Influence of substrate and sand characteristics on Roman cement mortar performance

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Abstract

When formulating repair mortars standard test specimens should be used with caution as these cannot be considered representative of samples of mortars collected on site. This work reports an approach to repair mortar formulation which takes into account the influence of porous substrates, sand characteristics and mortar thickness on the properties of both fresh and hardened Roman cement mortars. It is shown that mortars cast on a dry absorbent substrate show modified properties such as increased strength and decreased water absorption coefficient, the degree of which is a function of sand grading and surface characteristics, sample thickness and substrate sorptivity.

Keywords: mortar, substrate, sand, compatibility, compressive strength

1 Introduction

Repair mortars manufactured and tested in a laboratory are normally cast in standard 40 x 40 x 160 mm steel moulds. These standard test specimens cannot be considered representative of samples of mortars collected on site, which in most cases are applied in 10 - 20 mm thick layers on or between porous substrates such as brick or stone. Additionally, environmental conditions (e.g. rh, temperature, time, contaminant exposure etc) are not replicated in the laboratory and the conservator must interpret results to maximise compatibility of the repair mortar.

It has been observed [1-5] that a porous substrate such as brick absorbs water from the fresh mortar and that this phenomenon affects the properties of both the fresh and hardened mortar. The transfer of moisture from mortar to brick leads to a shorter workable life [1-3] and a reduction in the in-situ water/binder ratio of the mortar that influences strength in the hardened mortar [1,4,5] as well as its potential for shrinkage [6]. In particular, Anderegg [1] suggested that the compressive strength of the mortar bed-joint would increase with an increase in the initial rate of suction, while Forth and Brooks [6] showed that the transfer of moisture between mortar and brick decreases the mortar potential for shrinkage. It has been shown [7-9] that moisture flow from mortar to brick is a function of the absorption characteristics of the brick, the water retention capacity of the mortar and the mortar bed thickness and that the key period is within the first few minutes of mortar application. No clear relationship between pre-wetting the brick and moisture transfer has been identified [e.g. 10].

When specifying a repair mortar based on laboratory testing it is also necessary to account for the effect that size and shape of the tested specimen have on the measured strength [11-13]. Specifically, for a given width of the specimen, compressive strength increases as its height (thickness) decreases. A theoretical explanation of this is that the constraint of the lateral deformation of the tested specimen on the contact surface with the loading frame plate causes a tri-axial stress state in a part of the specimen. This has a greater influence on small specimens because the ratio of the contact surface to the volume of the specimen is higher and the proportion of the specimen volume occupied by the cones of constraint increases [14]. Drdacky [15] has shown that there is not a unique relationship between strength increase and sample geometry and that the relative strengths of the binder must be accounted for. He also states that the maximum sand grain size will be a factor in small samples. Thus, at its most fundamental, the strength of a mortar sample will be a complex function of substrate and mortar characteristics and sample testing regime.

The focus of this work has been to investigate the effect that different brick substrates, specimen thickness and aggregate mineralogy/grading have on strength, shrinkage, water absorption coefficient and pore structure of mortars. This way it is hoped to contribute to the correct evaluation of repair mortars produced in the laboratory under standard conditions. This work was carried out within the EU funded ROCARE project (Roman Cements for Architectural Restoration to New High Standards) and an introduction to these cements and associated mortars may be found elsewhere [16-21].

2 Materials and Methods

2.1 Cement and sand

A Roman cement developed during the ROCARE project from marls sourced in Gartenau, Austria, was used throughout this work. The cement was manufactured by The Institute of Ceramics and Building Materials (MBM) in Krakow, Poland; details may be found elsewhere [22].

Two sand sources, one silica from Leighton Buzzard (UK) and one carbonate from Peggau (Austria), have been used throughout the programme. Each aggregate was supplied in single size fractions so that desired gradings could be developed. To achieve this, each individual size fraction was first dry-sieved to determine its own precise grading. This permitted the design of nearly identical gradings for the silica and carbonate sands. Four gradings (1 to 4) have been used for each sand source for the mortar mixes (Fig. 1) and for clarity only the curves for grading 1 have been shown for both sands to illustrate the minimal variability achieved.

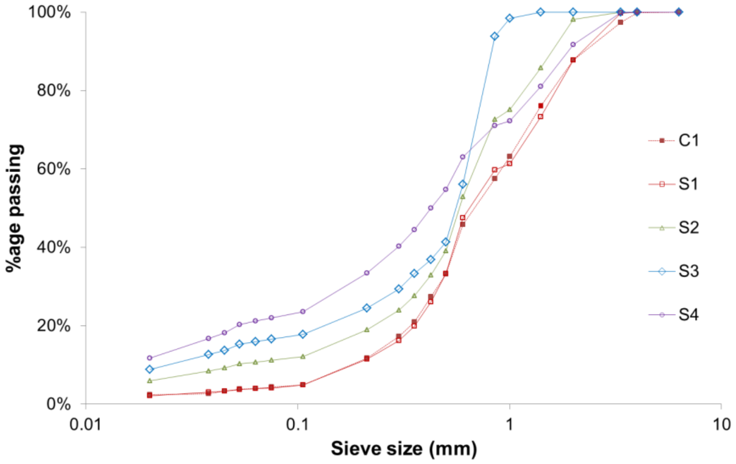

Figure 1: Grading of sands.

Obviously, it is not possible to control the surface texture in the same way and microscopic examination of the sands shows the silica sand to be smooth surfaced (Fig 2a) with the carbonate sand to be shagreened and with slightly sharper edges (Fig 2b).

(a) (b)

Figure 2: Silica sand (a) and carbonate sand (b) under the stereo microscope (0.6 – 1 mm fraction).

The bulk density of the sand was measured in accordance with BS EN 459-2:2010.

2.2 Substrates

Two brick sources characterised by low (4.11 kg/m^2/hr$^{0.5}$) and high (20.16 kg/m^2/hr$^{0.5}$) water absorption coefficient (WAC) have been evaluated. Fifteen millimetre thick brick slips have been carefully produced to form the sides of beam moulds and were belt-sanded to a smooth and flat finish. Special moulds have been manufactured to accommodate the slips to produce samples with brick-brick interfaces (Fig 3a), brick-steel interfaces (Fig 3b) and conventional steel-steel interfaces (Fig 3c) as control samples. Beams of thickness 10, 15, 20, 25, 30 and 40 mm were produced with a common width of 40 mm and length 160 mm with 3 samples being produced for each configuration. All brick slips were oven dried at 105^{o}C before being used. After each batch production the slips were immersed in a 10% hydrochloric acid solution, washed and dried. This procedure was adopted after being shown not to modify the WAC of the substrate.

(a) (b) (c)

Figure 3: Brick sided (a), brick – steel sided (b) and steel sided control (c) moulds.

2.3 Mortar production and testing

Mortars, suitable for render applications, were produced at a cement:sand volume ratio of 1:2.5 and constant water/cement ratio of 0.87 (by weight) with various combinations of sand and substrate type (Table 1). The Roman cement was retarded by means of a pre-hydration (or de-activation) process, which consisted of mixing a pre-determined amount of water (7%

of the cement weight) with the cement and storing for 30 minutes prior to subsequent formation into mortars. The retarded cement produced by this process has been termed De-Activated Roman Cement (DARC) and a detailed description of the process and mortar performance can be found elsewhere [22]. The retardation was necessary to achieve the required workable life of 1 – 2 hours for such mortars.

Table 1: Manufactured mortars

Sand	Substrate
S1, S2, S3, S4	Brick – Brick (Low WAC) Brick - Brick (High WAC)
C1, C2, C3, C4	Brick – Brick (High WAC)
S4	Brick (high WAC) – Steel
S2	Brick – Brick (High WAC soaked in water)

Mortars were produced by mixing the products of the de-activation process with water in a Hobart mixer for 30 sec at 62 rpm. At this time the mixer was stopped for 30 sec and the mixer bowl scraped. The mixing was then continued for 8 min at 125 rpm. To prevent adhesion of the mortar to the brick slips they were carefully wrapped in Japanese tissue which permitted transport of water but minimised that of solid particles. Samples were cast in two layers and vibration compacted. Immediately upon floating off the fresh mortar, each mould was covered by a polythene sheet and de-moulded after 24 hours. Upon de-moulding all mortars were placed in airtight boxes with wet tissues for a further 24 hours prior to transfer to water curing at 20^{o}C. The humidity in the boxes is unknown; however, condensation was observed in the boxes and it is assumed that the rh was close to 100%.

Since the moulding process was prolonged there was insufficient time to measure the workability of the fresh mortar. However, a companion programme assessed the rheology of identical mortars. The flow was measured according to BS EN 10153:1999. The “shear strength” and “plastic viscosity” were measured using a Viskomat NT in which the torque (T) was measured at various rotational speeds (N) which are related as shown in equation 1. The constants are proportional to the shear stress (g) and plastic viscosity (h) (see ref 23).

$$T = g + hN \qquad \text{Eq 1.}$$

The rotational speed was increased and subsequently decreased in increments of 50 rpm to a maximum of 250 rpm with the speed being maintained for 10 seconds at each increment. Data was collected at intervals of 1 second. The factor “g” was determined by extrapolating the experimental data by linear regression from the descending branch of the data-set.

