THE DEVELOPMENT OF MORTAR/UNIT BOND

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ABSTRACT

Over the last five years a detailed study of mortar/unit bond has been carried out at the University of Newcastle. A technique was developed to assess the tensile bond strength and mortar microstructure of masonry samples. This involved performing direct tension tests on 25 mm diameter brick/joint cores taken vertically through brickwork couplets. The microstructure of the broken samples was then investigated using both optical and scanning electron microscopy with polished sections across the joint also being studied. Differences were observed in the transport of cementitious material to the interface and, in the morphology and density of the microconstituents. Using this information a postulate of the development of bond process has been compiled. This process is discussed in relation to the observed mortar/unit interactions.

Key words: brick/mortar bond, bond mechanism, bond strength, mortar microstructure, scanning electron microscopy.

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INTRODUCTION

The primary functions of the hardened mortar in unreinforced masonry are to provide a durable and weather-tight bond of adequate strength. Bond strength is necessary for the effective performance of the masonry under shear and out-of-plane loads. The out-of-plane mode of failure is usually catastrophic and in these situations the capacity of the wall is a direct function of the flexural (tensile) mortar-to-unit bond strength and the support conditions of the masonry panel. Therefore the development of adequate flexural (tensile) mortar-to-unit bond strength is essential in masonry. Several studies have been directed at identifying the formation and nature of the bond between the fresh mortar and unit (Staley 1940, Chase 1984, Lawrence and Cao 1987, Marusin 1990, Groot 1993, Lange et. al. 1999, Sugo et. al. 1997 and 1998, and Reda and Shrive 2000). These investigations have shown that the formation of bond is complex involving the transport of mortar fluids and fines to the brick/mortar interface followed by the hydration of the cementing materials. Over the last five years a brick/mortar bond study has been carried out at the University of Newcastle using small-scale direct tension tests and optical and scanning electron microscopy to correlate the tensile bond strength to the macro and microconstituents formed at the interface. Using this information and general observations cited in the literature, it has been possible to divide the formation of mortar-to-unit bond into several stages. These stages are discussed in this paper.

EXPERIMENTAL PROCEDURE

Rationale Used in the Experimental Procedure

The purpose of the experimental program was to obtain a wide range of interactions between units and mortars, and examine the bond strength/failure mode/microstructure relationship whilst using materials representative of current construction practices in Australia. Thus four types of masonry units were selected. These were extruded clay, dry-pressed clay, concrete and calcium silicate with each type of masonry units varying in composition, surface texture and water absorption characteristics. The units were combined with three different mortars based on a 1:0:6 (cement:lime:sand by volume) as a reference mix. The two other mortars were a 1:0:6 containing a methyl cellulose additive and a 1:1:6 mortar. The purpose of using these two other mortars was to investigate the effects of methyl cellulose water thickener and lime on the bond/microstructure relationship. The 1:1:6 mortar is a general purpose mortar predominantly used in clay brickwork and has also been used traditionally for concrete and calcium silicate masonry although a 1:0:5 + methyl cellulose mix is now the preferred mortar with these latter type units. Since the effects of brick suction play an important role in the formation of bond the quantity of moisture absorbed by the units for each mortar/unit combination was monitored. This was achieved by separating 1-hour old brickwork joints and determining the residual moisture content of the mortar and the unit.

Experimental Materials

The mineralogical composition, water absorption and surface texture of the four unit types are presented in Table 1. Further description of the surface texture of typical fields of view at high magnifications can be observed in Figure 1. At this level of magnification the texture of the units can be seen to be different from one another. The extruded unit has a rather smooth appearance with few small round openings. The dry pressed clay unit has a highly crazed surface texture whilst the concrete unit has a fine pore structure associated with the cement hydration products. The calcium silicate unit has a relatively coarser mesh structure formed by the fibrous nature of the calcium silicate hydrate structure (CSH) produced in the autoclaving process.

The cement used was a general purpose Portland cement manufactured to comply with AS 3972. Similarly, the lime was a hydrated product conforming with AS 1672 The methyl cellulose material was water thickener produced commercially for use in masonry. The concentration used was 0.005 parts of methyl cellulose by weight of cement as recommended by the manufacturer. The mortar sand was a local washed and dried dune sand; its particle size distribution is shown in Table-2. Despite the narrow size distribution and lack of fines, this sand is used widely in masonry mortars due to its availability in the Newcastle area.

