

25 **Abstract**

26

27 Flexural bond strength is an important performance characteristic of masonry structures yet
28 there is no guidance for lime-mortared stonework in design codes of practice. This study
29 investigates the bond strength of natural hydraulic lime (NHL) and natural cement mortared
30 sandstone masonry. To this end, the flexural bond strength of masonry couplets, built with
31 mortars of three hydraulic strengths and one natural cement and having a water-content
32 adjusted to achieve a similar consistency, was measured with the bond wrench test. Practical
33 mortar compositions and natural curing conditions were used within the experimental
34 programme. Bond strength was found to be directly related to binder hydraulicity and
35 sandstone pre-wetting time - a positive effect in the case of the former and a negative
36 influence in the case of the latter. Pre-wetting time, however, had a greater influence on the
37 feebly hydraulic lime binder (NHL2) than on the moderately (NHL3.5) and eminently
38 hydraulic (NHL5) lime binders. The results presented will assist in improving our knowledge
39 of lime mortared sandstone masonry and in the development of design guidance.

40

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

43

44 **1.0 Introduction**

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

54
55 Hydraulic lime mortars, such as Natural Hydraulic Lime (NHL) and Natural Cement (NC)
56 mortars can set underwater and gain strength by both hydration and carbonation reactions,
57 unlike air-lime mortars which gain strength purely by carbonation. Hydraulic lime mortars
58 are both faster setting and stronger than air-lime mortars but have greater permeability and
59 reduced stiffness in comparison to Portland cement mortars [2]. Despite the advantages of
60 hydraulic lime mortars over cement mortars, their use is inhibited by a lack of published
61 design guidance and performance data. This lack of data also prevents accurate assessments
62 of the considerable quantity of existing masonry structures built from hydraulic lime
63 mortared natural stone. The flexural bond strength of masonry is a particularly important
64 performance characteristic which plays a significant role in the ability of a masonry structure
65 to resist lateral or eccentric loading.

66
67 No specific mention of lime mortars is made in Eurocode 6 [3]. Eurocode 6 (EC6) uses
68 performance based limit state design with mortars being designated according to compressive

69 strength in a standard 1:3 binder:aggregate mix ratio by mass. Within EC6 other strength
70 characteristics, such as masonry shear strength and masonry flexural strength, are derived
71 from the mortar compressive strength. Lime mortars have much lower compressive strength
72 than cement mortar and so for EC6 design, all other lime mortar masonry strength
73 characteristics are automatically designated within or below the lowest category. According
74 to EC6, the masonry flexural strength parallel to the bed joints for a standard mortar with
75 compressive strength under 5N/mm^2 and natural stone masonry is 0.05N/mm^2 - a very low
76 value. The UK national annex to EC6 [4] includes no masonry flexural strength data for
77 natural stone masonry or for mortar under 2N/mm^2 compressive strength.

78

79 There has been increasing academic interest in the flexural strength of lime-mortared
80 masonry, likely driven by an increasing awareness of the benefits of lime mortared masonry
81 and general paucity of bond strength data. Work has, in the main, focussed on modern clay
82 bricks of various types. For example, Zhou et al [5] tested clay bricks (perforated and
83 unperforated) of various absorptivity with hydraulic limes mortars of various hydraulicities
84 and mix ratios for curing periods up to 91 days. Not all configurations were tested and
85 experiments focussed on a NHL 3.5 mortar in a 1:2.25 mix ratio by volume (1:6.62 by mass)
86 using dry clay bricks with initial rate of absorption ranging from $0.1\text{-}2.4\text{kg}/(\text{m}^2\cdot\text{min})$. For a
87 NHL 3.5 mortar in a 1:2.25 mix ratio by volume, mean values of masonry flexural strength
88 (based on the bond-wernch test) were found to range from 0.09N/mm^2 for the highest suction
89 brick to 0.49N/mm^2 for a medium suction brick. The highest value of masonry flexural
90 strength was found to be 0.63N/mm^2 for a NHL 5 mortar in a 1:2.25 mix ratio by volume
91 with a medium suction brick. Pavia and Hanley [6] also tested clay bricks which were pre-
92 wetted to control suction using lime mortars of various hydraulicity and flow in a 1:2.5 mix
93 ratio (by mass) for a curing period of 28-days. For a NHL 3.5 mortar mean values of

94 masonry flexural strength were found to range from 0.20N/mm^2 for a low-flow mortar to
95 0.61N/mm^2 for a high-flow mortar. Mean values of masonry flexural strength for NHL 2 and
96 NHL 5 mortars ranged between these values and generally increased with greater mortar
97 hydraulicity and flow. Costigan and Pavia [7] tested dry, medium suction, frogged clay
98 bricks with hydraulic lime mortars of varying hydraulicity in a 1:3 mix ratio (by mass) for a
99 range of curing periods. For a curing period of 28-days, mean values of masonry flexural
100 strength were approximately 0.11N/mm^2 for NHL 2 mortar, 0.16N/mm^2 for NHL 3.5 and
101 0.15N/mm^2 for NHL 5 mortar. For a curing period of 6-months, mean values of masonry
102 flexural strength had increased and were, approximately, 0.19N/mm^2 for NHL 2 mortar,
103 0.40N/mm^2 for NHL 3.5 and 0.37N/mm^2 for NHL 5 mortar.

