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BOND-STRENGTH PERFORMANCE OF HYDRAULIC LIME AND NATURAL CEMENT MORTARED SANDSTONE MASONRY

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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 (NHL2) than on the moderately (NHL3.5) and eminently hydraulic (NHL5) lime binders. The results presented will assist in improving our knowledge of lime mortared sandstone masonry and in the development of design guidance.

Keywords: Natural hydraulic lime, natural cement, mortar, sandstone, bond strength, flexural strength.

1.0 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 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 5N/mm^2 and natural stone masonry is 0.05N/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 2N/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 0.1-2.4kg/(m$^{2}\cdot$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 0.09N/mm^2 for the highest suction brick to 0.49N/mm^2 for a medium suction brick. The highest value of masonry flexural strength was found to be 0.63N/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 0.20N/mm^2 for a low-flow mortar to 0.61N/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 0.11N/mm^2 for NHL 2 mortar, 0.16N/mm^2 for NHL 3.5 and 0.15N/mm^2 for NHL 5 mortar. For a curing period of 6-months, mean values of masonry flexural strength had increased and were, approximately, 0.19N/mm^2 for NHL 2 mortar, 0.40N/mm^2 for NHL 3.5 and 0.37N/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 1μm whereas calcium hydroxide crystals can only penetrate pore sizes above 1μm. It was concluded that bond strength of hydraulic lime mortars would improve with greater proportion of brick-surface pore sizes under 1μm. 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.

2.0 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. 215×102.5×65mm [16]. The physical properties of the sandstone blocks (as supplied by the manufacturer) were: compressive strength - 50MPa; tensile strength - 5MPa; 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 (2mm 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 170mm 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 5mm in a tray of water prior to bonding. Three immersion times were considered: 0 minutes (dry block), 1 minute immersion and 15 minutes 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 minute and 15 minute pre-wetting states and for each of the NHL 2, 3.5, 5 and NC lime grades. Three couplets were prepared for each test. As noted above, the bed-face of the blocks was immersed in a tray of water for the specified duration, removed and then wiped with a damp cloth prior to bonding. The bonded blocks were tamped down to create an 8-12mm thick bed-joint; all joint faces were made flush with the blocks (see Fig. 1). The couplets were prepared within 45 minutes of mortar mixing to limit evaporation and, in particular, setting of the NC binder. Immersed blocks were bonded within 5 minutes after immersion to limit evaporation.

The curing regime replicated both sheltered site conditions and common curing practice. Bonded sandstone couplets and mortar prism specimens were placed in a well-ventilated sheltered outdoor environment and completely enclosed under polythene tentage to ensure sufficient humidity for initial hydraulic set. After 7-days, the polythene sheeting and mortar sample moulds were removed for the remaining 21-days. Daily mid-day temperatures ranged between 15-20˚C.

2.5 Mortar strength and deformation

The flexural strength of the mortar for each lime grade after a 28-day cure was determined by three point loading on 6, 40×40×160mm prism specimens in accordance with BS EN 1015-11:1999 [22] using a 100kN Instron 4206 testing machine. The compressive strength of the mortar was then determined on the two parts resulting from the flexural strength test. To study the mechanical behaviour of the mortar under load, flexural and compressive load-deformation profiles were recorded to failure and subsequently converted to stress-strain curves.

2.6 Masonry bond strength

The bond-wrench method of establishing masonry (flexural) bond strength [20] was adopted in this study rather than the wall panel flexural test [3, 23]. It has been shown, however, that both tests produce similar results [5, 24]. In the bond-wrench method, a masonry stack-bonded prism or a couplet is subjected to an eccentric force which wrenches the upper block apart from the jointed lower block. The force is applied through a cantilevered arm arrangement and induces flexural stresses across the mortar bed joint.

The apparatus is shown schematically in Fig. 2 and, essentially, follows that described in BS EN1052-5:2005. The block/mortar couplet was loaded to failure by incrementally increasing the mass on the lever arm in 200gram increments. The mode of failure was recorded and the bond strength of masonry parallel to the bed-joint calculated in accordance with BS EN 1052-5:2005, assuming linear elastic behaviour of the mortar joint. With reference to Fig 2, the bond stress, f_w, at failure is given by,

$$f_w = \frac{F_1 e_1 + F_2 e_2 - \frac{2}{3} d \left(F_1 + F_2 + \frac{W}{4} \right)}{Z} \; N/mm^2$$

where, $Z = bd^2/6$; b is the mean width of the bed joint (mm); d is the mean depth of the specimen (mm); e_1 is the distance from the applied load to the tension face of the specimen (mm); e_2 is the distance from the centre of gravity of the clamping system from the tension face of the specimen (mm); F_1 is the applied load (N); F_2 is the weight of the bond wrench apparatus (N) and W is the weight of the masonry unit pulled off the specimen (N), together with any adherent mortar. The characteristic strength, f_{wk}, was subsequently evaluated based on a 95% confidence level of a lognormal distribution of results as prescribed in BS EN1052-5:2005.

3.0 Results and Discussion

3.1 Mortar Strength and deformation

Mean mortar strength, standard deviation (SD) and coefficient of variation (CoV) are presented in Table 3 for the four binder types. It is evident that binder hydraulicty had a profound effect on both flexural and compressive strength, with strength increasing with increasing hydraulicity. The presence of alite, calcium aluminates and elevated belite phases within the NC mortar has resulted in rapid strength gain within the 28-day cure period. The high belite content of the moderately (NHL3.5) and eminently (NHL5) hydraulic limes has also resulted in strength gains over the feebly hydraulic lime (NHL2). The presence of free lime within the NHL mortars, particularly NHL 2, leads to slow strength gains as hardening is primarily due to carbonation and the extent of carbonation over the 28-day period would be limited. The compressive strengths are in the range 2.0-2.5 times the flexural strength. The mortar strengths obtained are generally comparable to a study [5] utilising similar mix proportions and curing regime.