Table 1. Mineralogical Water Absorption Charcteristics of Masonry Units.

Masonry Unit Type	Mineral Phases (Identified by powder X-ray diffraction)	IRA (kg.m^{-2} .min^{-1})*	24 hr. cold water abs. (%)*	5 hr. boil water abs. (%)*	Saturation Coefficient
Dry Pressed Clay Unit	quartz, mullite, sillimanite, haematite, glassy phase, iron hydroxide (trace)	3.39±0.49♦	9.19±0.53	11.8±0.28	78
Extruded Clay Wire Cut Unit	cristobalite, quartz, mullite, haematite (trace)	1.24±0.11♦	7.31±0.33	12.2±0.28	60
Concrete Unit	quartz, microcline, portlandite, CSH[#] (trace)	1.45±0.37♣	6.59±0.14	10.9±0.39	61
Calcium Silicate Unit	quartz, portlandite, calcium carbonate, 1.1nm tobermorite[#] (trace)	1.33±0.32♣	14.4±0.48	19.8±0.59	73

[*] determined in accordance with AS/NZS4456, errors represent ± 1 standard deviation

♦ oven dried condition ♣ room conditioned to approximately 3% moisture content

[#] binder related phases

Table-2. Particle Size Distribution of Dune Sand.

Sieve Size	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
% Passing	100	100	96	25	1	0

Experimental Procedure

Only brief experimental details will be presented since these have been reported elsewhere (Sugo et. al. 1997). The clay units were oven-dried prior to the construction of brickwork specimens. The concrete and calcium silicate units were allowed to equilibrate under laboratory conditions for a period of 3-4 weeks before construction. The moisture content of the units at the time of laying was determined to be 2 % and 3 % by weight for the concrete and calcium silicate units respectively. The 1:0:6 batches consisted of 11.7% Type GP cement and 88.3% sand, whilst the 1:1:6 batch consisted of 11.2% (by weight) General Purpose Portland Cement, 4.8% hydrated lime and 84% sand. The quantity of water added to each mortar batch was recorded, with the amount used being left to the bricklayer's discretion. The mixing time was similar for all mortars.

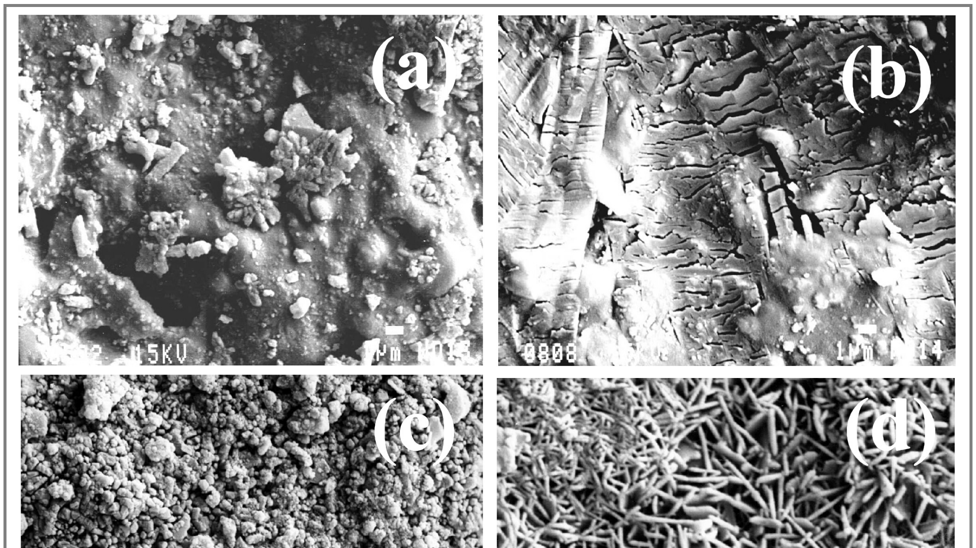


Figure 1. Photomicrographs of Masonry Unit Bed Surfaces, (a) dry pressed, (b) extruded clay, (c) concrete (d) calcium silicate. Secondary electron micrographs, bar length = 1μm.

Twenty brickwork couplets were constructed for each mortar/unit combination. Ten couplets from each batch were separated 1 hour after construction to evaluate the moisture distribution and the mortar moisture content in the joint. This moisture content has been converted to a w/c ratio to compare the effectiveness of the masonry units in dewatering the mortar bed joint. The fresh mortar properties of flow, cone penetration and gravimetric air content are presented in Table-3 together with the initial and 1-hour old mortar w/c ratio.

