TECHNICAL NOTE

CEMENT CONCRETE & AGGREGATES AUSTRALIA

Bond Strength in Masonry Construction

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INTRODUCTION

Bond strength is a measure of the ability of the units and mortar in masonry construction to remain bonded and resist applied stress and movement, particularly in tension. It is one of the most important properties of masonry, particularly in low-rise domestic and commercial buildings. Based on the outcome of a major research project on masonry bond strength, this note discusses the importance of bond strength, the basics of its development and the main factors affecting it. Practical guidelines are given on ways to ensure that adequate bond strength is achieved on site.

The term 'brick' is used in this note to refer to all types of masonry units including concrete, calcium silicate and clay units manufactured as either bricks or blocks.

THE IMPORTANCE OF BOND STRENGTH

Bond strength is important for the development of sufficient tensile strength in the masonry to resist wind and earthquake forces and minor movement. Inadequate bond strength will inevitably lead to cracking in masonry construction. Because this cracking is a brittle mode of failure and there is often little scope for redistribution of stresses, there is potential for widespread damage if bond strength is inadequate. The weakness might become apparent only when the masonry is subjected to an extreme load event, such as a high wind or an earthquake, when it might lead to collapse.

Cracking might also occur during the service life of the building, especially when it is caused by minor movements in the footings or by thermal gradients. The effect of this type of damage is primarily aesthetic, although it can also lead to long-term degradation, ingress of water into the building and a general lack of serviceability.

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REQUIREMENTS OF THE MASONRY STANDARD

Although not explicitly stated therein, AS 3700 *Masonry Structures* assumes that the characteristic tensile flexural bond strength will be not less than 0.2 MPa in all masonry. While a designer may assume less than this for strength calculations, this is rarely done. A designer is permitted to use a value higher than 0.2 MPa only if tests are carried out on site to verify that the higher strength is achieved.

AS 3700 is based on the strength at an age of seven days on the assumption that there might not be any significant increase in strength after this time. It is not usually convenient to continue testing beyond seven days where site control monitoring of strength is required.

AS 3700 provides different deemed-to-satisfy mixes depending on the cement type, eg General Purpose blended cement (Type GB) and General Purpose portland cement (Type GP). For example, in Table 10.1 of the Standard an M3 mortar with Type GP cement can be 1:1:6 (cement:lime:sand by volume) but must be 1:1:5 if the cement is Type GB. This implies that Type GB cement is less effective than Type GP, for strength or durability, or both.

Mixes other than those deemed-to-satisfy by the Standard can be used provided sufficient evidence of strength and durability performance is available.

RECENT RESEARCH

A far-reaching investigation[1] of factors affecting bond, methods of test, fundamental mechanisms of forming bond and the effect of age and curing conditions has been carried out recently by the University of Newcastle and the CSIRO with funding from various sources, including the Cement and Concrete Association of Australia. For this investigation, bricks and mortar mixes were chosen to be representative of common construction in Australia so the findings can be applied to masonry generally (although with some caution). The points in this Note are illustrated by some of the findings from this work.

The research program included the following:

Surveys and databases

An Australia-wide survey of the properties of masonry and its components pertaining to bond performance was carried out, and a comprehensive bond-strength database established. Individuals and companies in various States were asked to supply representative samples of bricks and sand and information on local site practices. Standard tests were then performed on the samples and the information collated. Data from previous bond-strength testing was also incorporated into the database.

Bond wrench studies

An experimental and analytical study of the bond wrench test was conducted with a view to standardising the apparatus to obtain consistent results and minimum levels of variability. Particular emphasis was placed on the tensile stress distribution induced at the brick-mortar interface by various wrench and specimen configurations, as this directly influences the measured bond strength.

Age and curing studies

A large-scale, experimental study was performed on the effects of age and curing conditions on bond strength. The first stage of this study held curing conditions constant while studying the effects of age. The second stage included the effect of curing by studying the effects of age on bond strength for parallel sets of specimens, one set cured internally (in the laboratory), the other externally and exposed to the elements. For both studies, bond strengths were investigated for a range of cements and unit types (clay, concrete and calcium silicate).