104

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

117

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

129

130 **2.0 Experimental Programme**

131 **2.1 Materials**

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

139 St. Astier NHL grades 2, 3.5 and 5 and a Vicat Prompt natural cement (NC), with a premixed
140 0.6% citric acid additive to retard the set of NC, were used throughout. Compositional data
141 for the St. Astier and NC binders are summarised in Table 1 [18, 19]. A well-graded building
142 sand (2mm maximum particle size) was used reflecting common site practice.

143 **2.2 Mix proportions and initial flow**

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

152

153 **2.3 Water absorption of Cullalo sandstone**

154 The rate of absorption of Cullalo sandstone was measured in accordance with BS EN772-
155 11:2011 [17] and based on the results from six (notionally) identical samples. The effect of
156 pre-wetting the sandstone blocks on bond strength was investigated by immersing the bed
157 faces of each block to a depth of 5mm in a tray of water prior to bonding. Three immersion
158 times were considered: 0 minutes (dry block), 1 minute immersion and 15 minutes
159 immersion.

160 **2.4 Block bonding, workmanship and curing**

161 Masonry couplets, as per BS EN 1052-5:2005 [21], of bonded blocks were prepared for each
162 of the dry, 1 minute and 15 minute pre-wetting states and for each of the NHL 2, 3.5, 5 and
163 NC lime grades. Three couplets were prepared for each test. As noted above, the bed-face of
164 the blocks was immersed in a tray of water for the specified duration, removed and then
165 wiped with a damp cloth prior to bonding. The bonded blocks were tamped down to create
166 an 8-12mm thick bed-joint; all joint faces were made flush with the blocks (see Fig. 1). The

167 couplets were prepared within 45 minutes of mortar mixing to limit evaporation and, in
168 particular, setting of the NC binder. Immersed blocks were bonded within 5 minutes after
169 immersion to limit evaporation.

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

176

177 ***2.5 Mortar strength and deformation***

178 The flexural strength of the mortar for each lime grade after a 28-day cure was determined by
179 three point loading on 6, 40×40×160mm prism specimens in accordance with BS EN 1015-
180 11:1999 [22] using a 100kN Instron 4206 testing machine. The compressive strength of the
181 mortar was then determined on the two parts resulting from the flexural strength test. To
182 study the mechanical behaviour of the mortar under load, flexural and compressive load-
183 deformation profiles were recorded to failure and subsequently converted to stress-strain
184 curves.

185

186 ***2.6 Masonry bond strength***

187 The bond-wrench method of establishing masonry (flexural) bond strength [20] was adopted
188 in this study rather than the wall panel flexural test [3, 23]. It has been shown, however, that
189 both tests produce similar results [5, 24]. In the bond-wrench method, a masonry stack-
190 bonded prism or a couplet is subjected to an eccentric force which wrenches the upper block

191 apart from the jointed lower block. The force is applied through a cantilevered arm
192 arrangement and induces flexural stresses across the mortar bed joint.

193 The apparatus is shown schematically in Fig. 2 and, essentially, follows that described in BS
194 EN1052-5:2005. The block/mortar couplet was loaded to failure by incrementally increasing
195 the mass on the lever arm in 200gram increments. The mode of failure was recorded and the
196 bond strength of masonry parallel to the bed-joint calculated in accordance with BS EN 1052-
197 5:2005, assuming linear elastic behaviour of the mortar joint. With reference to Fig 2, the
198 bond stress, f_w , at failure is given by,

$$199 \quad f_w = \frac{F_1 e_1 + F_2 e_2 - \frac{2}{3} d \left(F_1 + F_2 + \frac{W}{4} \right)}{Z} \text{ N/mm}^2$$

200 where, $Z = bd^2/6$; b is the mean width of the bed joint (mm); d is the mean depth of the
201 specimen (mm); e_1 is the distance from the applied load to the tension face of the specimen
202 (mm); e_2 is the distance from the centre of gravity of the clamping system from the tension
203 face of the specimen (mm); F_1 is the applied load (N); F_2 is the weight of the bond wrench
204 apparatus (N) and W is the weight of the masonry unit pulled off the specimen (N), together
205 with any adherent mortar. The characteristic strength, f_{wk} , was subsequently evaluated based
206 on a 95% confidence level of a lognormal distribution of results as prescribed in BS EN1052-
207 5:2005.