The bond strength was determined from uniaxial tension specimens obtained by coring the brickwork couplets after curing for 7 days . Five 25mm diameter cores were removed along the center line of each couplet using a custom made thin walled diamond coring drill. The specimen details are given in Figure-2. For each brick/mortar combination, between 10 and 15 specimens were tested under a controlled rate of cross-head displacement of 0.5 mm/min. The maximum load and failure mode were recorded for each specimen and are reported in Table-3. After failure the fracture surfaces of the specimens were studied using an Olympus SZ6045 stereo microscope, with further investigations being carried out using a JEOL 840 Scanning Electron Microscope (SEM). Sawn, fractured and polished thin sections across the bed joints were also examined.

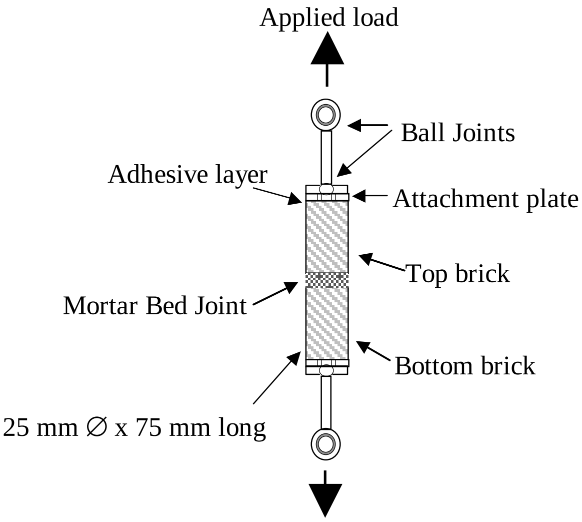


Figure-2. Details of Small Scale Uniaxial Tension Specimens.

RESULTS

The fresh mortar properties, moisture distribution and tensile bond strength results are summarized in Table-3. The results show that there is a range of mortar flows and consistencies produced by allowing the mason to judge the quantity of water added to the mortar. The range of air contents varies slightly, typically the 1:0:6 + methyl cellulose mortars had the highest air content, in the order of 10%, which is approximately double the air content of two other mortar types. The effects of brick suction on the 1-hour mortar moisture content can also be observed by the differences between the initial and final water/cement ratios. With the exception of the 1:0:6 + methyl cellulose/concrete masonry unit combination, the 1:1:6 mortar retained a greater proportion of moisture in all other combinations compared to the lime-free mortars. The 1:1:6 mortars developed greater tensile bond strengths. For the extruded clay and concrete units these were adhesive strengths (failure along the interface) whist for the dry pressed and calcium silicate units the mortar in the joint failed cohesively or in a mixed mode. The lime-free mortars were observed to have an insufficient volume of paste. This highlights another important contribution that lime makes to the batch.

The macro and microstructural characteristics of the unit/mortar combinations have been described previously and will not be detailed here (refer to Sugo et al 1997 and 1998). Briefly, the dry pressed and calcium silicate combinations showed that a distinct layer of cementitious material had been transported to the interface. This was more pronounced for the lime-free mortars and was consistent with the observed mode of failure for these combinations. At the micro-level there were some minor variations in the microconstituents. For the concrete and calcium silicate units the main microconstituents were CSH products and small amounts of $Ca(OH)_2$. For the clay units, larger $Ca(OH)_2$ deposits intermixed with CSH products could be identified for all mortar types. A variation of the morphology of the CSH products could be noted between the mortar types. The Portland cement-lime mortar producing a layer of rod-shaped CSH products adjacent to the interface. Small quantities of ettringite fibers were identified for the dry-pressed and concrete unit combinations.

Table-3. Summary of Mortar Properties, Moisture Content and Tensile Bond Strengths.