It is apparent that the NHL binder designation overstates the mortar compressive strength achieved in practice. This is due to the 1:3 mortar mix ratio (binder:sand by mass) prescribed in the building lime mortar classification [25] and strength testing codes [26]. Specifying a mix ratio by mass for relatively low density limes results in an overly rich mix generally not used for mortars in practice. Also, it is important to note that the strength of the mortar within the masonry joints is likely to be different from that of mortar prisms due to factors such as masonry suction reducing the water content of the mortar and the reduced exposed surface area affecting carbonation.

Flexural and compressive stress-strain results are presented in Figs. 3 and 4 for the four binders. Each Figure presents the complete curves for five, notionally identical mortar samples. From Figs. 3(a)-(d), it is evident that, in flexure, all mixes strain linearly until fracture, which occurs suddenly with no plastic deformation. Although the flexural tensile stress at failure increases monotonically with increasing hydraulicity of binder, the strain at failure generally lies in the region 0.003-0.004mm/mm. Based on the slope of the linear portion of the plots, the stiffness range obtained for each binder type is presented on these figures with stiffness increasing with increasing hydraulicity.

With reference to Fig. 4, under compression, the binders display an initial linear-elastic region with deviation from linearity generally lying in the range 0.0075-0.01mm/mm strain. Unlike the flexural response, plastic deformation is evident; however, the extent of plastic deformation decreases with increasing hydraulicity of the binder with the NC binder displaying a well-defined descending branch to the compressive stress-strain curve over the stress range presented. The stiffness range for the binders obtained from the plots is displayed on the respective figures and are in general agreement with those obtained from the flexural test.

3.2 Cullalo Sandstone water absorption rate

The capillary absorption test results for the Cullalo sandstone are presented in Fig. 5, with data plotted on a square-root-time axis. Fig. 5(a) presents the test results taken over a 72-hour absorption period and Fig. 5(b) presents the curve over the initial 1-hour absorption. The error bars on the data markers represent one standard deviation on either side of the mean and where the error bar appears to be missing, the marker is larger than the error bar. The slope of the initial linear portion of the graph gives the coefficient of water absorption due to capillary action which was obtained as 305g/($m^2s^{0.5}$). Comparison of the rate of absorption of Cullalo sandstone with other types of stone was not possible as published values are scant and is due to the rate of absorption being a non-mandatory test. It is also difficult to compare absorption rates of Cullalo stone with blocks of other materials to BS EN 772-11:2011 as there are different immersion durations and units of measurement for different block materials. Supplementary absorption rate tests showed that one sample of a clay engineering brick and one sample of a high alumina concrete fire brick have, respectively, a coefficient of water absorption due to capillary action of 20g/($m^2s^{0.5}$) and 900g/($m^2s^{0.5}$) when measured in the same manner as natural stone (Fig. 5(c)). This indicates that dry Cullalo sandstone has a moderate rate of absorption.

The immersion times of 1 minute and 15 minutes are highlighted on Fig. 5(b) and show that at these times, 51g and 125g of water (respectively) had been absorbed into an individual sandstone block prior to bonding. This represents, respectively, 1.6% and 4.0% absorption of the dry weight of the block or 33% and 81% of the total water absorption at 72 hours. The overall porosity of the sandstone specimens was evaluated as 11%. With reference to Fig. 1, this figure also highlights the position of the water-front in the sandstone units which have been subjected to 0-minutes and 1-minute pre-wetting. The water-front for 0-minutes will represent water absorbed from the mortar bed-joint during the period after bonding and when the image was taken, which was approximately 5-minutes.

3.3 Flexural bond strength

The mean (f_w) and characteristic (f_{wk}) bond strengths of the masonry couplets are presented in Table 4 for the three bed-face pre-wetting times viz. 0, 1 minute (1.6% absorption) and 15 minutes (4% absorption); the standard deviation and CoV of the test results are also presented. Considering the characteristic strength results, all NHL masonry tested at 28-days ranged between 0.05-0.31MPa indicating that they all complied with the value quoted for natural stone masonry in the masonry design code [3] i.e. bond strengths >0.05MPa for failure parallel to bed-joints. Characteristic strengths for the NHL3.5 and NHL5 masonry at 28-days (4% absorption) were 0.16MPa and 0.23MPa respectively, which is greater than the value of 0.15MPa given in the specification of masonry mortar code [27] and comparable to the 0.2MPa strength quoted for M2 cement mortar bonded to concrete and calcium silicate blocks in the UK annex to the masonry design code [4]. Mean bond strengths of all NHL masonry tested were within the range 0.07-0.33MPa. This is lower than the range 0.2-