208

209 **3.0 Results and Discussion**

210 ***3.1 Mortar Strength and deformation***

211 Mean mortar strength, standard deviation (SD) and coefficient of variation (CoV) are
212 presented in Table 3 for the four binder types. It is evident that binder hydraulicity had a
213 profound effect on both flexural and compressive strength, with strength increasing with

214 increasing hydraulicity. The presence of alite, calcium aluminates and elevated belite phases
215 within the NC mortar has resulted in rapid strength gain within the 28-day cure period. The
216 high belite content of the moderately (NHL3.5) and eminently (NHL5) hydraulic limes has
217 also resulted in strength gains over the feebly hydraulic lime (NHL2). The presence of free
218 lime within the NHL mortars, particularly NHL 2, leads to slow strength gains as hardening
219 is primarily due to carbonation and the extent of carbonation over the 28-day period would be
220 limited. The compressive strengths are in the range 2.0-2.5 times the flexural strength. The
221 mortar strengths obtained are generally comparable to a study [5] utilising similar mix
222 proportions and curing regime.

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

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

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

247

248 *3.2 Cullalo Sandstone water absorption rate*

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

263 the same manner as natural stone (Fig. 5(c)). This indicates that dry Cullalo sandstone has a
264 moderate rate of absorption.

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

274

275 **3.3 Flexural bond strength**

276 The mean (f_w) and characteristic (f_{wk}) bond strengths of the masonry couplets are presented in
277 Table 4 for the three bed-face pre-wetting times viz. 0, 1 minute (1.6% absorption) and 15
278 minutes (4% absorption); the standard deviation and CoV of the test results are also
279 presented. Considering the characteristic strength results, all NHL masonry tested at 28-days
280 ranged between 0.05-0.31MPa indicating that they all complied with the value quoted for
281 natural stone masonry in the masonry design code [3] i.e. bond strengths >0.05 MPa for
282 failure parallel to bed-joints. Characteristic strengths for the NHL3.5 and NHL5 masonry at
283 28-days (4% absorption) were 0.16MPa and 0.23MPa respectively, which is greater than the
284 value of 0.15MPa given in the specification of masonry mortar code [27] and comparable to
285 the 0.2MPa strength quoted for M2 cement mortar bonded to concrete and calcium silicate
286 blocks in the UK annex to the masonry design code [4]. Mean bond strengths of all NHL
287 masonry tested were within the range 0.07-0.33MPa. This is lower than the range 0.2-

288 0.61MPa reported by Pavia and Hanley [6] utilising a richer 1:2.5 mix ratio (by mass) but
289 within that of 0.05-0.63MPa reported by Zhou et al [5] utilising a longer curing duration (91
290 days); it also lies within the 0.11-0.16MPa range reported by Costigan and Pavia [7] utilising
291 the same curing duration. An additional possible reason for the greater strength results found
292 in previous studies [5, 6] is their use of perforated bricks allowing mortar to flow in and bond
293 to the perforation sides which may have led to overestimated bond strengths due to a greater
294 bond area than that assumed. The failure strength of all NC samples was undetermined as a
295 bond stress of 1.09MPa - the limit of the testing equipment - did not induce failure. The
296 upper limit of expected bond strength is assumed to be approximately 1.5MPa as found in
297 mortar flexural strength testing. However, the value of 1.09MPa bond stress is in excess of
298 even the highest characteristic value given in any masonry code of practice; the national
299 annex to BS EN 1996-1-1:2005 gives a value of 0.7MPa for low absorption clay masonry
300 bonded by a mortar designation (*i*) of strength class M12 (the number following the letter M
301 is the compressive strength for the class at 28-days in MPa)

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

308 The results of these tests indicate values that could be achieved in practice as the specimens
309 were subjected to realistic site curing conditions over a 28-day period and using realistic mix
310 proportions, albeit sheltered from rain. Previous studies on NHL mortars [7] have found
311 substantial increases in bond strength between 28-days and 6-months therefore the values
312 presented may thus represent less than half the expected long-term bond strength. The work

313 presented in this paper has shown, however, that it is still practical to use 28-day data despite
314 NHL mortars slow strength gain.

315 ***3.4 Block absorption and bond strength***

316 Fig. 7 presents the relationship between bond strength and block pre-wetting time, in terms of
317 percentage absorption of dry weight. It is evident that increasing pre-wetting time of the dry
318 Cullalo sandstone block results in decreasing bond strength; furthermore, as the pre-wetting
319 time increases, the scatter in the results, as quantified in the CoV (Table 4), increases for all
320 NHL mortar types. It is anticipated that this is related to the inherent variations in porosity
321 through the individual blocks, particularly near to the bed-joint surface of the sandstone
322 block. The evidence for this can be seen from Fig. 5(b) which shows that the standard
323 deviation of the cumulative absorption at 15 minutes is greater than that at 1 minute. In
324 addition, the influence of pre-wetting on the bond strength becomes less significant with
325 increasing hydraulicity of the binder: for example, considering the mean bond strength with 1
326 minute pre-wetting, relative to the dry block, bond strength this is reduced by 29%, 17% and
327 5% for, respectively, NHL2, NHL3.5 and NHL5.