Masonry Unit	Type of Mortar	Flow (%)$^\#$	Cone (mm)$^\#$	Air Cont. (%)$^\#$	Initial w/c	Final w/c	Bond Strength (MPa)	Failure Mode
Extruded Clay	1:0:6	110	90	5.3	1.85	0.27	0.93±0.24	I/A
	1:0:6 + m. cell.	120	80	9.5	1.58	0.62	0.49±0.20	I/A
	1:1:6	130	50	4.5	1.79	0.71	1.37±0.26	I/A
Dry Pressed Unit	1:0:6	120	60	5	1.84	0.17	0.84±0.22	M/C
	1:0:6 + m. cell.	100	70	11	1.55	0.22	0.75±0.18	M/C
	1:1:6	85	70	4	1.90	0.46	1.69±0.20	M/C
Concrete Unit	1:0:6	100	50	4.2	1.76	0.67	0.51*	I/A
	1:0:6 + m. cell.	110	90	7.3	1.75	1.22	0.38±0.22*	I/A
	1:1:6	120	60	3.9	1.81	0.92	1.21±0.22	I/A
Calcium Silicate Unit	1:0:6	110	70	4.0	1.84	0.08	0.87±0.18	M/C
	1:0:6 + m. cell.	90	50	9.6	1.58	0.22	0.31±0.24	M/C
	1:1:6	110	60	3.0	1.83	0.35	1.30±0.16	Mixed

$^\#$ Determined in accordance with AS2701

* determined from a limited number of specimens, values are upper bound strengths

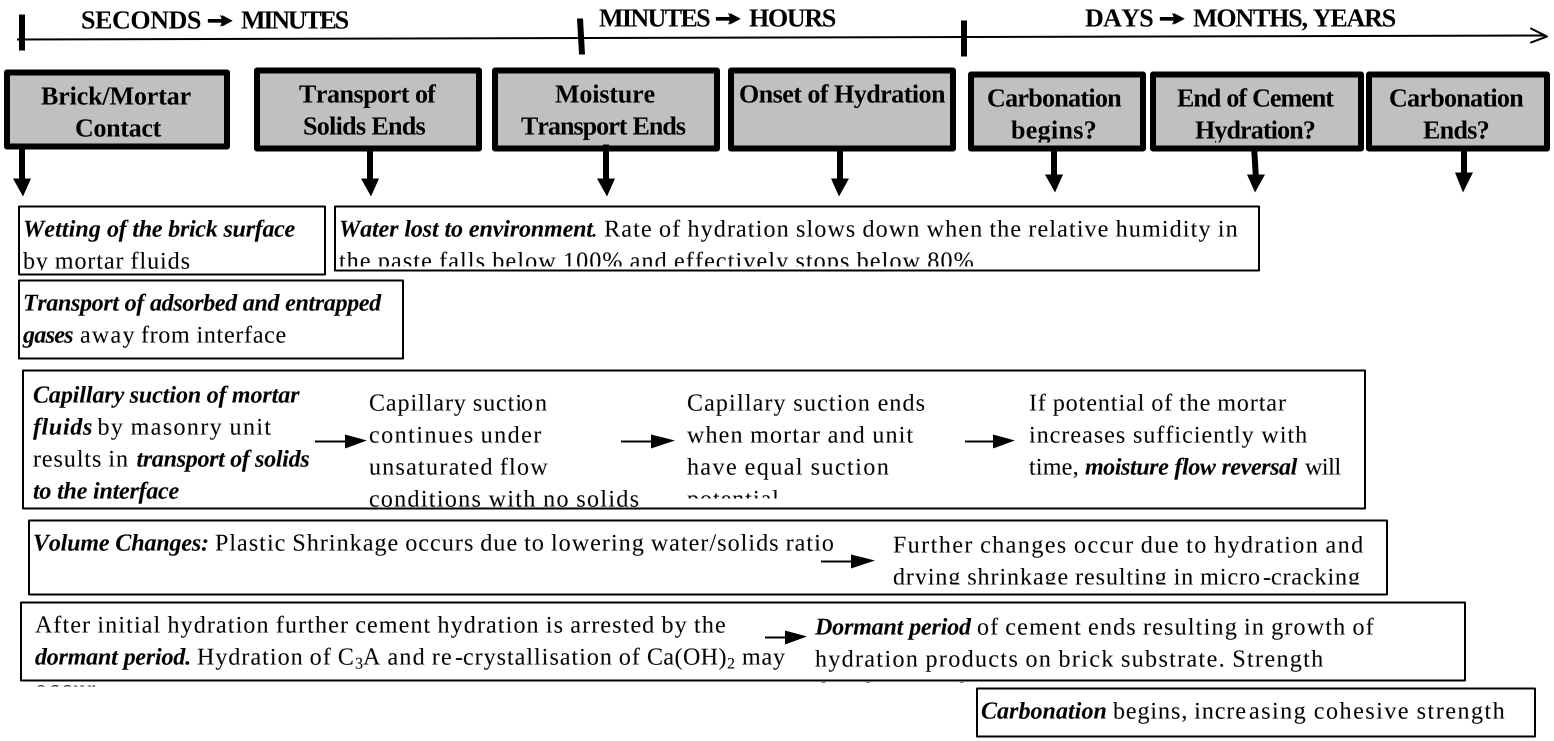
I/A, failure occurred along the interface M/C, mortar joint failed cohesively