The air content of the fresh mortar was measured according to BS EN 1015-7:1999 using a type B meter manufactured by Capco.

Strength testing was undertaken at 28 days. An Instron 4206 was used at a crosshead speed of 1 mm/min for compressive strength and 0.5 mm/min for flexural strength determinations; three samples being tested for each mortar.

Water Absorption Coefficient (WAC) was measured at 28 days according to BS EN 1015-18:2002 with the exception that the test was conducted with a moulded face exposed to the water so that the influence of the various substrates could be assessed. Thus, the exposure surface was approximately 40 x 80 mm.

A small number of subsidiary tests were undertaken to support various aspects of the main programme, i.e. transfer sorptivity, shrinkage and pore structure as detailed below.

The water retaining ability of fresh mortars (relative transfer sorptivity) was tested by placing 100 x 100 x 15 mm high WAC brick prisms in contact with 100 x 100 mm fresh mortar beds of 40, 30, 20 and 10 mm thickness for one minute and recording the weight of the brick at 0 and 1 min elapsed time. This time period was chosen following unpublished research in this laboratory showed the first minute to be the key period for densification of the mortar surface. A sketch of the experimental set up is shown in Figure 4.

Figure 4: Sketch of the experimental set-up for the transfer sorptivity test.

Relative transfer sorptivity was calculated as the ratio between the water uptake from the mortar bed (transfer sorptivity) and the water absorption coefficient (WAC) of the brick. This was determined on an individual basis for each brick so that variations in WAC between samples of the same brick type could be minimised.

Drying shrinkage was measured for 20 x 20 x 80 mm samples cut from 20 x 40 x 160 mm mortar prisms. Following 28 days of hydration the specimens were transferred to a glass tank equipped with inductive displacement transducers from RDP Electronics Ltd, in which the shrinkage was measured. Relative humidity inside the vessel was kept at 45% by means of a saturated potassium carbonate solution. Glass plates were applied to the sample surfaces in contact with the transducers' sensor to provide a stable datum. A quartz beam was used as a reference specimen to correct the thermal expansion of the mounting system induced by temperature variations in the laboratory. Drying shrinkage was continuously measured with data recorded every minute. Further details may be found in ref (24).

Pore structure was assessed by means of Mercury Intrusion Porosimetry performed at an age of 28 days on approximately 5 mm mortar slices sawn from the surface in contact with the substrate and from the core of 40 x 40 x 160 mm and 15 x 40 x 160 mm (core only) beams. Hydration was stopped at 28 days through immersion in iso-propyl alcohol for six days and subsequent drying in a desiccator for a further six days. The pore structure of the samples was then determined using a PoreMaster 60 mercury intrusion porosimeter from Quantachrome. The contact angle was taken to be 140°. The porosity measurement range was 1 - 0.006 µm.

3 Results

3.1 Introduction

Five separate factors have been investigated, i.e. substrate characteristics, substrate condition, composite substrates, sand characteristics and mortar thickness. In the light of the various interactions it is not possible to report on each factor separately whilst maintaining coherence and continuity. Hence, several factors have been combined within the first section.

3.2 Influence of sand characteristics, substrate type and mortar thickness

3.2.1 Rheology

Table 2 shows the data for flow, “shear strength” and “plastic viscosity” of the mortars. As expected the flow decreases and the shear strength increases as the amount of fines increases from grading 1 to 4. However, this is accompanied by a decrease in viscosity; a similar phenomenon has been reported elsewhere [25]. Unfortunately, the viscometer did not respond to the stiffest mortar, C3, with the lowest flow. It is noted that the shear strength of the mortars with the finest sands (S4 and C4) is similar indicating that the influence of shape and texture is minimised as the “paste” content of the mortar is increased. Westerholm et al [25] have reported similar findings. At its simplest mortar may be considered as coarser sand particles suspended in a paste matrix. However, both solid fractions (cement and sand) exhibit continuous gradings which overlap such that the “paste” may be considered as a mixture of fine sand, cement and water. In this study fine sand was arbitrarily defined as being that fraction less than 100 microns being that similar to the maximum grain size of the cement. “Pastes” were made representative of that fraction of each mortar by mixing deactivated cement with fine sand and water. The batching process was different for the mortars and pastes. Whilst each mortar was produced based upon “as supplied” Gartenau cement which was subsequently “deactivated”, the companion paste was produced with deactivated Gartenau cement; the process to produce deactivated cements which was used for manufacturing pastes can be found elsewhere [22]. Allowance was made in the calculation of w/c ratio for the pastes to account for the combined deactivation water in order to maintain a constant ratio of water to dry cement in both mortars and pastes.

Table 2 Rheology data for the manufactured mortars and pastes

Sand	**Mortar**			**Paste**		**Ratio Mortar:Paste**	
	Flow (cm)	**Shear strength *g*** (N·mm)	**Viscosity *h*** (N·mm·s)	**Shear strength *g*** (N·mm)	**Viscosity *h*** (N·mm·s)	**Shear strength**	**Viscosity**
S1	20.5	34	0.12	2.3	0.015	14.5	8.0
S2	19.5	51.0	0.104	5.8	0.035	8.8	3.0
S3	19.5	58	0.096	11.39	0.061	5.1	1.6
S4	16	143	0.077	26.12	0.117	5.5	0.7
C1	18.2	70	0.224	1.7	0.012	42.2	18.7
C2	18.8	82	0.181	4.1	0.022	19.9	8.2
C3	15.8	-	-	10.3	0.043	-	-
C4	16.5	141	0.161	23.6	0.075	6.0	2.1

It is apparent that the trends are different for the pastes and mortars. Whilst the “shear strength” for both pastes and mortars increases as the fine sand content increases the “viscosity” of the pastes increases but that of the mortars decreases as the fine sand content increases. Given that the w/c ratio was maintained constant in all mixes an increase in the fine sand content within the pastes is accompanied by a decrease in water content for each mix.

The rheology of mortars is influenced by the properties of the paste, the interaction between the paste and the coarser sand particles as a function of surface characteristics and by the potential for interaction between the coarser sand particles bridging across the paste. In the present study the latter influence is reduced as the paste content is increased and the properties of the mortar would be expected to be more influenced by those of the paste. Indeed, Table 2 shows this influence increasing as the ratio of mortar:paste for both rheological parameters decreases with increased fine sand content. Thus, the decreasing mortar viscosity with increasing fine sand content can be considered as a compromise between paste viscosity and coarse sand interaction. This is considered further in Section 4.2.

3.2.1 Strength

Tables 3 and 4 show the 28 day compressive and flexural strengths of mortars manufactured with S1, S2, S3 and S4 sand and cast in 10 to 40 mm high WAC brick, low WAC brick and steel sided moulds. The data for mortars cast in steel moulds is generally the average of 9 samples from 3 separate batches whilst that for mortars cast between brick slips is the average of 3 samples from a single batch.

As expected, for steel moulded mortars the compressive strength increases for thinner samples, such that it was not possible to test the compressive strength of the 10 mm samples without causing damage to the testing machine. The influence of sand grading upon compressive strength is dependent upon mortar thickness. Whereas in standard 40 mm thick samples the finest sand S4 yields the highest strength in the order S4>S3=S2=S1, in the thinnest samples (15 mm and 20 mm) sands S1, S3 and S4 yield similar strengths with S2 being the weakest (all tests at 95% confidence). By way of contrast, there is little influence of mortar thickness on flexural strength; only for sands S2, S3 and S4 is there a significant strength increase as thickness is decreased from 40 mm to 30 mm, thereafter there is no significant variation in strength. The influence of sand grading is broadly similar to that observed in compression. In standard 40 mm beams the order is S4>S3=S2=S1 (with S3>S1) and in 15 mm beams S4=S3=S2 (with S4>S2>S1).

Table 3: 28 day compressive strengths (MPa) of the mortar produced with S1, S2, S3 and S4 sand and cast in 40 to 15 mm high WAC brick, low WAC brick and steel sided moulds. Parentheses indicate standard deviations.