0.61MPa reported by Pavia and Hanley [6] utilising a richer 1:2.5 mix ratio (by mass) but within that of 0.05-0.63MPa reported by Zhou et al [5] utilising a longer curing duration (91 days); it also lies within the 0.11-0.16MPa range reported by Costigan and Pavia [7] utilising the same curing duration. An additional possible reason for the greater strength results found in previous studies [5, 6] is their use of perforated bricks allowing mortar to flow in and bond to the perforation sides which may have led to overestimated bond strengths due to a greater bond area than that assumed. The failure strength of all NC samples was undetermined as a bond stress of 1.09MPa - the limit of the testing equipment - did not induce failure. The upper limit of expected bond strength is assumed to be approximately 1.5MPa as found in mortar flexural strength testing. However, the value of 1.09MPa bond stress is in excess of even the highest characteristic value given in any masonry code of practice; the national annex to BS EN 1996-1-1:2005 gives a value of 0.7MPa for low absorption clay masonry bonded by a mortar designation *(i)* of strength class M12 (the number following the letter M is the compressive strength for the class at 28-days in MPa)

For the NHL mortared couplets, two failure modes were observed: the NHL5 samples generally failed at the interface between the mortar and upper block shown in Fig. 6(a) whereas the NHL2 and NHL3.5 couplets generally failed by tension failure diagonally across the mortar bed joint shown in Fig. 6(b). No couplets failed due to failure of the block. As noted above, the NC couplets did not fail under the maximum load which could be applied to the wrench apparatus.

The results of these tests indicate values that could be achieved in practice as the specimens were subjected to realistic site curing conditions over a 28-day period and using realistic mix proportions, albeit sheltered from rain. Previous studies on NHL mortars [7] have found substantial increases in bond strength between 28-days and 6-months therefore the values presented may thus represent less than half the expected long-term bond strength. The work presented in this paper has shown, however, that it is still practical to use 28-day data despite NHL mortars slow strength gain.

3.4 Block absorption and bond strength

Fig. 7 presents the relationship between bond strength and block pre-wetting time, in terms of percentage absorption of dry weight. It is evident that increasing pre-wetting time of the dry Cullalo sandstone block results in decreasing bond strength; furthermore, as the pre-wetting time increases, the scatter in the results, as quantified in the CoV (Table 4), increases for all NHL mortar types. It is anticipated that this is related to the inherent variations in porosity through the individual blocks, particularly near to the bed-joint surface of the sandstone block. The evidence for this can be seen from Fig. 5(b) which shows that the standard deviation of the cumulative absorption at 15 minutes is greater than that at 1 minute. In addition, the influence of pre-wetting on the bond strength becomes less significant with increasing hydraulicity of the binder: for example, considering the mean bond strength with 1 minute pre-wetting, relative to the dry block, bond strength this is reduced by 29%, 17% and 5% for, respectively, NHL2, NHL3.5 and NHL5.

Guidance regarding pre-wetting of masonry units is limited in current execution codes of practice. BS800-3:2001 [28], for example, advises that stone units should have trial courses built dry to test bond prior to possible wetting whereas BS EN 1996-2:2006 [29] simply states that the specification should be consulted and, if there is none, to consult the manufacturers of the blocks and mortar. The results obtained in this study indicate that blocks with moderate absorption rates of $\leq 300 g/(m^2 \times s^{0.5})$ should be kept as dry as possible for optimum bond.

3.5 Mortar strength and masonry bond strength

Fig. 8 presents the relationship between the compressive/flexural strength of the mortar and masonry bond strength. Unlike mortar flexural strength, compressive strength exhibits an almost linear relationship with bond strength. This would imply that, for the NHL mortars, compressive strength would be a good indicator of Cullalo sandstone bond strength.

According to the UK National Annex to Eurocode 6 [4], cement mortars with a compressive strength of 12MPa bonded to low absorbency clay bricks have a masonry flexural strength of 0.7MPa with the plane of failure parallel to the bed joint. Considering that NC mortars have a similar total proportion of hydraulic components to cement mortars, their compressive strength is lower than cement mortars yet their bond strength is higher. The bond strength of NC mortar may therefore have benefited from the high calcium aluminate content which brings a rapid set and strength gain resulting in optimal water transfer for the absorption rates experienced.

4.0 Conclusions and Concluding Comments

This study has presented both mortar strength and sandstone bond-strength data using practical mortar compositions, stored and cured under natural conditions - an area where there is, currently, a dearth of information. The work would find application in developing guidance and specifications when such materials are used in conservation, restoration or refurbishment work and also where structural assessment is required. The following can be drawn from the investigation:

(1) In flexure, all the mortar mixes strained linearly until failure whereas under compression a plastic region was detectable, the extent of which decreased with increasing hydraulicity of binder. Mortar stiffness increased with increasing hydraulicity of binder.

(2) The bond strengths of NHL3.5 and NHL5 mortared stone masonry after a 28-day cure were observed to be comparable to low-strength cement mortared brickwork. The bond strength of NC mortared stone masonry at 28-days exceeded even high strength cement mortared brickwork.

(3) Block pre-wetting had a significant influence on flexural bond strength of sandstone masonry, with bond strength decreasing with increasing pre-wetting time. The results of this study indicate that for optimum bond, blocks with moderate absorption rates of ~300g/($m^2s^{0.5}$) and under, such as the Cullalo sandstone tested, should be kept as dry as possible.

(4) Mortar compressive strength had a profound effect on the flexural bond strength of sandstone masonry exhibiting a positive linear relationship; as a result, flexural bond strengths of stone masonry should continue to be categorised by mortar compressive strength in design codes of practice.

The work would also indicated that mortar strength testing, and NHL binder designation codes of practice [25, 26], should relate to mix ratios commonly used in practice (as this study has used), for example, a 1:2.5 mix by volume rather than the 1:3 mix by mass. Despite the slow strength gain of NHL mortar, the work has shown that it is still practical to use 28-day data as prescribed in current codes of practice [26] but the strength obtained may represent less than half the expected long-term strength [7]. The work presented will also serve to promote awareness of hydraulic lime mortared sandstone masonry and to enable more confident design and assessment of this material.