Interface studies

Fractured bond surfaces were systematically studied using optical and scanning electron microscopes as well as X-ray diffraction techniques. Polished sections through the brick/joint were also studied to allow factors such as the migration of cement paste in the joint to be examined. Specimens were prepared from a range of brick/mortar combinations, with some mortars containing plasticising admixtures.

KEY FACTORS AFFECTING BOND STRENGTH

The research project was designed to investigate the effect of the major factors, when acting in combination, on bond strength. The effect of the major factors is summarised below.

Masonry units

Generally, masonry units in Australia are made from clay, concrete or calcium silicate. Compressive strength is often the only property provided by manufacturers and this has no bearing on the bonding properties of the masonry unit. The surface characteristics and suction of the units are the important properties in determining bond. The three types of masonry units differ in their surface characteristics, pore structure and suction properties, and it could therefore be expected that different mortars would be required for the development of optimum bond strength. Whereas AS 3700 includes different deemed-to-satisfy mortar mixes for clay, concrete and calcium silicate units, it does not recommend specific mixes as

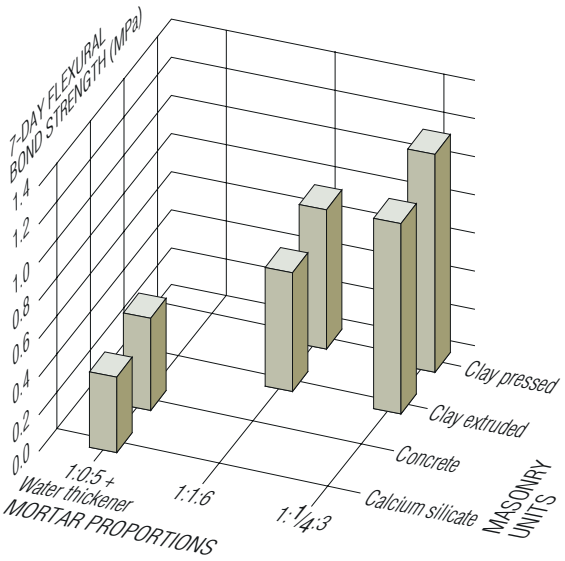

Figure 1: Mix and masonry unit effect on 7-day flexural bond strength

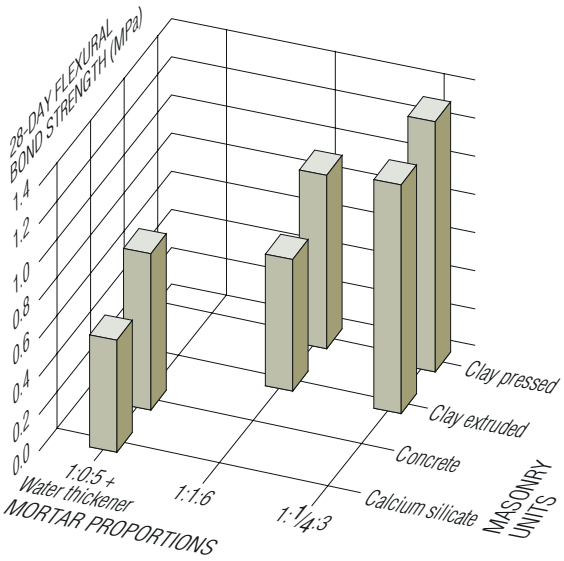

Figure 2: Mix and masonry unit effect on 28-day flexural bond strength

optimum and does not provide for any different levels of strength for mortar in combination with various unit types.

It is sometimes mistakenly thought that the presence of holes in extruded clay bricks is to produce an interlocking action with the mortar. The form of the bricks is generally determined by manufacturing considerations and has no bearing on the bond strength.