Thickness (mm)	**S1**			**S2**			**S3**			**S4**		
	steel	low	high	steel	low	high	steel	low	high	steel	low	high
15	24.2 (1.49)	31.44 (2.21)	46.15 (2.11)	22.42 (1.45)	29.24 (3.70)	37.4 (1.27)	25.18 (1.81)	32.87 (1.91)	34.74 (0.85)	23.9 (1.17)	27.02 (1.22)	32.61 (0.19)
20	17 (0.39)	21.36 (2.15)	23.4 (2.09)	15.67 (1.50)	20.15 (2.74)	21.99 (1.59)	17.41 (1.92)	21.99 (1.62)	21.85 (1.36)	17.97 (2.24)	18.47 (0.13)	22.91 (0.71)
25	13.17 (0.47)	14.82 (1.49)	18.92 (0.60)	12.36 (0.56)	16.15 (1.32)	16.91 (0.96)	13.87 (0.88)	17.45 (0.70)	16.95 (0.88)	14.95 (0.82)	15.74 (0.74)	18.2 (0.77)
30	11.36 (0.83)	13.33 (1.04)	15.51 (1.21)	11.20 (0.88)	13.01 (0.21)	13.87 (0.90)	12.89 (0.86)	13.97 (0.58)	14.05 (0.91)	14.13 (0.50)	13.82 (0.12)	16.51 (0.41)
40	10.66 (0.29)	10.54 (0.50)	10.19 (0.33)	10.80 (1.33)	11.87 (0.25)	11.49 (0.76)	11.60 (1.37)	13.48 (0.55)	12.37 (0.88)	13.46 (0.85)	13.05 (0.62)	13.71 (0.36)

Table 4: 28 day flexural strengths (MPa) of the mortar produced with S1, S2, S3 and S4 sand and cast in 40 to 10 mm high WAC brick, low WAC brick and steel sided moulds. The low WAC brick data for S1 sand is missing due to a temporary fault with the testing machine. Parentheses indicate standard deviations.

Thickness (mm)	**S1**			**S2**			**S3**			**S4**		
	steel	low	high	steel	low	high	steel	low	high	steel	low	high
10	2.98 (1.09)	-	5.18 (0.01)	3.97 (0.38)	4.87 (0.48)	5.21 (0.40)	3.71 (0.43)	4.99 (0.54)	4.69 (0.23)	4.75 (0.22)	4.54 (0.55)	5.08 (0.41)
15	3.22 (0.07)	-	4.67 (0.14)	3.91 (0.23)	3.77 (0.40)	4.16 (0.31)	3.91 (0.47)	4.32 (0.14)	4.69 (0.16)	4.34 (0.42)	4.23 (0.74)	4.7 (0.11)
20	3.38 (0.33)	-	3.29 (0.29)	3.70 (0.44)	4.13 (0.63)	4.37 (0.27)	3.82 (0.23)	4.46 (0.17)	4.39 (0.04)	4.03 (0.35)	4.35 (0.27)	4.34 (0.97)
25	3.16 (0.18)	-	3.86 (0.16)	3.72 (0.31)	4.06 (0.35)	4.09 (0.45)	4.03 (0.11)	3.78 (0.43)	4.34 (0.38)	4.18 (0.52)	4.4 (0.41)	4.69 (0.21)
30	3.12 (0.15)	-	3.58 (0.36)	3.66 (0.30)	3.85 (0.39)	4.09 (0.18)	4.04 (0.37)	4.45 (0.09)	4.24 (0.15)	4.21 (0.22)	4.42 (0.19)	4.99 (0.01)
40	3.17 (0.15)	-	3.46 (0.28)	3.31 (0.41)	3.71 (0.54)	3.82 (0.57)	3.51 (0.27)	4.27 (0.29)	4.49 (0.17)	3.91 (0.22)	4.17 (0.41)	4.53 (0.11)

In order to examine the influence of the substrate on strength, the mortar strength for each masonry substrate has been divided by the strength of control samples of the same thickness (see Section 2.2). The results are shown in Figure 5. It is apparent that compressive strength enhancement is a function of the mortar thickness, sorptivity of the substrate and sand grading (Figs 5a & 5b). For a given sand the strength enhancement increases as the mortar thickness reduces and is more apparent in mortars cast upon the high WAC brick (Fig 5a) than the low WAC brick (Fig 5b). Additionally, the low WAC brick also reduces the influence of sand grading exhibited by a smaller spread of strength ratios at a given mortar thickness. It can be seen that the smallest strength enhancement is generally shown by the finest sand (S4). However, there is no consistent pattern of strength enhancement being a simple function of sand grading, either expressed as % <0.1 mm or % >1 mm, for all mortar thickness and substrate WAC suggesting additional factors may influence the strength enhancement.

The influence of the substrate and sand grading on flexural strength is similarly demonstrated and shown in Figures 5c and 5d. Any strength enhancement is much less than that observed in compression and trends are less discernible but show that the flexural strength of mortars cast on the high WAC brick yields the greater enhancement, particularly for the coarser sands as the mortar thickness is reduced (Fig 5c). As before, the finest sand, S4, generally yields the lowest strength enhancement and also shows similar strengths for all substrates. There is no discernible pattern for mortars cast on the low WAC brick (Fig 5d).

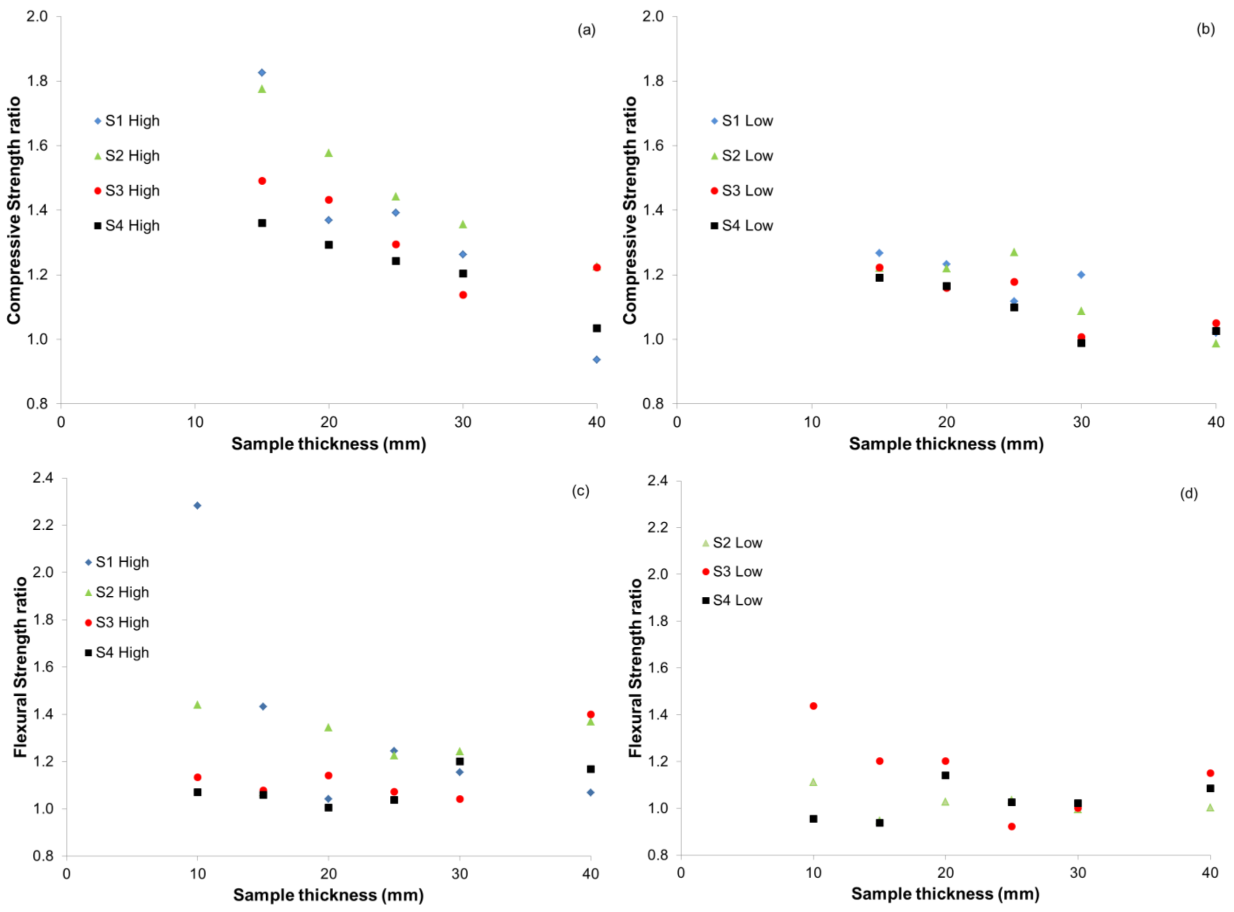

Figure 5: Relative compressive strengths, High WAC brick (a) and Low WAC brick (b); Relative flexural strengths, High WAC brick (c) and Low WAC brick (d). The data for S1 mortar in (d) is missing due to a temporary fault with the testing machine.

The influence of sand mineralogy and grading on compressive strength has been compared for mortars cast in high WAC brick sided and steel sided moulds. Table 5 shows the ratio of compressive strength (carbonate:silica sanded mortars) for all gradings and both substrates. For both substrates there is a general trend for the carbonate sand to yield higher strengths in 40 mm thick samples, i.e. indicated by a ratio >1.00 which then reduces as the sample thickness is reduced. In the case of steel moulded mortars this suggests that any differences in mortar characteristics resulting from the sand are masked by the consequence of the changing stress distributions within the samples as they become thinner. The change in relative strength is most marked in mortars cast between the high WAC brick; indeed, the carbonate sand yields the higher strength in the 40 mm samples but the lower in the 15 mm samples. The spread of relative strength from thickest to thinnest samples reduces with increases in the fineness of the sand until there is no effect of either grading or sample thickness for the finest sand. Thus, mineralogy per se does not appear to be an independent factor; rather, relative performance is a combined factor of mortar thickness, grading and substrate with the influence of the substrate on the fresh mortar being particularly strong; the latter appears to be enhanced in the coarser gradings of the silica sanded mortars.