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27. British Standards Institution, BS EN 998-2:2010. *Specification for mortar for masonry - Part 2: Masonry mortar* BSI, London.

28. British Standards Institution, BS8000-3:2001. *Workmanship on building sites – part 3: code of practice for masonry* BSI, London.

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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

Table 2: Mortar batch proportions and initial flow

Binder			Sand		Water		Mix ratio (Binder:Sand)		Consistency
Grade	Density (kg/m^3)	Mass (kg)	Density (kg/m^3)	Mass (kg)	Mass (kg)	*w/l*	By vol.	By mass	Initial flow (mm)
NHL 2	500	1.38	1560	8.61	2.1	1.52	1 : 2	1 : 6.24	167
NHL 3.5	650	1.72	1560	8.27	2	1.16	1 : 2	1 : 4.80	170
NHL 5	700	1.83	1560	8.16	1.9	1.04	1 : 2	1 : 4.46	169
NC	1100	2.60	1560	7.38	1.8	0.69	1 : 2	1 : 2.84	179

Table 3: Summary of strength test results for mortar binders.

Binder Type	Flexural Strength			Compressive Strength		
	Mean (MPa)	SD (MPa)	CoV (%)	Mean (MPa)	SD (MPa)	CoV (%)
NHL 2	0.198	0.019	9.45	0.355	0.029	8.31
NHL 3.5	0.235	0.023	9.75	0.690	0.070	10.18
NHL 5	0.517	0.038	7.34	1.090	0.052	4.74
NC	1.501	0.059	9.65	4.245	0.302	7.12

Table 4: Summary of bond strength results for different pre-wetting times.

Binder Type	0 minutes				1 minute				15 minutes			
	f_w (mean) (MPa)	SD (MPa)	CoV (%)	f_{wk} (mean) MPa	f_w (mean) (MPa)	SD (MPa)	CoV (%)	f_{wk} (mean) MPa	f_w (mean) (MPa)	SD (MPa)	CoV (%)	f_{wk} (mean) MPa
NHL 2	0.107	0.008	7.9	0.094	0.076	0.003	3.8	0.072	0.069	0.013	19.4	0.050
NHL 3.5	0.233	0.006	2.4	0.224	0.193	0.005	2.7	0.185	0.185	0.017	9.0	0.159
NHL 5	0.329	0.010	2.9	0.313	0.311	0.005	1.7	0.303	0.253	0.012	4.8	0.233
NC	1.091*	+	+	+	1.091*	+	+	+	1.091*	+	+	+

* did not fail at maximum load on bond-wrench apparatus

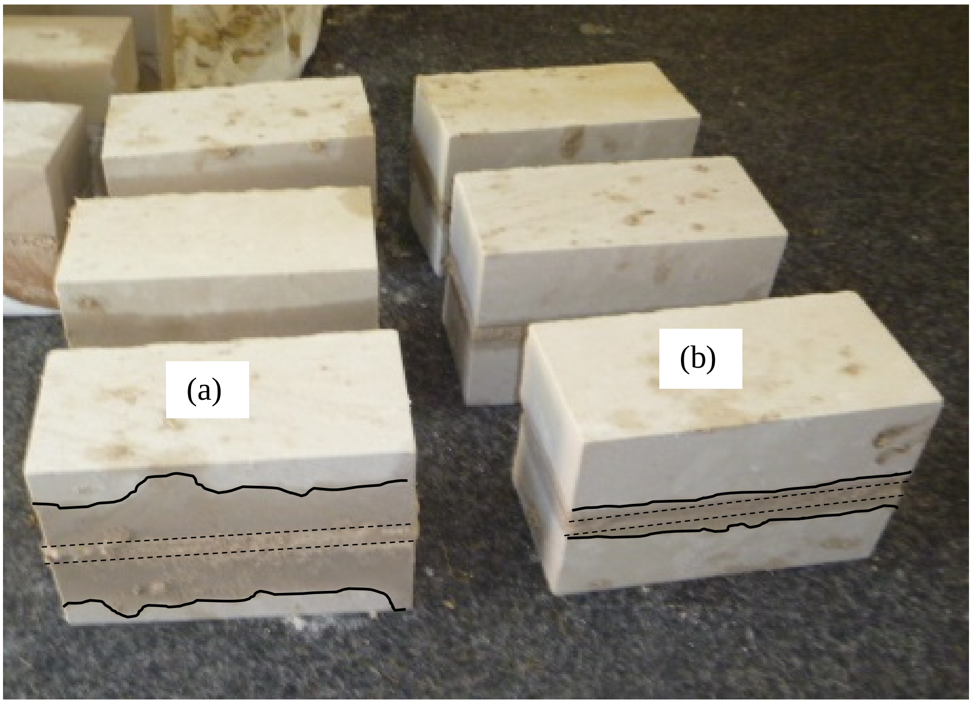


Fig. 1 Cullalo sandstone couplets approximately 5 minutes after bonding. This figure also shows the position of the water-front in the sandstone units (a) for those units with 1-minute pre-wetting, and, (b) for those units with 0-minutes pre-wetting. The water-front is indicated with a solid line and the mortar bed-joint indicated with dashed lines. In (b) the water-front will represent the water absorbed from the mortar bed-joint.