BOND DEVELOPMENT PROCESS

From the results it may be observed that the bond strength and mode of failure are influenced by: the volume of paste; the transport of mortar fluids and cementitious material to the interface; and the density and degree of the hydration of the microconstituents. Using these observations a postulate of the processes that occur during bond formation has been formed and is presented in Figure-3. Each stage is described in the following text to highlight the possible mortar/unit interactions.

Wetting of the Brick Surface

The contact of fresh mortar with the brick allows the mortar fluids to wet the brick surface (the mortar fluids/brick surface contact angle must be less than 90º). This process is necessary if capillary suction is to occur. Wetting of the brick surface is also necessary for the nucleation and growth of $Ca(OH)_2$ or CSH products on the brick substrate.



Wetting of the brick surface by mortar fluids

Water lost to environment. Rate of hydration slows down when the relative humidity in the paste falls below 100% and effectively stops below 80%

Transport of adsorbed and entrapped gases away from interface

Capillary suction of mortar fluids by masonry unit results in ***transport of solids to the interface*** → Capillary suction continues under unsaturated flow conditions with no solids → Capillary suction ends when mortar and unit have equal suction potential → If potential of the mortar increases sufficiently with time, ***moisture flow reversal*** will

Volume Changes: Plastic Shrinkage occurs due to lowering water/solids ratio → Further changes occur due to hydration and drying shrinkage resulting in micro-cracking

After initial hydration further cement hydration is arrested by the ***dormant period.*** Hydration of C_3A and re-crystallisation of $Ca(OH)_2$ may occur. → ***Dormant period*** of cement ends resulting in growth of hydration products on brick substrate. Strength

Carbonation begins, increasing cohesive strength

Figure-3. Outline of the different processes occurring during bond development in masonry.

Brick/mortar combinations where only small amounts of de-watering occurs would produce relatively porous hydration products due to the initially high water/cement ratio of the mortar. Due to the small volume of water absorbed a poor contact layer between the mortar and unit would also result. The combination of these factors would lead to the development of poor bond strength. An example of this is the concrete unit/1:0:6 + methyl cellulose combination investigated in this study.

Transport of Adsorbed and Entrapped Gases

The surface of a masonry unit has macro voids, which will form air pockets when the mortar layer is placed on the unit, or when the unit is placed on the mortar bed. Much of this entrapped air will be swept out as the excess mortar is squeezed from the joint. At a molecular level the brick surface and capillary pores are covered with a layer of adsorbed atmospheric gases. Without investigating this phenomenon further it is difficult to say if the volume or path taken by the desorbed gases has a significant influence on the bond process. However, polished sections of mortars with adequate paste content and fluidity showed regions of entrapped air located adjacent but not at the interface. This implies that there may be a mechanism whereby paste is transported to the interface around the voids.

Capillary Suction

Capillary suction is an important process for the strengthening of the cohesive and adhesive mortar strengths. The capillary suction process in masonry results in the de-watering of the mortar (decreasing the initially high water/cement ratio) and transport of mortar fines to the brick/mortar interface. The 1-hour moisture retention tests shows the degree of de-watering that can occur as a result of the capillary suction effects. The transport of cementitious material to the interface was observed for some combinations in both the sawn and polished sections. Capillary suction of the mortar fluids by the unit will occur provided the fluids wet the brick surface and that a suction potential exists between the relatively dry (unsaturated) porous brick and the wet (saturated) mortar. The transport of fluids into the brick surface lowers the suction potential of the unit and increases the corresponding suction potential of the mortar. The process continues until the suction potential difference between unit and mortar approaches zero. This process is localised and will initially induce sharp moisture and suction potential gradients in the zones near the interface. Capillary suction is also the driving mechanism for the transport of solids to the interface, plastic shrinkage and moisture flow reversal. From the data presented in Tables 2 and 3 it can be observed that the amount of moisture removed from the mortar is not dependent on the IRA of the unit. The extruded clay, concrete and calcium silicate units had similar IRA values yet yielded a very wide range of 1-hour moisture contents.