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

335

336 ***3.5 Mortar strength and masonry bond strength***

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

341 According to the UK National Annex to Eurocode 6 [4], cement mortars with a compressive
342 strength of 12MPa bonded to low absorbency clay bricks have a masonry flexural strength of
343 0.7MPa with the plane of failure parallel to the bed joint. Considering that NC mortars have
344 a similar total proportion of hydraulic components to cement mortars, their compressive
345 strength is lower than cement mortars yet their bond strength is higher. The bond strength of
346 NC mortar may therefore have benefited from the high calcium aluminate content which
347 brings a rapid set and strength gain resulting in optimal water transfer for the absorption rates
348 experienced.

349 **4.0 Conclusions and Concluding Comments**

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

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

- 360 (2) The bond strengths of NHL3.5 and NHL5 mortared stone masonry after a 28-day cure
361 were observed to be comparable to low-strength cement mortared brickwork. The bond
362 strength of NC mortared stone masonry at 28-days exceeded even high strength cement
363 mortared brickwork.
- 364 (3) Block pre-wetting had a significant influence on flexural bond strength of sandstone
365 masonry, with bond strength decreasing with increasing pre-wetting time. The results
366 of this study indicate that for optimum bond, blocks with moderate absorption rates of
367 $\sim 300\text{g}/(\text{m}^2\text{s}^{0.5})$ and under, such as the Cullalo sandstone tested, should be kept as dry as
368 possible.
- 369 (4) Mortar compressive strength had a profound effect on the flexural bond strength of
370 sandstone masonry exhibiting a positive linear relationship; as a result, flexural bond
371 strengths of stone masonry should continue to be categorised by mortar compressive
372 strength in design codes of practice.

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

381

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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 ₃ S - Alite (%)	0	0	0	10
C ₂ S - 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)	<i>w/l</i>	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)	SD	CoV	f_{wk} (mean)	f_w (mean)	SD	CoV	f_{wk} (mean)	f_w (mean)	SD	CoV	f_{wk} (mean)
	(MPa)	(MPa)	(%)	MPa	(MPa)	(MPa)	(%)	MPa	(MPa)	(MPa)	(%)	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

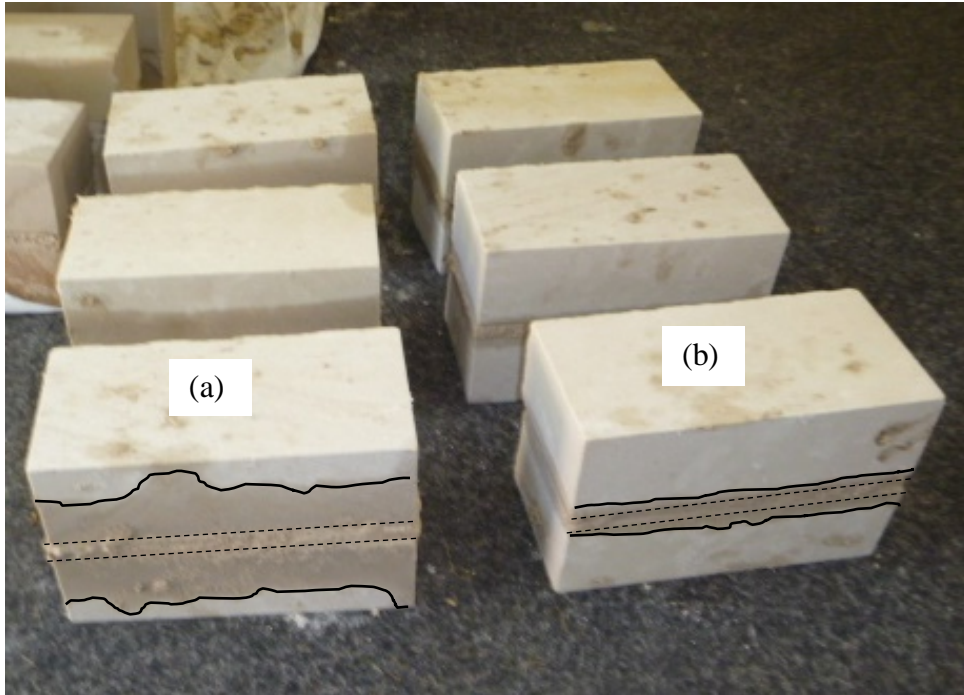


Fig. 1 Cullalo sandstone couplets approximately 5 minutes after bonding. This figure also shows the position of the water-front in the sandstone units (a) for those units with 1-minute pre-wetting, and, (b) for those units with 0-minutes pre-wetting. The water-front is indicated with a solid line and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