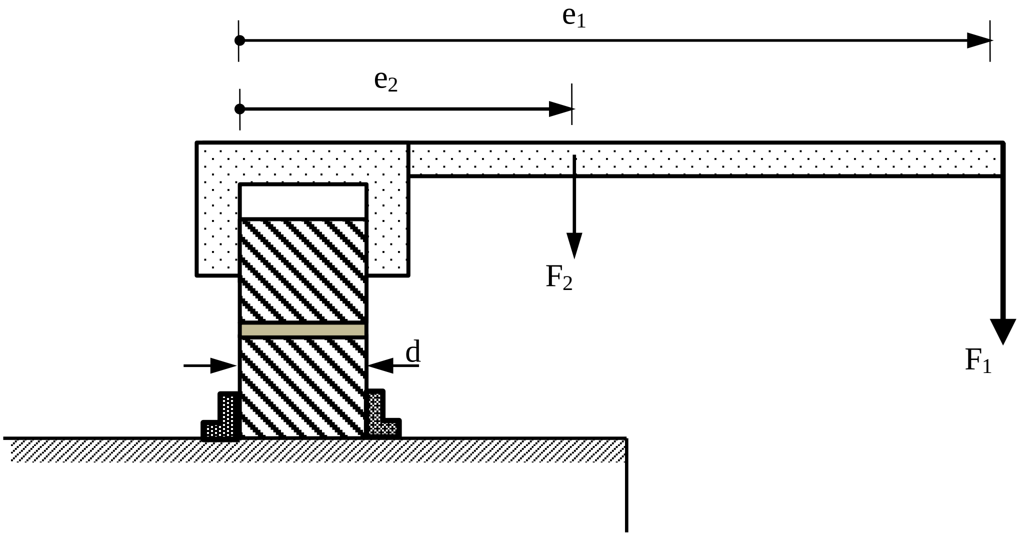
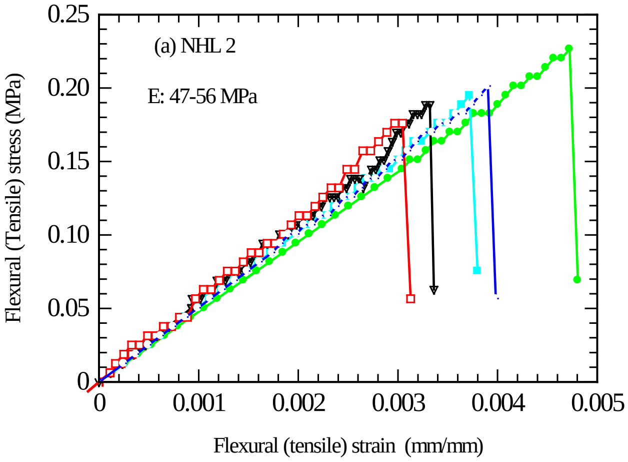
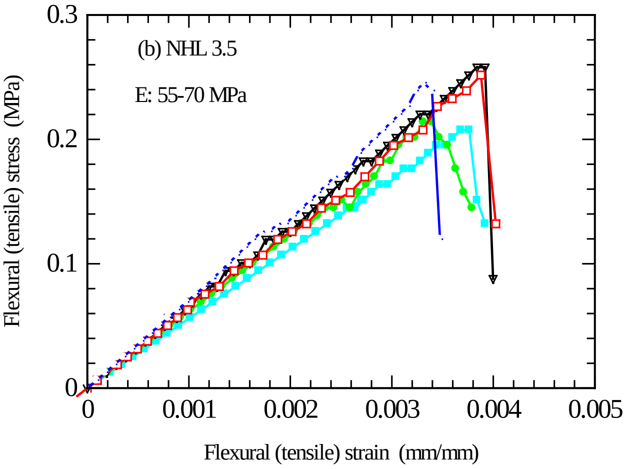


Fig. 2 Schematic diagram of wrench-test


(a) NHL 2
E: 47-56 MPa
Flexural (Tensile) stress (MPa)
0
0.05
0.10
0.15
0.20
0.25
0
0.001
0.002
0.003
0.004
0.005
Flexural (tensile) strain (mm/mm)


(b) NHL 3.5
E: 55-70 MPa
Flexural (tensile) stress (MPa)
0
0.1
0.2
0.3
0
0.001
0.002
0.003
0.004
0.005
Flexural (tensile) strain (mm/mm)