Table 5: Ratio of compressive strength for carbonate:silica sand mortars for two substrates and 4 gradings; parentheses indicate significance of ratio (determined by means of a student's t-test).

Substrate	Sand	15 mm	20 mm	25 mm	30 mm	40 mm
Steel	**1**	0.99 (N)	0.92 (Y)	0.97 (N)	1.03 (N)	1.07 (N)
	2	1.00 (N)	1.04 (N)	1.02 (N)	1.03 (N)	1.23 (Y)
	3	0.98 (N)	0.98 (N)	1.07 (N)	1.14 (Y)	1.19 (Y)
	4	0.91 (Y)	0.86 (N)	0.94 (Y)	0.93 (Y)	0.94 (N)
Brick	**1**	0.78 (Y)	0.97 (N)	0.90 (Y)	1.07 (N)	1.34 (Y)
	2	0.84 (Y)	0.99 (N)	1.01 (N)	1.15 (Y)	1.20 (Y)
	3	0.87 (Y)	0.98 (N)	0.97 (N)	1.13 (N)	1.18 (Y)
	4	0.99 (N)	0.99 (N)	0.99 (N)	1.04 (N)	1.02 (N)

3.2.2 Water Absorption Coefficient (WAC)

Water absorption by capillarity tests were performed following 28 days of hydration on mortars produced with all of the 8 sands and cast in high WAC brick sided and steel sided moulds. The S1 sand mortar was cast also between low WAC brick in order to compare the influence of the two different brick substrates. The tests were performed on 40, 30, 20 and 10 mm thick samples.

Figure 6 shows that the mortar (S1 sand) cast in brick sided moulds has a lower water absorption coefficient than that cast in steel sided moulds with the lowest value being recorded for the mortar cast in high WAC brick sided moulds. It can also be seen that whilst the WAC of the mortars cast in steel moulds is essentially constant, that of mortars cast in brick sided moulds decreases for thinner samples with the influence of the substrate increasing with reductions in mortar thickness. This is commensurate with the trend previously seen in Figure 5a for compressive strength.

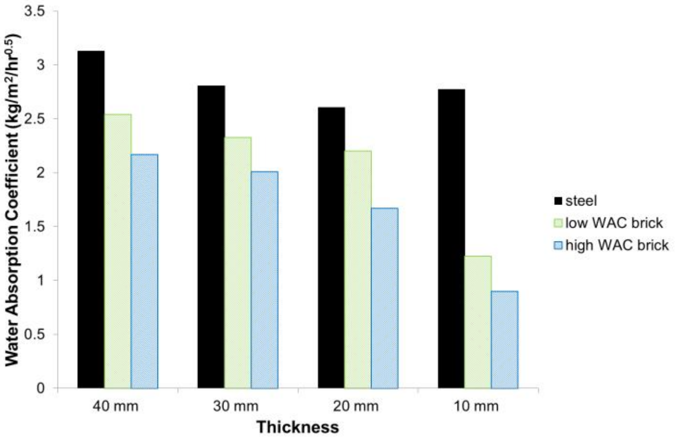

Figure 6: WAC of the S1 mortar cast in high WAC brick sided, low WAC brick sided and steel sided moulds.

Figure 7a shows the influence of mortar thickness on WAC of mortars using all 8 sands and cast in steel moulds and a clear trend is not apparent. Two sands, S1 and C4, display essentially constant WAC where-as the remainder exhibit a reduction in WAC with a reduction in mortar thickness to varying degrees. The reason for this is unclear but may be associated with a greater relative thickness of a surface zone as the sample thickness is reduced. In most cases the carbonate sand yields a higher WAC than its silica counterpart at a given mortar thickness, a trend not observed in the strength assessment (Table 5).

The WAC for the same mortars cast between high WAC brick is shown in Figure 7b. It is apparent that the brick substrate has greatly reduced the WAC for a given mortar and more so for the thinner mortars. Additionally, the silica sands generally yield a greater reduction than do the carbonate sands. For example the average reduction for all silica sands in 10 mm samples is 51% whilst that for the carbonate sands is 45% which may be related to the desorption of the mortar by the substrate. Mortars produced with the sands of lower fines content (S1, S2, C1 & C2) show a consistent WAC reduction trend as the sample thickness decreases, independent of their mineralogy. When finer sand is used a consistent WAC reduction with thickness is observed for only the S4 sand mortar cast in the brick mould (Fig 7b). Unlike the influence of sand “mineralogy” on strength (see section 3.2.1) there is a consistent influence on WAC. In 29 of the 32 mortar combinations measured the WAC of the carbonate sanded mortars was higher than their silica counterparts and no influence of grading, sample thickness or substrate was observed. The average of the ratio of WAC carbonate:silica sands was 1.41 for the brick substrate and 1.27 for the steel substrate although the difference is not statistically significant.

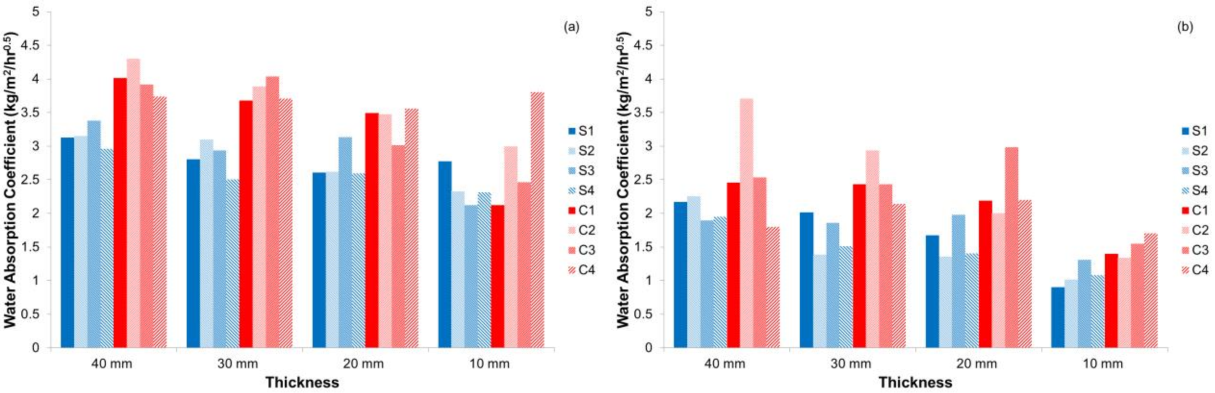

Figure 7: WAC of mortars produced with all of the 8 sands and cast in steel sided (a) and high WAC brick sided (b) moulds.

3.3 Influence of substrate condition

3.3.1 Strength and Water Extraction

Good site practice is to wet high suction bricks to maintain workability of the fresh mortar although this is rarely specified with precision. In order to investigate the effect on strength of the hardened mortar a mix was produced using S2 sand and cast in 15 mm high WAC brick sided moulds. The specified mortar was chosen because considerable influence of the substrate on the compressive strength was observed for the silica mortars cast into 15 mm thick samples, especially for the coarser sands, i.e. S1 and S2 (Table 3). The mortar was cast in both oven dried brick moulds and in moulds where the surface of the brick slips in contact with the mortar was soaked in water for 35 and 45 sec prior to moulding. The results are shown in Table 6. The only significant result is that a 45 second soak of the substrate has reduced the compressive strength from that obtained from the use of a dry substrate suggesting a reduced suction of the soaked brick.

Table 6: Properties of mortars cast in 15 mm samples between high WAC brick slips.

Substrate	**% total water uptake**	**Strength**	**Transfer sorptivity**
		(MPa)	**(kg/m^2)**
Dry brick	0	34.3	0.254
35 s soak	*51*	30.8	-
45 s soak	*57*	29.1	-
1 min soak	65	-	0.312
2 min soak	83	-	0.136
5 min soak	97	-	0.025
30 min soak	100	-	0.021
60 min soak	100	-	0.033

A further set of tests were undertaken whereby 15 mm brick slips were placed in contact with the same mortar for 1 minute and the transfer sorptivity was measured in terms of water extracted per unit area. Prior to the transfer measurement the transfer surface was placed in a shallow water bath for periods of time from 1 to 60 minutes; each time is expressed as a percentage of the full saturation of the slips. Excess surface water was removed prior to locating the slip on the mortar bed. The data is shown in Table 6 and each value is the average of 3 determinations. It is apparent that following 1 minute prior soaking there is no reduction in the transfer sorptivity when compared to an oven dried brick. This soaking period is equivalent to 65% of the maximum water uptake such that during the transfer from water bath to mortar surface the slip remains capillary active and it is possible that the hydraulic connectivity was broken during the surface drying whilst transferring the slip from water bath to mortar bed. Following a 2 minute soak, equivalent to generating 83% saturation, a reduction in transfer sorptivity is observed. The low values obtained for 5, 30 and 60 minutes soaking are related to the 97%, 100% and 100% saturations respectively.