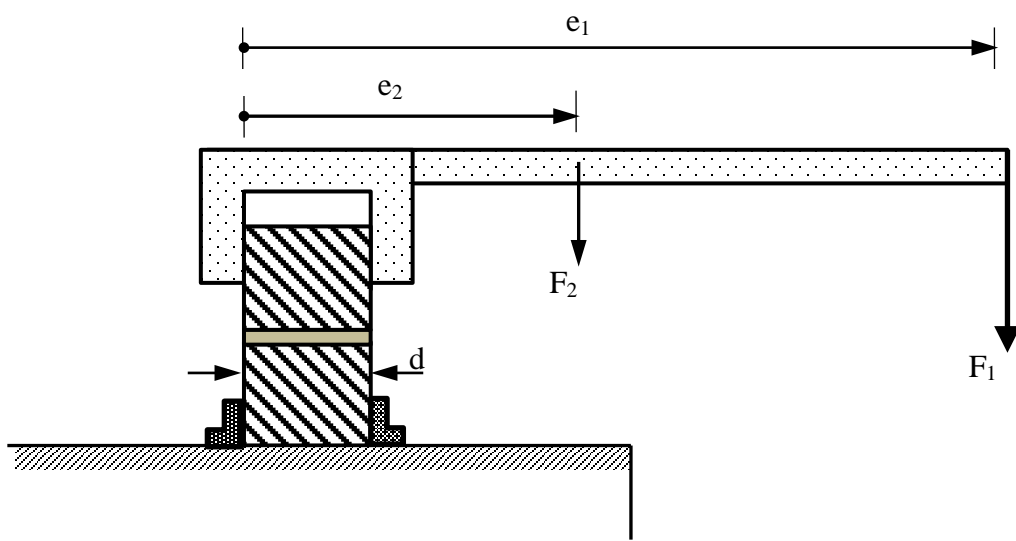
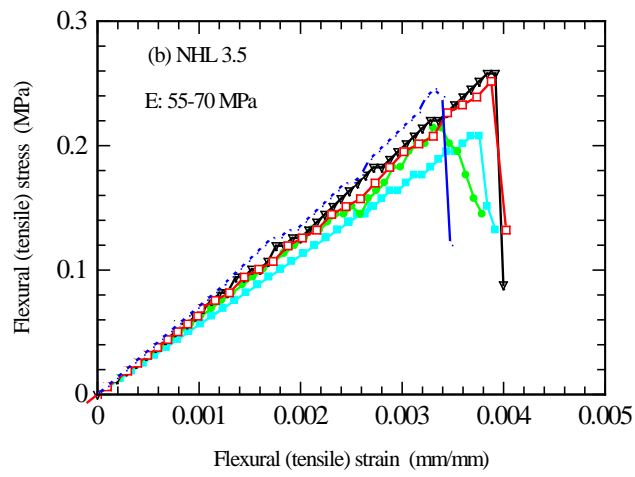
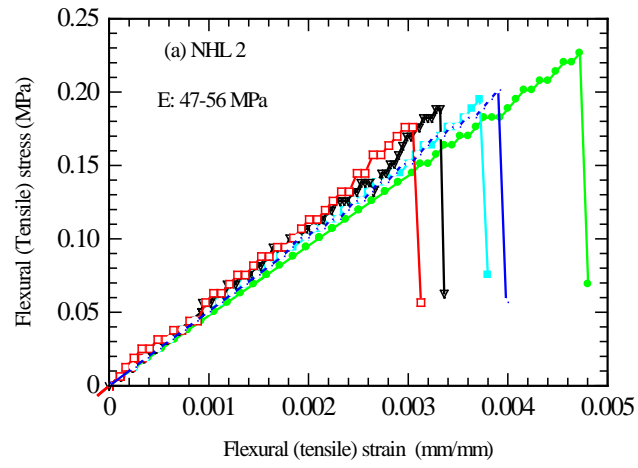


