To ensure adequate workability, and to replicate common site practice, an initial flow of approximately 170 mm was specified. The water demand to achieve similar consistency decreased with increasing lime grade; as a consequence, the water-content decreased by almost 10% for the prescribed consistency over the range of binders used within the experimental programme. The mortar mixes used within the experimental programme are presented in Table 2.

2.3. Water absorption of Cullalo sandstone

The rate of absorption of Cullalo sandstone was measured in accordance with BS EN772-11:2011 [17] and based on the results from six (notionally) identical samples. The effect of pre-wetting the sandstone blocks on bond strength was investigated by immersing the bed faces of each block to a depth of 5 mm in a tray of water prior to bonding. Three immersion times were considered: 0 min (dry block), 1 min immersion and 15 min immersion.

2.4. Block bonding, workmanship and curing

Masonry couplets, as per BS EN 1052-5:2005 [21], of bonded blocks were prepared for each of the dry, 1 min and 15 min pre-wetting states and for each of the NHL 2, 3.5, 5 and NC lime grades. Three couplets were prepared for each test.

Table 1
Main mineralogical and physical data for the binders studied.

Binder:	NHL 2	NHL 3.5	NHL 5	NC
C_3S – alite (%)	0	0	0	10
C_2S – belite (%)	17	35	43	50
Calcium aluminates (%)	2	2	3	21
$Ca(OH)_2$ free lime (%)	58	25	22	2
Density (kg/m^3)	500	650	700	1100