The saturation levels cited for the 35 and 45 second soaking periods for the strength evaluation samples have been calculated on the basis of a linear relationship between water uptake and root time in the first minute of soaking. An inference of the data is that a substantial degree of saturation is required before the influence of the substrate is modified.

3.4 Influence of composite substrates

3.4.1 Strength and Shrinkage

Whilst the experimental set-up of casting between two brick slips mimics the case of a jointing mortar it does not reflect the practicality of a render which is applied to only one face of a substrate with the other exposed to the atmosphere. In order to produce a sample which could be tested on opposite faces a further mortar was manufactured with S4 sand and cast in special steel – high WAC brick sided moulds (Fig. 3b) with mortar thicknesses of 15 – 40 mm. The same mortar was also cast in steel sided control moulds and between a pair of high WAC brick slips. Both strength and shrinkage were measured for this mortar.

Figure 8 shows that the influence of the nature of the substrates on compressive strength is more pronounced as the thickness of the mortar is reduced. The compressive strengths of mortars made between composite brick-steel faces are some 92% of the strength of the same mortar made between 2 brick faces. As for flexural strength, Figure 9 shows that for all thicknesses flexural strength is higher when the side of the mortar sample which was cast in contact with the brick is in tension. For thinner samples (20 and 15 mm), the flexural strength of the mortar with the brick side in tension is also significantly higher than that of the mortar cast in steel sided control moulds. This confirms that the effect of a porous substrate on mortar strength is more significant for thinner samples. It is interesting to note that the flexural strength of mortars cast between steel moulds is higher than that measured with the "steel" face in tension of the composite moulded samples. It is possible that whilst the brick has removed water from the mortar, densification has occurred on the brick face where-as the removal of water on the steel face has simply reduced effective hydration.

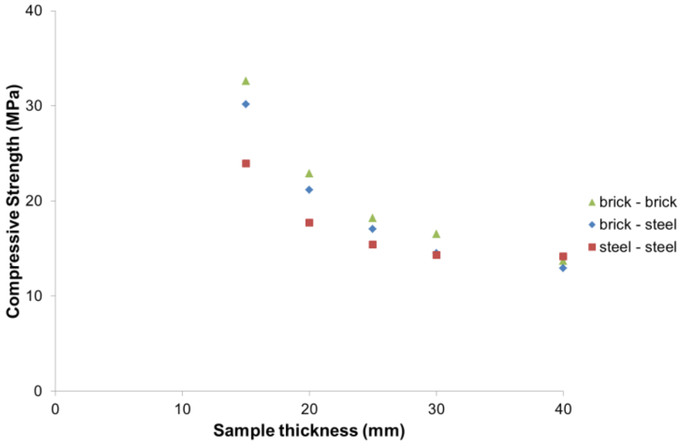

Figure 8: Compressive strength of S4 mortar cast in high WAC brick, high WAC brick - steel and steel sided moulds.

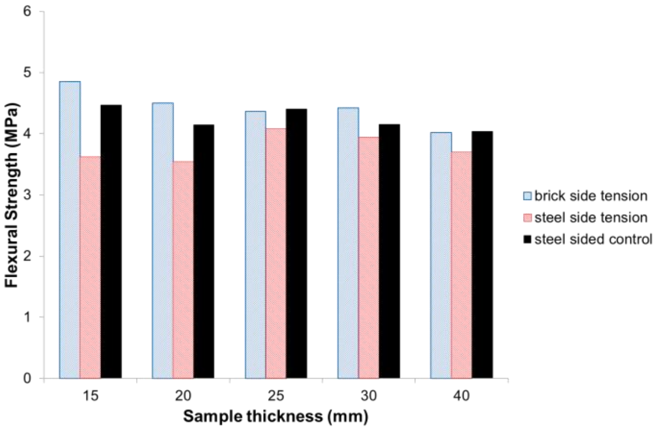

Figure 9: Flexural strength of S4 mortar cast in steel - high WAC brick sided and steel sided moulds. Strengths for both the brick side and the steel side in tension are shown.

Figure 10 shows that the lowest shrinkage occurs in mortar cast between high WAC brick slips and the highest in the steel control moulds; the composite brick-steel moulds yield an intermediate shrinkage. This sequence is the same as that obtained for compressive strength but in the reverse order. The reduction of shrinkage can be connected with suction of water in the brick-brick composite, which leads to changes in the pore structure (i.e. pore diameter and porosity) (see section 4.4) as the most important factor on drying shrinkage [26].

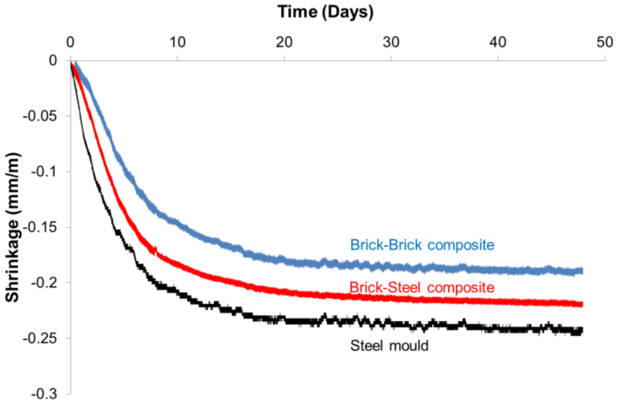

Figure 10: Drying shrinkage of a mortar produced with S4 sand and cast in high WAC brick, high WAC brick – steel and steel sided moulds.

4 Discussion

4.1 In summary

The following key findings have been drawn from the previous sections.

- The coarser carbonate sand gradings yield a lower mortar workability than the coarser silica sand gradings.
- Measured compressive strength increases as the thickness of the sample is reduced.
- Mortars cast on a dry absorbent substrate show increased strength, the degree of which is a function of sand grading, sample thickness and substrate sorptivity. This effect is more pronounced for compressive than flexural strength.
- The comparative compressive strength between carbonate and silica sanded mortars depends upon the substrate, grading and sample thickness.
- The WAC of the mortar decreases as the WAC of the substrate increases with the influence of the substrate being more apparent in thinner samples and also in the silica sanded mortars.
- The comparative WAC between carbonate and silica sanded mortars is much simpler than that observed for strength with the carbonate sanded mortars yielding a higher WAC than the silica sanded mortars regardless of grading, sample thickness and substrate.
- The potential for a reduction in transfer sorptivity is only achieved if the substrate is wetted to a high degree of saturation.
- A tensile strength gradient is generated across render mortars between the opposite faces when water extraction is in one direction only.

The following sections explore some of these findings in more detail.

4.2 Is mineralogy a factor?

It is apparent that both shear strength and viscosity (Table 2) are greater for the carbonate sand for a given grading, especially gradings 1 – 3. The rheological properties of the paste fraction of each mortar pair are broadly similar. In order to prepare the sands for presentation in Figure 2 they were vibrated in the sieves for 10 minutes. Even so, it is apparent that the carbonate grains remain coated by very fine particles (Fig 2b) whilst those of the silica sand are clean (Fig 2a). The significance is that the fine fractions of the coarser gradings of sand blends will be slightly higher in the carbonate sands; however, this is not considered sufficient to explain the difference in rheological properties between the mortar sets.

Rather, the differences are related to the different packing efficiencies of each grading and the “excess” paste available to lubricate the mortar. Table 7 shows the dry bulk density of the coarse fraction of each sand (>0.1 mm) and the associated voidage once the specific gravity of each mineralogy has been accounted for. Knowing the batch weights of a given mortar and the weight of a known volume of fresh mortar the density of the coarse sand in a given mortar may be calculated and the voidage of the remainder of the ingredients calculated (paste and air). Knowing the air content of each mortar a simple subtraction yields the excess (XS) paste present which is not required to simply fill the voidage between the coarse sand particles and hence which may be thought of as lubricating paste. The values of excess paste should be considered indicative rather than absolute since they are based on the packing efficiency of the dry sand subject to a specific amount of work involved in dropping the sand from the upper hopper to measuring cylinder; this contrasts with the vibration of wet sand in the mortar. Thus, the calculation of a negative excess paste for C1 mortar should be viewed with caution. In the light of the calculated values of excess paste the difference in rheological properties between carbonate and silica sanded mortars of the same grading (Table 2) can be related to the differences in excess paste and therefore the degree of interaction between the coarse sand particles.

Table 7 Excess paste available to each of the manufactured mortars

Sand	Dry bulk density	Voidage in sand	Density of sand in mortar	Voidage in mortar	Vol of XS paste and air	Vol of air	Vol of XS paste
	(kg/m^3)	(%)	(kg/m^3)	(%)	(%)	(%)	(%)
S1	1748	34.8	1530	42.9	8.1	4.7	3.4
S2	1765	34.1	1404	47.6	13.5	5.0	8.5
S3	1655	38.2	1300	51.5	13.2	5.5	7.7
S4	1855	30.8	1222	54.5	23.6	5.2	18.4
C1	1625	39.8	1473	45.2	5.4	6.1	-0.7
C2	1566	42.0	1341	50.1	8.1	7.2	0.9
C3	1516	43.9	1268	52.9	9.0	6.9	2.1
C4	1676	37.9	1199	55.4	17.5	4.6	12.9

Thus, the importance of packing density rather than simply grading as a key factor for the rheological behaviour of mortars has been confirmed (see e.g. [27, 28]). The shear strength, in particular, is influenced by the rheological properties of the paste fraction and the volume of excess paste. At lower volumes of excess paste, the shape and texture of the coarser sand particles also impact on the shear strength.