Loss of Moisture to the Environment

The loss of moisture to the environment during the initial brick/mortar contact period is small and is not likely to influence the relatively rapid processes of capillary suction and transport of solids but will influence the cement hydration that occurs over several days.

Note that the rate of hydration diminishes rapidly and approaches zero when the paste relatively humidity falls below 80% (Cather, 1994).

Transport of Solids to the Interface

Given the right conditions, transport of fluid within the mortar will create a build up of mortar fines along the brick/mortar interface. The critical properties of the unit and mortar which determine the amount of solids transported are those that influence the rate and volume of capillary flow together with the particle size of the fines and rheology of the mortar paste. It is also unlikely that transport of solids will occur once the mortar paste becomes unsaturated, (therefore this has been assumed to be the end point for the transport of solids shown in Figure-3). Thus the volume of fluids that the mortar can hold in excess of its saturation point, whilst still maintaining adequate workability, will be an important parameter affecting bond. For a low IRA unit the end point of solids transport will occur after a few minutes. In contrast, with a high IRA unit the mortar will stiffen in a few seconds as it becomes unsaturated, causing a workability problem for the mason.

The transport of solids to the interface provides continuity of contact along the two materials. From the bond strength viewpoint, there is likely to be an optimum amount of cementitious material required at the interface. Insufficient amounts will lead to adhesive failures at the interface, whilst an excessive build up of material will lower the cohesive (tensile) strength of the mortar layer adjacent to the interface (paste-depleted layer) as observed for the dry pressed and calcium silicate units combined with the lime-free mortars. The build up fines at the interface also forms a barrier reducing the fluid (and solids transport), and if a paste-depleted layer forms adjacent to the interface, the induced porosity of this layer further reduces the effective area for capillary flow. This phenomenon mainly affects the transport of fluids from the central regions of the mortar joint and may explain the previous observation that high IRA clay bricks extract less water from the mortar joint than mid-range IRA units (Davison, 1961).

Volume Changes within the Paste

During the capillary suction process de-watering of the mortar occurs. Whilst the mortar is saturated this process increases the mortar density. Once the mortar becomes unsaturated the coarser aggregate particles form a 3-dimensional grid which will resist any further volume contraction. Shrinkage of the paste surrounding the coarse aggregate particles will then take place until a moisture content is reached where the small particles are no longer able to re-arrange themselves. Although further extraction of moisture from the paste may occur by capillary suction, no further compaction of the cement particles will then occur. This point will determine the end of plastic shrinkage and the final packing of the cement particles in the mortar paste and can be considered analogous to the mix water/cement ratio in concrete.

If the moisture extraction occurs whilst the paste is still sufficiently plastic to accommodate the volume changes, then the capillary suction (and shrinkage) processes are beneficial to bond development by decreasing the cement particle spacing. Incompatibilities may arise if suction is excessive and insufficient quantities of moisture are available for hydration, or conversely if capillary suction is inadequate for the mortar water retention properties, leaving a high water/cement ratio paste (and also a poorly developed contact layer between the unit and mortar).

Following plastic shrinkage, autogenous shrinkage (shrinkage from the cement hydration) will occur as the bulk of the calcium silicate components are consumed. Autogenous shrinkage will be followed by drying shrinkage due partial dehydration of the CSH structure as moisture from within the bed joint is consumed and/or lost to the environment. The carbonation of the lime component will also contribute to the mortar shrinkage. The shrinkage effects may cause reductions in bond and mortar cohesive strengths due to micro-cracking (note that the CSH drying shrinkage is in part reversible). The magnitude and timing of these effects depends upon the characteristics of the mortar components and factors such as the rate of moisture loss from the joint.

Reversal of Moisture Flow

The degree of hydration of the cement compounds will increase the suction potential of the mortar due to the formation of CSH products which have high surface areas and are hygroscopic in nature. This time-based process is likely to be responsible for the experimentally observed moisture flow reversal occurring several hours after construction noted by Groot (1993). The reversal of moisture flow, from the masonry unit back to the mortar, most likely has a positive effect on bond strength by providing moisture to aid the hydration process. The flow reversal would explain the reasonable levels of hydration observed with some of the mortar/unit combinations reported to have very low 1-hour moisture contents in Table-3.