Fig. 2 Schematic diagram of wrench-test



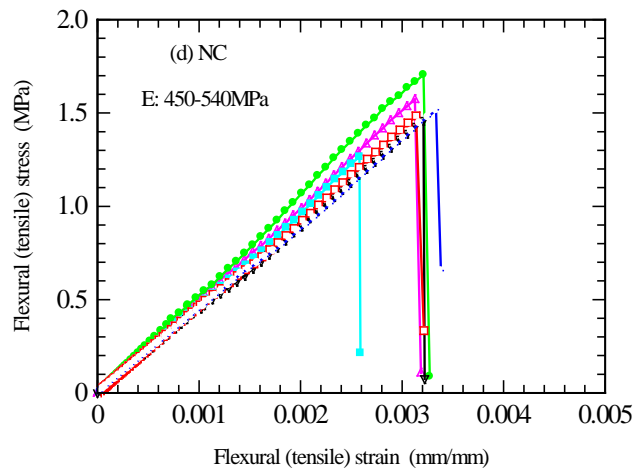
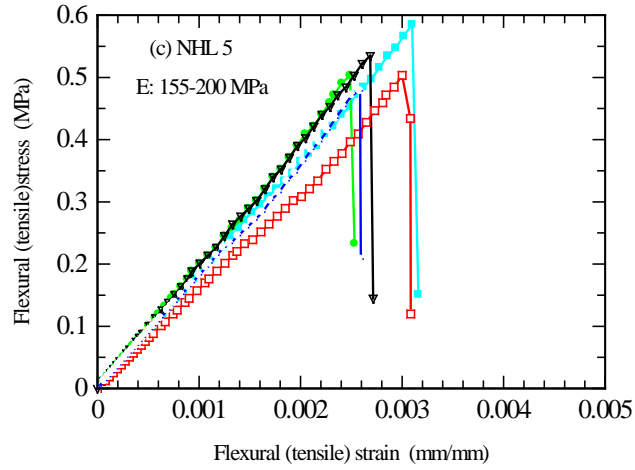
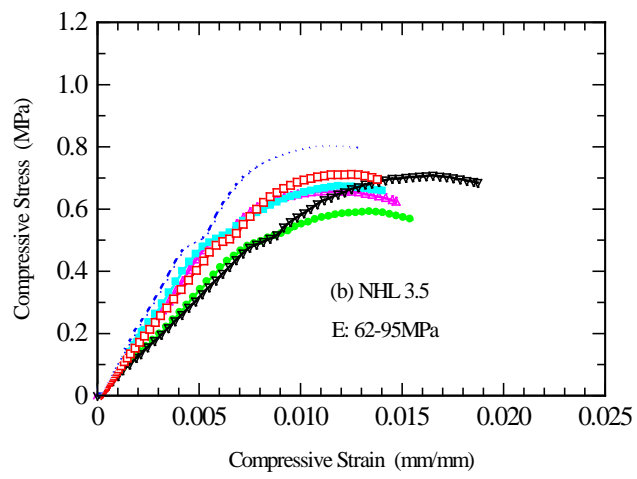
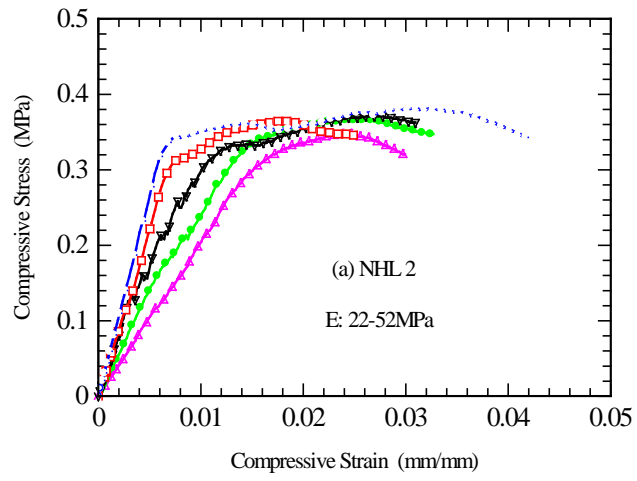


Fig. 3 Flexural stress-strain curves for five mortar prisms a) NHL 2, (b) NHL 3.5, (c) NHL 5, and (d) NC. Note: stiffness range denoted E on Figures.



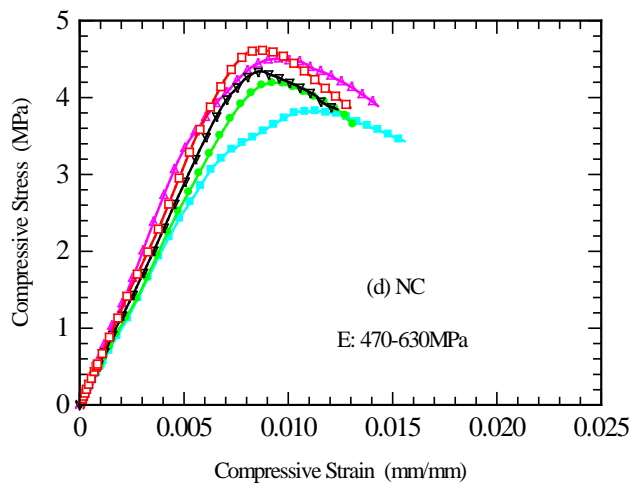
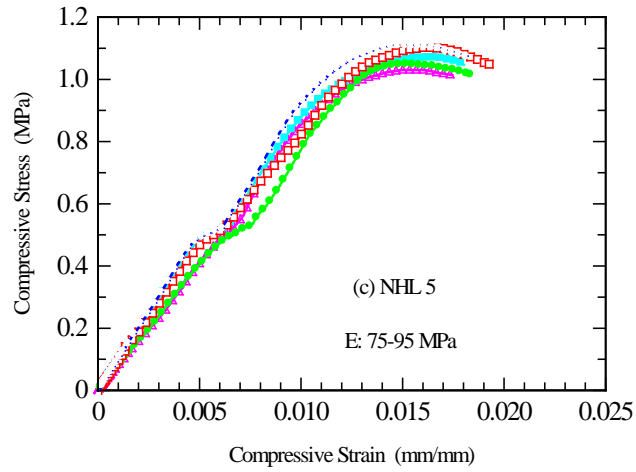
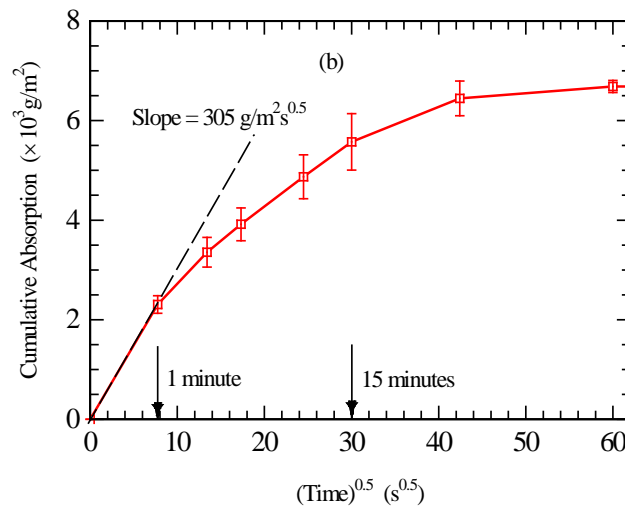
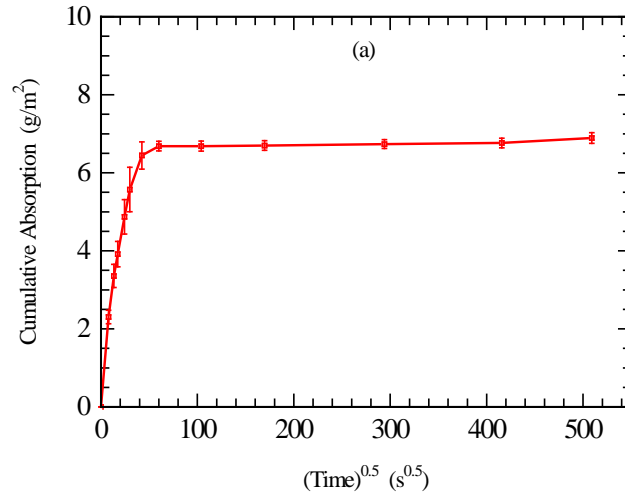