In an associated programme pastes with 2 concentrations of fine sand were produced. No influence of mineralogy in either the evolving mineralogy during the DARC process or the initial heat evolution was observed; additionally, only minor differences in the secondary peak of AFm hydration (see Fig 3 of ref [22]) were noted and no influence on belite hydration was observed. The influence of mineralogy upon strength can only be considered for mortars cast in 40 mm steel moulds where the stress distribution is the closest to being uniaxial compression; of the 3 mortars indicating a higher strength in carbonate mortars only 2 of the differences are significant. Hence, it is believed that any differences in strength may be attributed to the physical phase distributions rather than hydration products. A lower value of excess paste suggests less paste continuity throughout the mortar and more opportunity for crack blunting as crack propagation encounters surfaces of the coarse sand particles.

Thus, it is considered that mineralogy per se does not influence the mortar properties; rather, the packing efficiency of the coarse sand particles as influenced by particle shape and texture is more relevant.

4.2 Comparison with previous published strength data

Drdacky et al [15] have cited power related equations showing the relationship between the strength of various mortars and slenderness ratio for samples of 40 mm base length which are reproduced in the Figure 11a. The average strengths from 19 DARC Gartenau mortars using all 8 sands and cast in steel moulds have been superimposed upon this data and it is apparent that the Roman cement mortars occupy a position between the Lime-Metakaolin-Portland Cement and Lime-Metakaolin mortars; however the rate of increase in strength as slenderness ratio reduces is not as acute.

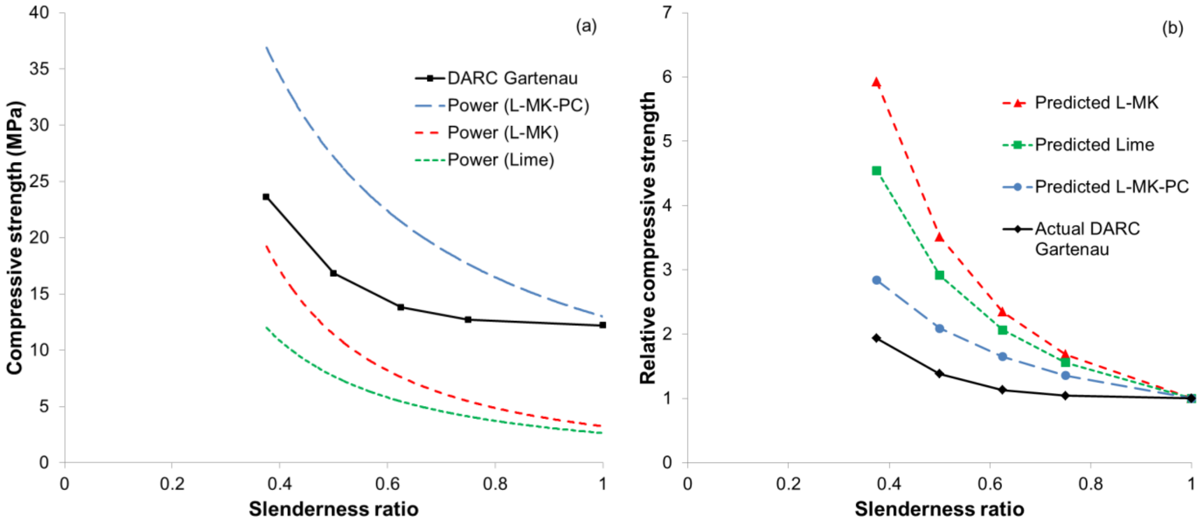

Figure 11: Strength (a) and relative strength (b) as a function of slenderness ratio for DARC Gartenau, Lime-Metakaolin-Portland Cement, Lime-Metakaolin and Lime mortars.

This is further illustrated in Figure 11b in which the strengths at any value of slenderness ratio are proportioned to that of a ratio of 1. Indeed, it can be seen that the RC mortars show the slowest rate of increase in relative strength of all mortars considered. The difference may be a function of the cementitious component or the different sample configurations; where-as Drdacky et al used samples with a square cross-section the current data used half beams (~80 x 40 mm) positioned between 40 x 40 mm platens. The data in Figure 11b disguises slight differences in behaviour between the silica and carbonate sanded mortars; each data point is the average of the 4 gradings of the specified mineralogy. The silica sand increases relative strength slightly more rapidly than does the carbonate sand with the average values being 2.06 and 1.83 at a slenderness ratio of 0.375 (i.e. 15 mm thickness).

In contrast to mineralogy and its accompanying physical differences, the influence of substrate and sand grading is more profound. As would be expected from the data in Table 3 the increase in relative strength is more marked as the sorptivity of the substrate increases. For the sake of clarity Figure 12a shows the different performance of S1 mortar cast between the 3 substrates. Additionally, the grading of the sand influences the increase in relative strength on a given substrate. The relative strengths of the 4 silica mortars cast between the high WAC substrate are shown in Figure 12b and it can be seen that the differences become more apparent as the slenderness ratio is reduced to the range within which mortars sampled from a render would be located. The relative strength within this range reduces as the fineness of the sand increases. The influence of grading is much less in the carbonate mortars with the extremes of grading being shown in Figure 13. Whilst the finest grading yields a similar performance, the coarsest grading shows a large difference between the silica and carbonate sands.

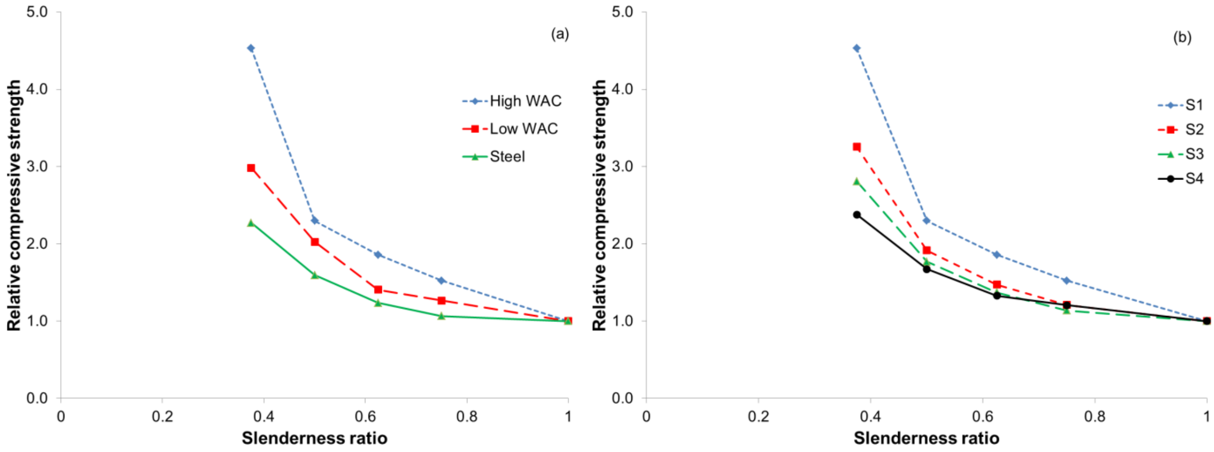

Figure 12: (a) Influence of substrate on the relative strength of S1 mortar; (b) Influence of grading on relative strength of mortars cast between the high WAC substrate.

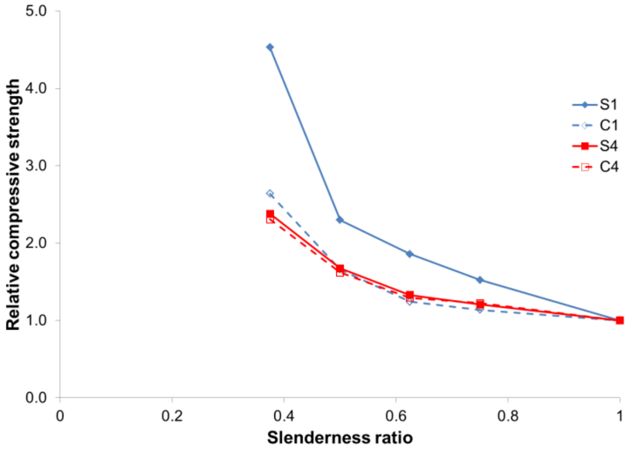

Figure 13: Influence of grading on relative strength of mortars manufactured with carbonate and silica sand and cast between the high WAC substrate.

The significance of this data is that it is not possible to apply a single relationship between the strength of a mortar sampled from a render to that of a 40 mm standard laboratory sample or the selection of a comparable repair mortar. The relationship will be a function of the sorptivity of the substrate, grading and packing efficiency of the sand as well as the absolute strength of the mortar as suggested by Drdacky et al [15].