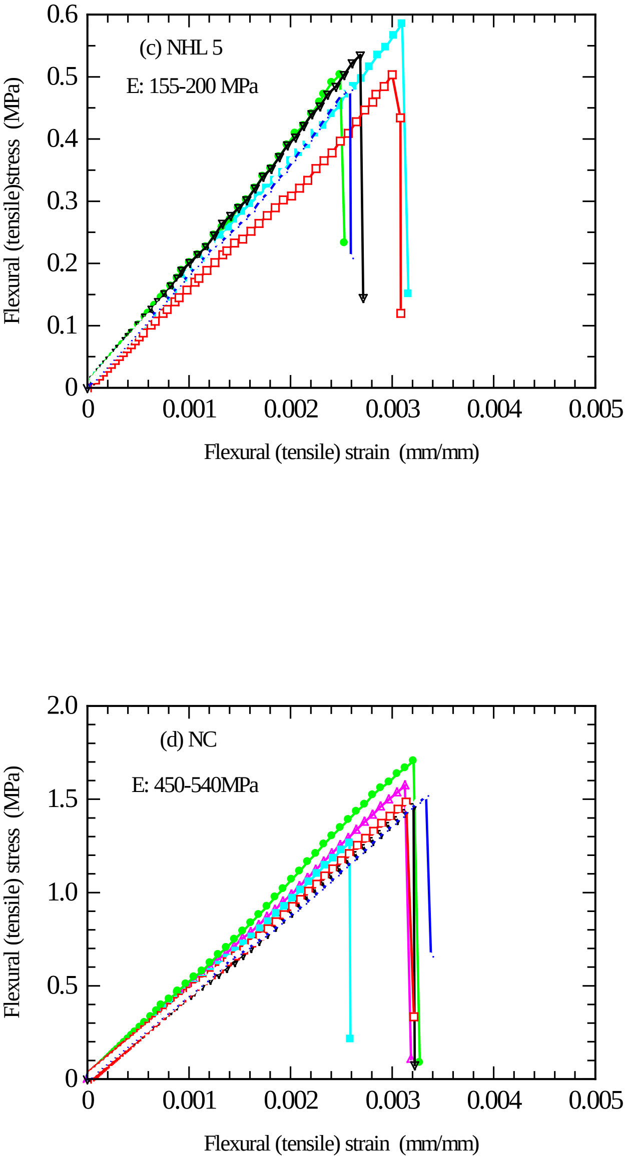
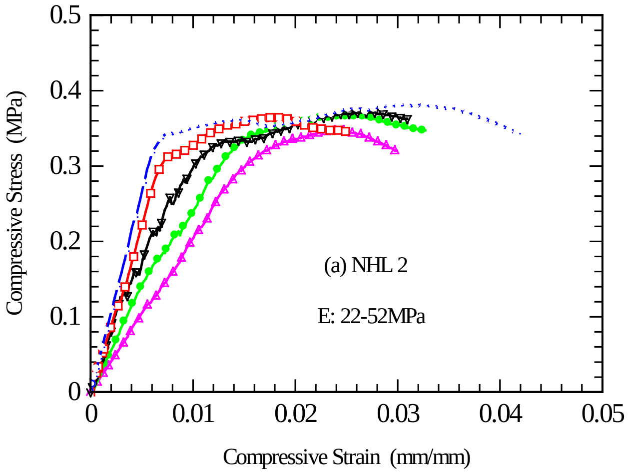
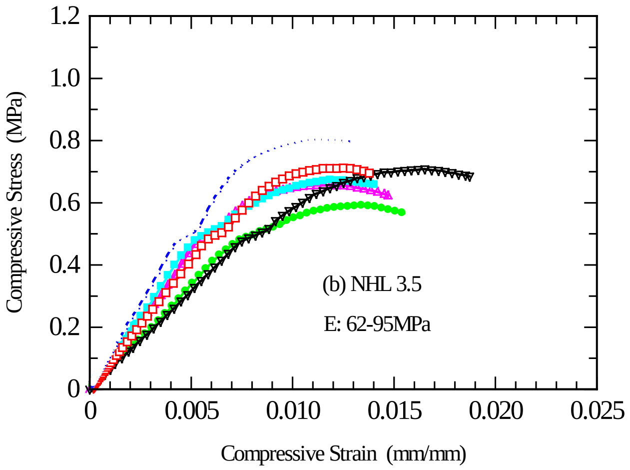
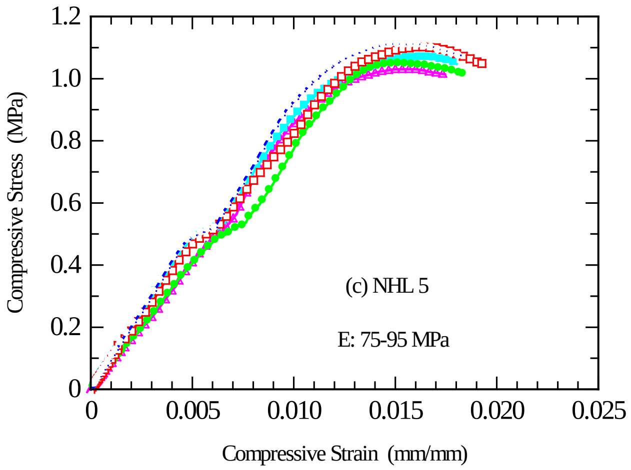


Fig. 3 Flexural stress-strain curves for five mortar prisms a) NHL 2, (b) NHL 3.5, (c) NHL 5, and (d) NC. Note: stiffness range denoted E on Figures.


0.5
0.4
0.3
0.2
0.1
0
Compressive Stress (MPa)
0
0.01
0.02
0.03
0.04
0.05
Compressive Strain (mm/mm)
(a) NHL 2
E: 22-52MPa


1.2
1.0
0.8
0.6
0.4
0.2
0
Compressive Stress (MPa)
0
0.005
0.010
0.015
0.020
0.025
Compressive Strain (mm/mm)
(b) NHL 3.5
E: 62-95MPa