Fig. 4 Compressive stress-strain curves for five mortar prisms a) NHL 2, (b) NHL 3.5, (c) NHL 5, and (d) NC. Note: stiffness range denoted E on Figures.



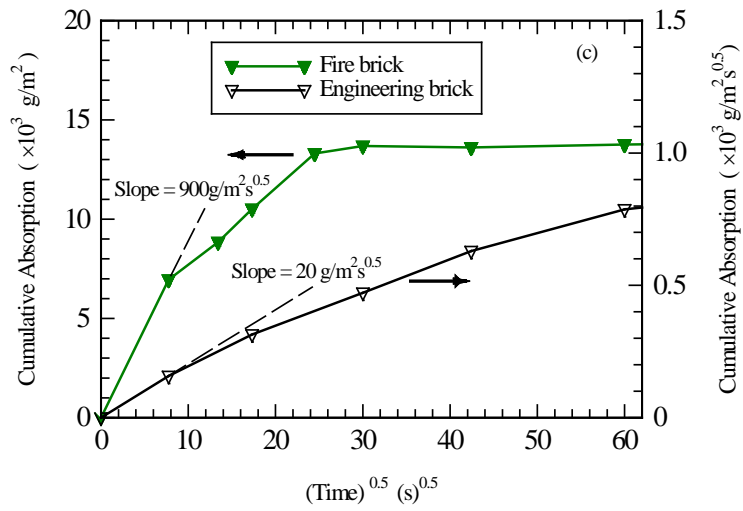
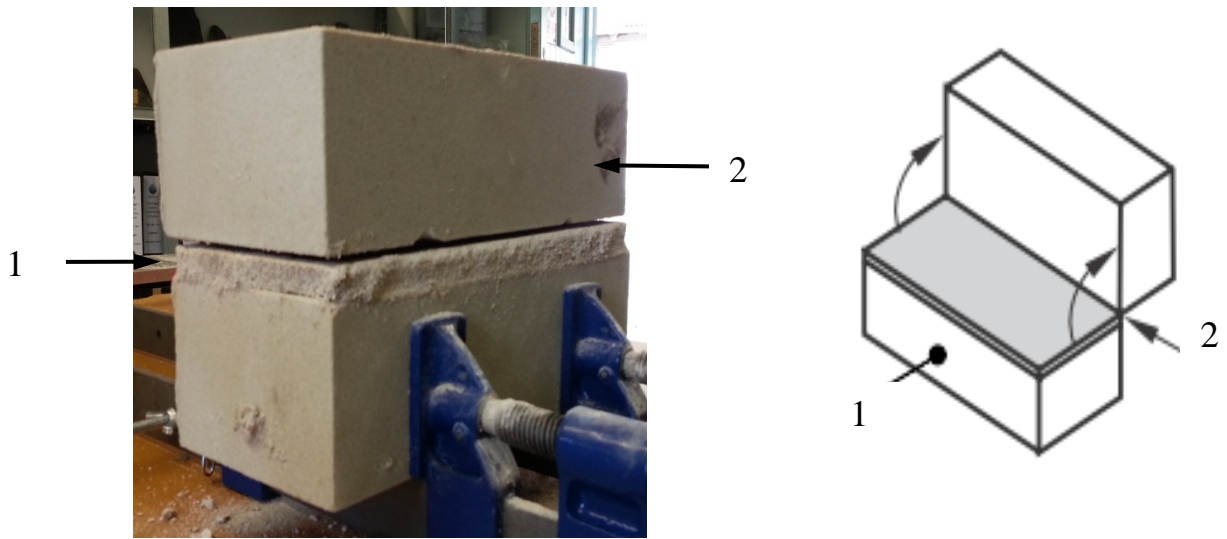
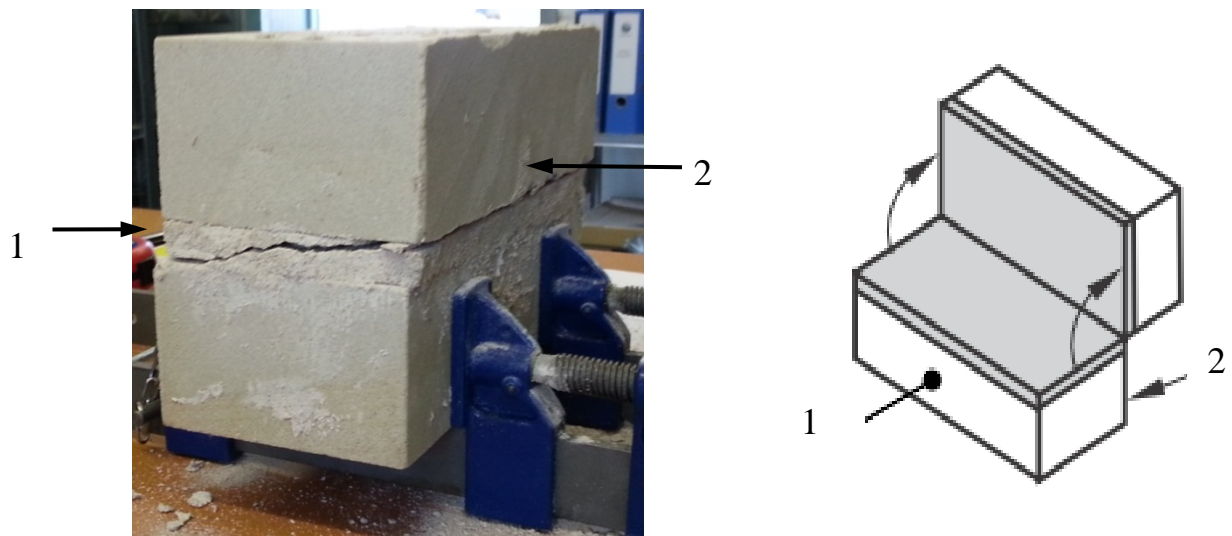