4.3 Relative transfer sorptivity

Previous unpublished work has shown that desorption of the mortar bed is accompanied by a densification of the mortar when measured on the hardened mortar at an age of 28 days. Thus, greater desorption might be expected to yield greater densification and consequential impact on hardened mortar properties. Whilst there is no influence of mineralogy on strength for 20 mm thick mortars with sand gradings 1 and 3 applied to the high WAC brick (Table 5) the ratio of WAC for the carbonate sand with respect to the silica sand increases from 1.31 for sands C1 and S1 to 1.51 for sands C3 and S3; these ratios have been extracted from data in Fig 7b.

It is possible that the difference in performance of the two sand types may be a function of a different interaction between the mortar and substrate, i.e. desorption of the mortar by the substrate. Thus, assessments of the relative transfer sorptivity between the high WAC brick and fresh mortars manufactured with C1, S1, S2, C3 and S3 sand were performed; this was conducted at the end of the study and was constrained by material availability. Figure 14 shows the results of the tests (average of 3) for 20 mm thick mortar beds and the lowest values (highest water retention) are displayed by sands S2 and C3. There is no apparent relationship between grading or mortar/paste rheology. Ince [29] has reported a limited study of the influence of grading on the desorptivity of mortar and concluded that desorptivity reduces with a reduction in sand grain size. However, it should be noted that the grain size distributions of the four sands are each uni-modal and, as such, not representative of practical sands. Thus, further detailed study is required to identify any particular relationships between desorptivity and constituent characteristics or mortar rheology.

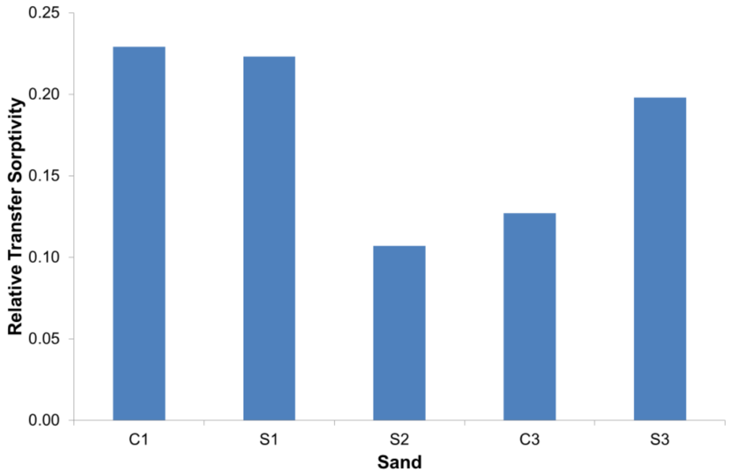

Figure 14: Relative transfer sorptivity between the high WAC brick and mortars C1, S1, S2, C3 and S3.

In the current study, whilst the lower relative transfer sorptivity of the C3 mortar may explain the apparent additional influence of the sand “mineralogy”, it does not explain the higher WAC of the C1 mortar in relation to its S1 counterpart with these mortars having similar values of relative transfer sorptivity. The ratio of WAC for mortars with the steel substrate is remarkably similar at 1.34 so the difference is probably related to mortar characteristics rather than to a different response to the substrate in mortars C1 and S1. The lack of influence on strength can be explained by the high proportion of the 20 mm sample being subject to tri-axial compression, which is precisely that most impacted by densification. Presumably, the former phenomenon dominates the influence of the latter.

Further tests were carried out for 40, 30 and 10 mm thick S3 mortar beds and the results are shown in Figure 15. The value cited on each bar is the relative transfer sorptivity expressed as in Figure 14 which does not account for the different mortar thickness. Whilst the water extracted generally decreases in thinner mortar beds it can be seen that the water extraction increases for thinner mortar beds when calculated per millimetre thickness, i.e. the relative impact on the mortar is greater. This could explain the stronger influence of the brick substrate on strength and WAC observed for thinner mortars.

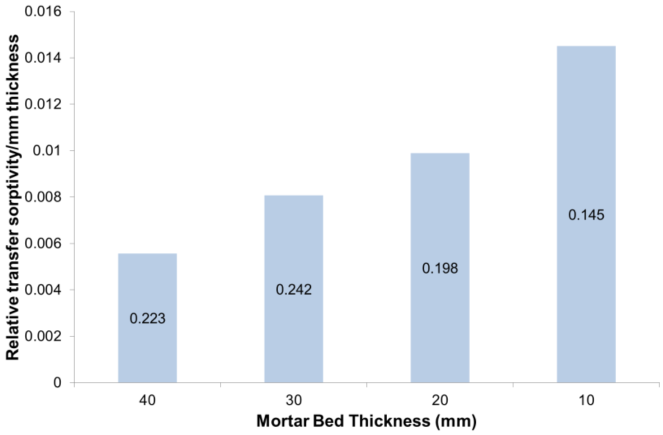

Figure 15: Relative transfer sorptivity per mm thickness (S3 sand).

4.4 Pore structure

Only a limited series of evaluations were made to illuminate the influence of the substrate and the sand mineralogy for one brick substrate alone. No comparison of sand mineralogy on mortar pore structure from standard steel moulds is available.

The pore structure properties and pore size distribution of a 15 mm thick mortar produced with S4 sand and cast between high WAC brick, low WAC brick and steel sided moulds are summarised in Table 8. It is evident that the brick substrate affects the pore structure of the mortar by reducing the threshold pore diameter and the porosity and increasing the total surface area. Whilst the influence of brick substrate on threshold pore size and total surface area is negligible the high WAC brick yields a lower porosity than that for the low WAC brick. The pore size distributions are shown in Figure 16 and the reduction in porosity can be attributed to a reduction in pore volume in the region of the threshold pore size which is accompanied by a slight increase in the finest pore volume. It has already been shown that the strength increases (Figs 5a & 5b) and WAC decreases (Fig 6) with increases in the sorptivity of the substrate. This is fully compatible with the differences in pore structure shown in Table 8 which can be attributed to the extraction of water from the mortar. Although not undertaken in this study, it is reasonable to assume that the water extraction by the low WAC brick would be lower than that measured for the high WAC brick.

Table 8: Pore structure properties of a mortar produced with S4 sand and cast in 15 mm high WAC brick – steel sided and steel sided moulds.

Substrate	Sand	Threshold pore diameter (μm)	Porosity (%)	Total surface area (m^2/g)
steel	**S4**	0.044	19	14.50
low WAC brick	**S4**	0.025	17	17.57
high WAC brick	**S4**	0.023	14	17.95
high WAC brick	**C4**	0.036	16	13.24

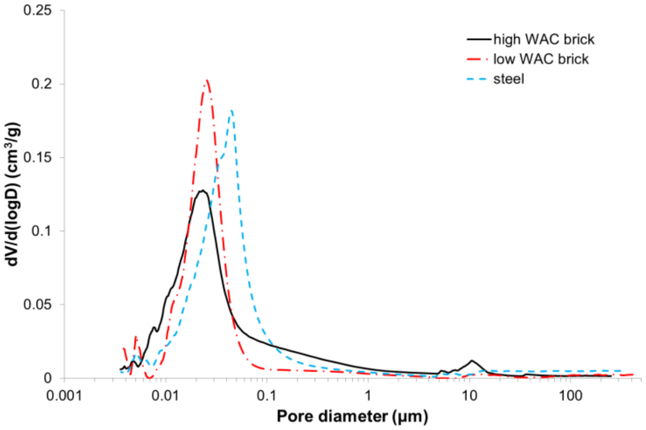

Figure 16: Differential volume of intruded mercury versus pore diameter of a 15 mm thick mortar produced with S4 sand and cast between high WAC brick, low WAC brick and steel sided moulds.

To investigate the effect of sand mineralogy, 15 mm samples manufactured with the C4 sand and cast between high WAC brick were also analysed. Table 8 shows that the C4 mortar is characterised by higher porosity and threshold pore diameter and lower total surface area than its silica counterpart. It is tempting to suggest that the differences in pore structure are a simple reflection of a greater water extraction in fine grained silica mortars which consequently yields a lower WAC in the silica mortars (Fig 7b). However, the water extraction from the S1 and C1 mortars is the same yet the carbonate mortar still yields the higher WAC. Indeed, a similar relative performance is also observed in mortars made in steel moulds such that other factors such as the packing efficiency of each sand may be dominant (Table 2). It is apparent that a detailed study is required in order to address this issue.

As shown by the strength and WAC test results, the influence of the brick substrate is more significant on thinner mortar samples. In order to correlate strength and WAC data with pore structure, MIP analyses have been performed on extractions from the cores of 40 to 10 mm thick beams produced with the S4 mortar and cast between high WAC brick faces. Table 9 shows that the threshold pore diameter decreases with decreases in thickness of the mortar sample with an increase in the total surface area. No substantial differences in total porosity were observed for the different thicknesses. A bimodal pore size distribution with the peak values at 0.021 and 0.033 μm is observed for 20 and 25 mm samples which appear to be a transition between the unimodal distributions of thinner and thicker samples.