Another possible influence of moisture flow reversal is the change in solution chemistry of the fluids flowing back to the mortar. The mortar fluid in the masonry unit capillaries may dissolve adsorbed CO_2 or SO_3 compounds. The transport of these ionic species back to the mortar may influence the microconstituents formed in the interface zone. A solution rich in carbonate ions may lead to the formation of calcium carbonate at the interface. This will densify the microstructure and is likely to be beneficial to bond strength. The presence of significant amounts of sulphate ions may lead to the formation of ettringite and the high volume expansion associated with the crystallisation of ettringite may weaken the microstructure.

End of the Dormant Period

During the mixing of the mortar the contact of Portland cement and water lead to the rapid hydration of the tricalcium aluminate compounds forming ettringite. The hydration of the tricalcium silicates (C_3S) and dicalcium silicate (C_2S) compounds does not occur till the end dormant period. For a general purpose Portland cement the dormant period may last 4-6 hours under normal ambient conditions. It is during this time period that the changes in water/cement ratio of the mortar occur from the capillary suction effects. The rapid increase in the rate of formation of CSH products at the end of the dormant period is the beginning of actual bond formation. Hydration of the C_3S and C_2S components will continue until they are consumed, or until hydration ceases due to insufficient moisture availability.

Carbonation

Carbonation reactions will progressively take place with the ingress into the mortar of water-carrying carbonic ions or atmospheric CO_2. Carbonation of $Ca(OH)_2$ is a cementing reaction and has been reported as being beneficial to the long-term bond strength. The dissolution of $Ca(OH)_2$ and re-deposition/carbonation has been observed to densify the brick/mortar interface and provide a mechanism for crack healing (Staley 1940).

DISCUSSION

From this description of the bond formation process it can be observed that suction of the mortar fluids and associated transport of solids to the brick/mortar interface form an important role in the development of bond. The mortar dewatering affects the adhesive and cohesive strength and mode of failure of the joint through the development of a uniform contact layer between the unit and mortar and by the reduction of the initially high mortar w/c ratio. This interaction between the unit and mortar limit the usefulness of basic tests like IRA to predict bond strength. A more complex model incorporating the unit suction characteristics, rheology of the paste and its suction properties is required to assess the mortar-to-unit compatibility.

The experimental work showed that the addition of hydrated lime is beneficial to bond. The hydrated lime material increases the workability, moisture retentivity and contributes to the volume of paste. The examination of the microconstituents at the brick/mortar interface showed that for the clay units $Ca(OH)_2$ and CSH products were formed for the Portland cement and Portland cement-lime mortars with some minor variations in the morphology of the CSH products. Only small amounts of $Ca(OH)_2$ was observed at the interface of the calcium silicate and concrete masonry units combinations. The CSH products formed with the concrete units were less dense and more fibrous in nature. This is likely to be a result of the very high final w/c ratios observed with this particular masonry unit. The experimental work also showed that when lime is omitted from the batch the quantity of Portland cement should be increased to provide a greater volume of paste. This is consistent with the guidelines in the Australian masonry code and the manufacturers recommendations of the methyl cellulose product. The 1:1:6 mortar developed good tensile bond strengths with the four masonry unit types despite the differences in suction characteristics, mineralogy and surface texture shown in Figure-1. The extruded clay and concrete units have different surface textures and suction characteristics yet similar tensile bond strengths and modes of failure were observed. The dry pressed unit developed a higher mean strength and a mortar cohesive mode of failure. This highlights the versatility of the Portland cement system to bond to surfaces with different properties. The tensile bond strengths values obtained by selectively coring along the centerline of a brick work couplet may not be representative of the true masonry flexural strength as a loss of bonded area around the edges of the joint is usually observed (van der Pluijm 1992).

CONCLUSIONS

The purpose of this study was to obtain a greater understanding of factors affecting bond strength for a range of unit characteristics (suction, surface textures, mineralogy) and mortar properties commonly encountered in masonry. It was found that both macro and micro scale factors control bond strength. Capillary suction by the brick causes the transport of cementitious material to the interface. The formation of a coherent layer of paste at the interface ensures mortar-to-brick contact at the macro level. The de-watering process also increases the packing density of the cement particles allowing the hydration products to form a dense structure at the micro level, increasing the cohesive strength of the paste at the interface and within the bulk of the mortar.

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