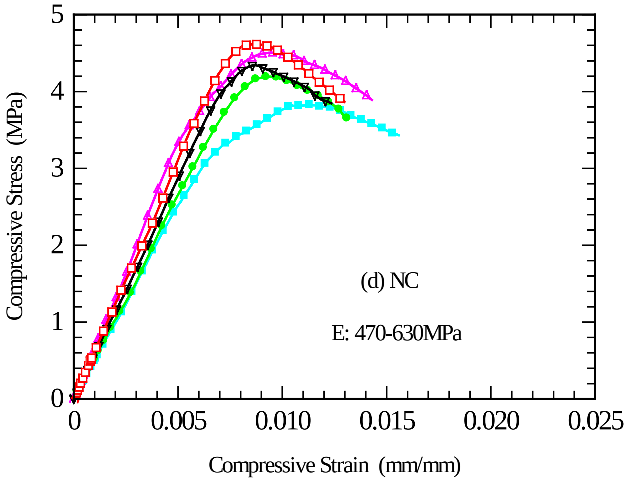
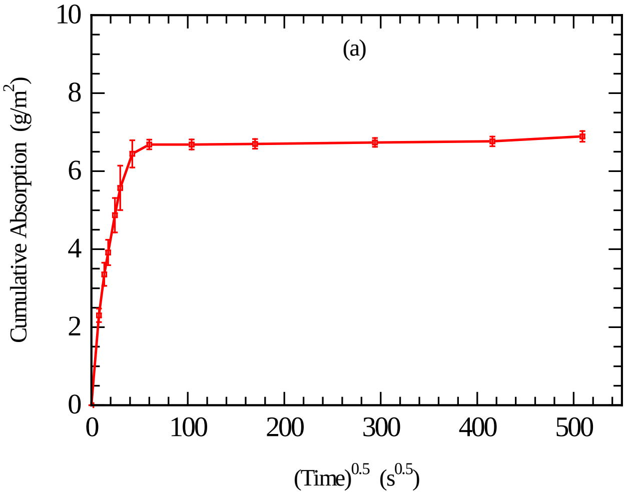
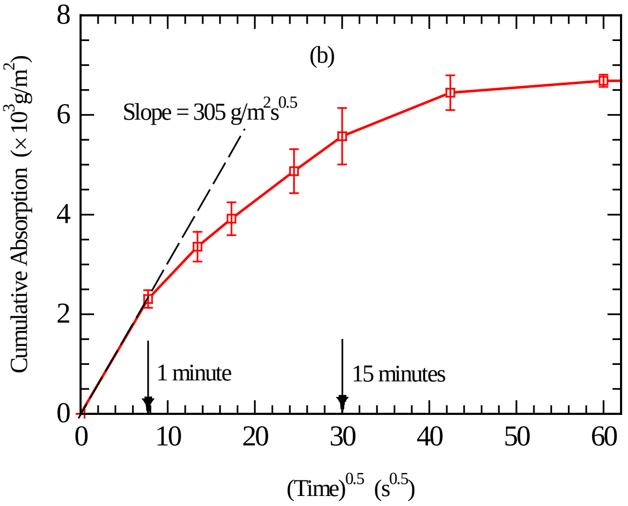


Fig. 4 Compressive stress-strain curves for five mortar prisms a) NHL 2, (b) NHL 3.5, (c) NHL 5, and (d) NC. Note: stiffness range denoted E on Figures.


(a)
Cumulative Absorption (g/m^2)
(Time)$^{0.5}$ (s$^{0.5}$)
0
2
4
6
8
10
0
100
200
300
400
500


(b)
Slope = 305 g/m^{2}s$^{0.5}$
1 minute
15 minutes
Cumulative Absorption (× 10^{3}g/m^2)
(Time)$^{0.5}$ (s$^{0.5}$)
0
2
4
6
8
0
10
20
30
40
50
60