Table 9: Pore structure properties of 40 to 10 mm samples produced with the S4 mortar and cast between high WAC brick faces.

Thickness	**Threshold pore diameter**	**Porosity**	**Total surface area**
(mm)	**(μm)**	**(%)**	**(m^2/g)**
10	0.021	13	16.11
15	0.023	14	17.95
20	0.021 & 0.033	14	13.45
25	0.022 & 0.034	14	12.84
30	0.032	14	11.89
40	0.031	14	11.86

To better understand the effect of the brick substrate on mortar samples of different thicknesses, MIP analyses were performed on samples collected from the surface in contact with the substrate and from the core of 40 mm and 15 mm (core only) mortars produced with S4 sand and cast in high WAC brick and low WAC brick. Whilst the total porosity is lower for the high WAC substrate, reflecting the higher strength shown in a comparison of Figures 5a and 5b, it is independent of mortar thickness in both instances (Table 10). In contrast, it is apparent that the substrate itself has little effect on the reduction in threshold pore diameter as the sample thickness is reduced from 40 to 15 mm.

In order to investigate the influence of composite substrates MIP analyses were performed on 15 and 40 mm mortar samples produced with S4 sand and cast in high WAC – steel sided moulds where one side only of the mortar is in contact with the brick substrate. The data in Tables 8 and 10 shows that the high WAC substrate yields lower porosity than the steel control mortars even when one side only of the mortar is in contact to it. The threshold pore sizes of mortars from both the composite moulds and the high WAC brick moulds are similar although the composite moulds yield mortars of slightly higher porosity which reflects the lower strength observed in 3.4.1.

It is perhaps surprising that no difference in either threshold pore size or total porosity is shown throughout the profile of the composite brick-steel substrates. However, the total surface area is shown to differ. Figure 17 shows the pore size distribution across the profile and subtle differences are apparent. The lowest pore volume at the threshold size is shown at the core of the sample which also shows slightly higher fine porosity. It would seem that irrespective of any densification at the surface enhanced hydration occurs at the core.

The influence of “surface layers” with different characteristics to the bulk of the sample is likely to be more reflected in physical properties associated with those “layers” i.e. WAC and flexural strength rather than compressive strength in which not only material parameters but the restraint offered by the test frame are significant. The low spatial resolution offered by MIP does not permit a detailed description of the densification and correlation with physical properties such that the study of differences in pore structure using more refined sampling and evaluation techniques would benefit this area of interest. Further investigation of the pore structure profile across the section of the 40 mm samples is required.

Table 10 Pore structure properties at the surface and core of 40 and 15 mm thick mortars produced with S4 sand and cast between high WAC brick, low WAC brick and high WAC brick - steel sided moulds.

Substrate	**Thickness (mm)**	**Location**	**Threshold pore diameter (µm)**	**Porosity (%)**	**Total surface area (m^2/g)**
high WAC brick	15	core	0.023	14	17.95
	40	core	0.030	14	11.86
		brick side	0.032	13	14.39
low WAC brick	15	core	0.025	17	17.57
	40	core	0.032	18	16.20
		brick side	0.031	17	13.19
high WAC brick - steel	15	core	0.021	16	19.12
	40	core	0.029	15	18.60
		brick side	0.029	16	16.84
		steel side	0.029	16	14.20

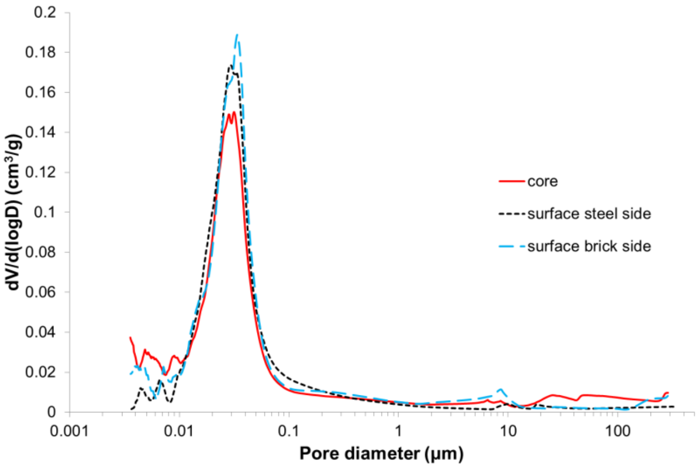

Figure 17: Differential volume of intruded mercury versus pore diameter across the profile of a mortar produced with S4 sand and cast in high WAC – steel sided moulds.

5 Conclusions and significance for practical mortars

This work has shown that substrate characteristics (WAC, condition and composite substrates), sand characteristics (shape & texture and grading) and mortar thickness interact with each other to affect the properties of both fresh and hardened mortars in which a constant w/c ratio of 0.87 was adopted. This value was chosen to permit the successful production of samples of the lowest workability in the thinnest beams utilising substrates of the highest WAC. Some of the mortars exceed the normal levels of workability of render mortars (typically flow in the range 15.5 cm to 17.5 cm). Consequently, the water content of some practical mortar combinations could be reduced with concomitant increases in absolute strength and reductions in WAC. The workable life of Roman cement render mortars is a function of the de-activation process and workability of the fresh mortar and values between 1 and 2 hours were obtained in the current programme; fine tuning of these parameters will deliver the desired value for a particular application.

This works has shown that:

- for a given sand grading both shear strength and viscosity is greater for the carbonate sand mortar, and particularly so for the coarser gradings
- mortars cast in brick sided moulds have higher strength than those cast in steel sided moulds; for a given sand the strength enhancement increases as the mortar thickness reduces and such increase is more apparent in mortars cast upon the high WAC brick than the low WAC brick
- for a given sand, the mortar cast in brick sided moulds has a lower WAC than that cast in steel sided moulds, with the lowest value being recorded for the mortar cast in high WAC brick sided moulds; the WAC of mortars cast in brick sided moulds decreases for thinner samples, with the influence of the substrate increasing with reductions in mortar thickness
- the brick substrate affects the pore structure of the mortar by reducing the threshold pore diameter and the porosity and by increasing the total surface area, with the high WAC brick yielding a lower porosity than that for the low WAC brick; the threshold pore diameter decreases and the total surface area increases with decreases in thickness of the mortar sample
- the water extraction increases for thinner mortar beds when calculated per millimetre thickness, which could explain the stronger influence of the brick substrate on strength, WAC and pore structure observed for thinner mortars
- 45 second soak of the high WAC substrate reduces the compressive strength of a 15 mm thick mortar from that obtained from the use of a dry substrate
- the high WAC substrate yields higher strength, lower porosity and lower shrinkage than the steel control mortars even when one side only of the mortar is in contact with it; also in this case the effect of the substrate on strength is more pronounced as the thickness of the mortar is reduced.

Thus, the principal factors are WAC of the substrate, sand characteristics as they relate to rheology, water retention and strength and mortar thickness. It is evident that, in order to maximise compatibility, the influence of such factors has to be taken into account when formulating or specifying a repair mortar. The development of a compatible repair mortar requires the characterisation of the physical-mechanical properties, constituents and proportions of the mortar that is to be matched. Compressive strength, mineralogy and grading of the aggregate, and an estimate of the binder/aggregate ratio are normally measured provided that sufficient material is available for the analysis. The collected information is then used to select compatible constituents and to design a mortar mix with the desired strength. The implication of the results of the present work is that the strength of the original mortar, which in most of the cases is measured on 15-20 mm thick samples collected from a porous substrate such as brick or stone, cannot be taken as the target strength of the repair mortar, which is normally measured on 40 mm thick samples cast in steel moulds. In fact, the strength measured for the original mortar will have to be corrected to account for the observed influence of both substrate and specimen thickness. This work has shown that depending on the selected sand grading (Figure 1), the compressive strengths of 40 mm thick Gartenau mortars cast in steel moulds are some 23% (S1 mortar), 29% (S2 mortar), 33% (S3 mortar) and 41% (S4 mortar) of those of the same mortars cast into 15 mm samples between 2 high WAC brick faces (Table 3). It was also shown that the influence of the substrate on strength is reduced if the substrate is wetted before moulding, and if the mortar is applied to only one face of a substrate with the other exposed to the atmosphere. The influence of the substrate may be entirely negated by the inclusion of a water retention admixture, such as methyl cellulose, within the repair mortar.

The precise relationships established from the current study should only be used to support the development of repair mortars manufactured with Gartenau cement. Further work is needed to investigate the behaviour of other binders before a modelling of the substrate-sand-mortar thickness-mortar strength interactions can be attempted. Alternatively, repair mortar specimens should be manufactured in special moulds similar to those used in this study, in order to take into account the effect of substrate and of mortar thickness. Provided that slips replicating the original substrate can be obtained, using this experimental set-up allows casting repair mortars with the same composition and thickness as the originals in contact with 1 or 2 faces of the substrate, as required by each specific case. Furthermore, the influence of wetting the substrate can be also considered. Obviously testing age and long term strength development of the repair mortar will have to be considered when specifying target strength.

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