Fig. 5 (a) Cumulative absorption of Cullalo sandstone over 72-hour test period, (b) enlargement of (a) showing initial 1-hour absorption, and (c) cumulative absorption for a fire brick and an engineering brick.



(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])

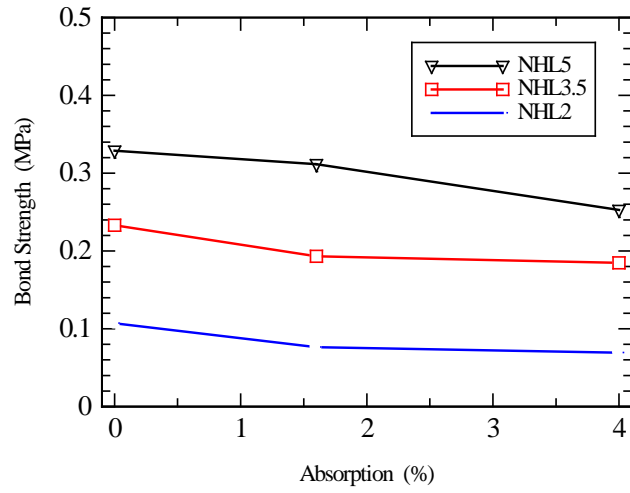


Fig. 7 Influence of pre-wetting on sandstone bond-strength

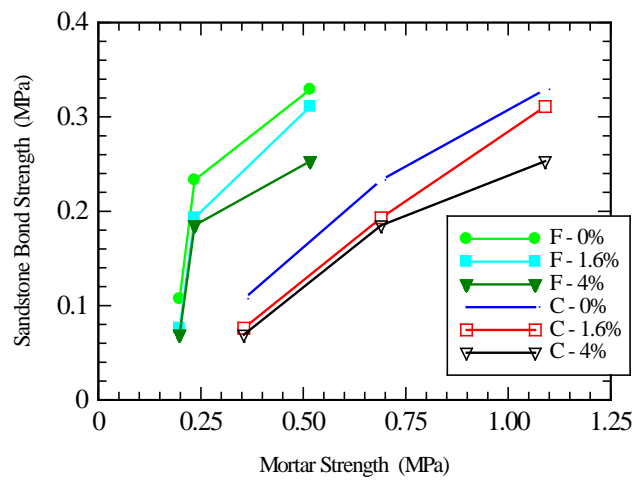


Fig. 8 Influence of mortar strength (F = flexural; C = compressive) on sandstone bond strength for 0%, 1.6% and 4% absorption (pre-wetting).