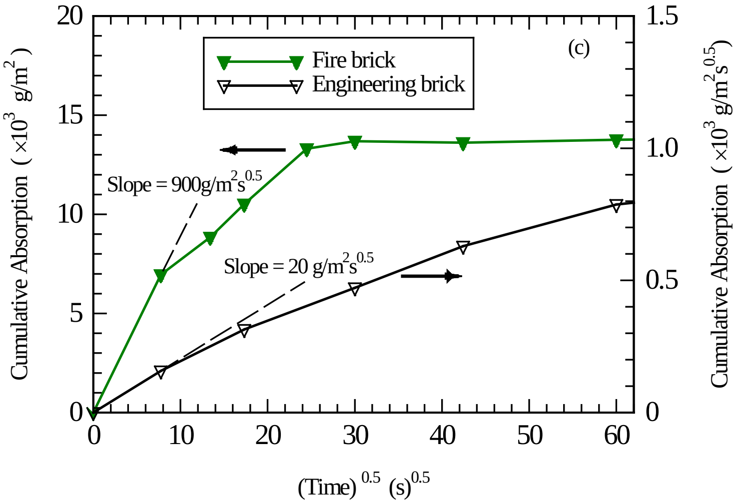
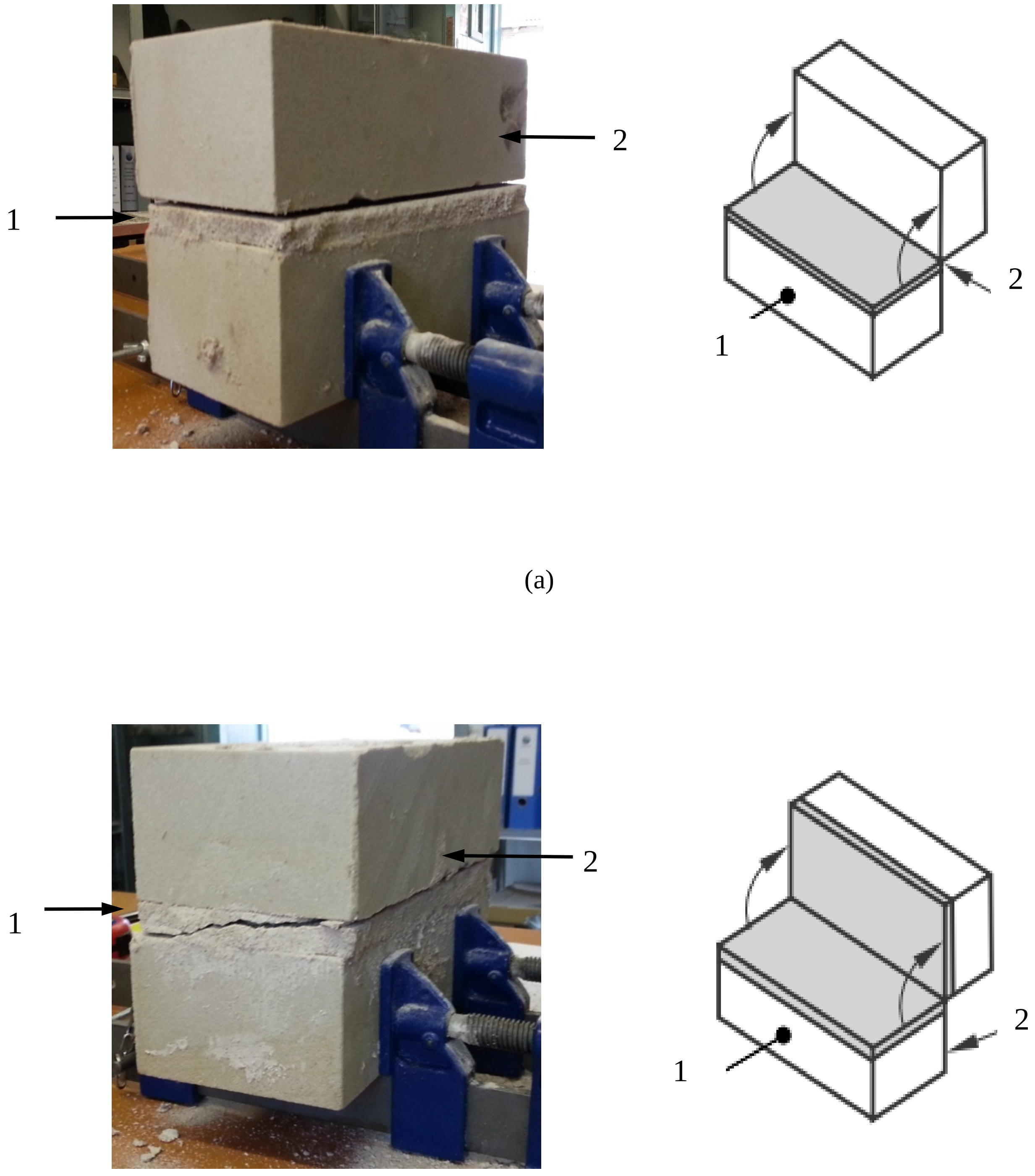


Fig. 5 (a) Cumulative absorption of Cullalo sandstone over 72-hour test period, (b) enlargement of (a) showing initial 1-hour absorption, and (c) cumulative absorption for a fire brick and an engineering brick.



(a)

(b)

Fig. 6 Failure of mortar bed-joint showing (a) tension failure at interface between mortar and upper block, and (b) diagonal tension failure within mortar bed-joint. (Note: 1 = tension face, 2 = compression face; schematic diagrams in (a) and (b) adapted from [21])

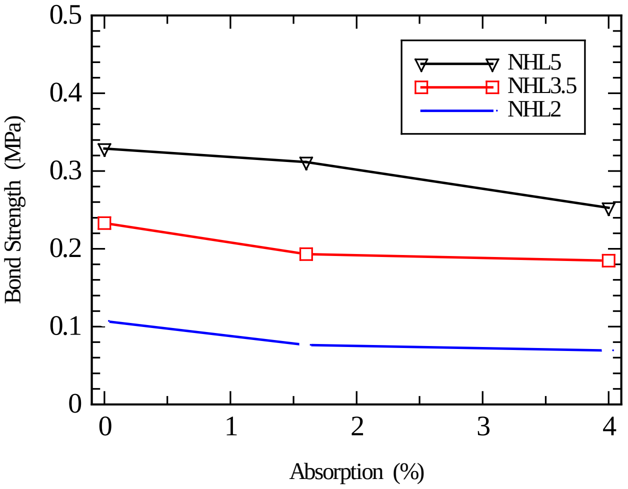


Fig. 7 Influence of pre-wetting on sandstone bond-strength

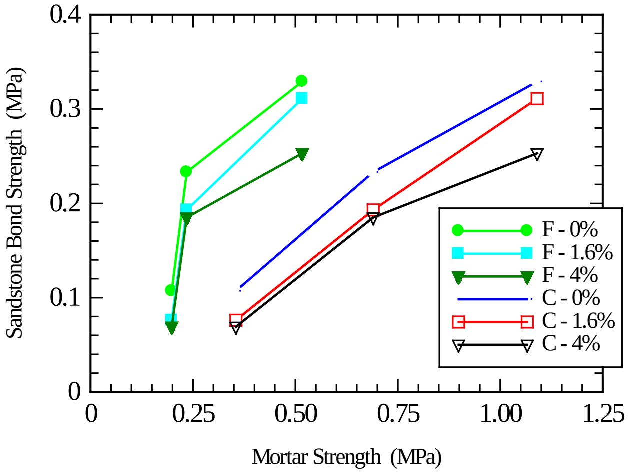


Fig. 8 Influence of mortar strength (F = flexural; C = compressive) on sandstone bond strength for 0%, 1.6% and 4% absorption (pre-wetting).