It is difficult to generalise about the effect of masonry unit type. For some of the mortar mixes and cements tested, clay bricks produced higher levels of bond strength than concrete or calcium silicate units **Figures 1–4**. However, pressed and extruded clay bricks behaved differently, giving different bond strength levels with different cements and responding differently to inside and outside curing.

However, if the brick effect is pooled for clay bricks, on the basis that it is not practical in a regulatory sense to distinguish between pressed and extruded clay bricks, then the mix composition and curing were the major effects. These are discussed below.

Mix composition

Cement hydration is the primary mechanism for development of bond strength, provided the necessary transport of fluids and solids and a continuing presence of water for hydration are assured. It would therefore seem reasonable that bond strength should be influenced positively by an increase in cement content.

The age and curing studies included 1:1/4:3 and 1:1:6 mortars for clay units and 1:0:5 mortar with water thickener for concrete and calcium silicate units. The results therefore provide the opportunity to examine the difference in bond strength between two mortars of different cement contents used with clay bricks. The study showed that at an age of 7 days, the average bond strength with 1:1/4:3 mortar was 62% higher than that with 1:1:6 mortar **Figure 1**. At an age of 28 days the difference between the two mortars was 40% **Figure 2**. Although other factors were present in these experiments, the results provide a clear indication that increased cement content gives higher bond strength.

The interface studies showed that lime produces a denser microstructure and adds plasticity to the mortar during the crucial early stages of setting. The use of lime in mixes for clay bricks is therefore beneficial and the recommended mixes are 1:1:6 for general purpose work, 1:1/4:3 for high-strength work and 1:2:9 for small structures. Of course this choice will also be influenced by the durability requirements of the particular exposure environment and AS 3700 Table 5.1 should be consulted.

The surveys carried out as part of the research asked recipients for the commonly used mixes with clay, concrete and calcium silicate units. Responses showed a wide range of mixes in common use, with no clear pattern of consistency within or between States. The recommendations in the various manuals and codes of practice published over the last 20 years regarding appropriate mixes seemed to be either unknown or largely ignored. In particular, there was much less use of lime than expected, despite its beneficial effects, and little understanding of the best mixes to use with concrete and calcium silicate units.

The best mixes for use with concrete and calcium silicate units have consistently been shown to be those using clean, sharp, well-graded sand with no clay content and the addition of a water thickener.

Sand

The research has shown that the movement of fine particles (cementitious components and fine sand) towards the brick/mortar interface while the mortar is still fluid is extremely important in developing bond. Sand properties thus have an effect on bond strength.

Sand properties had been investigated earlier[2]. It was found in that study that the sands used for masonry mortar in the particular geographic area (around Sydney) were sourced and blended by the suppliers and bricklayers so that they did not exhibit wide variations in grading. The same is likely to be true in other parts of Australia, although the common characteristics will vary from area to area.

The surveys showed that sands from northern New South Wales and the Melbourne-Geelong region tend to have a higher fines content than other Australian sands. Nevertheless, most sands have a fine fraction below the upper limit of 10% that is often recommended, and this limit can therefore be adopted as a useful guideline for masonry mortar sands in Australia. Many Australian sands, especially from Brisbane, Western Sydney and South Australia, have coarse fractions above the recommended upper limit of 1% (percentage retained on the 4.75-mm and 2.36-mm sieves). This excessive coarse fraction might have adverse effects on bond strength.

Based on the research it is recommended that sands have a limit of 50% on the difference in percentage passing any two successive sieves and a limit of 25% on the difference between the percentage passing the 150-µm and the 300-µm sieve.

Sands should be clean and free of clay content. Clay or 'fire-clay' should not be added to the sand as this markedly reduces bond strength.

Cement

The age and curing studies showed that at ages of 7 days and 28 days there is no significant difference between GP and GB cements (either slag blends or fly ash blends) for concrete and calcium silicate units **Figures 3 and 4**.

For clay units, the age and curing studies showed interaction between the brick category (pressed and extruded), cement and curing effects, as mentioned earlier. These interactions make it difficult to draw general conclusions about the effect of cement. In general, adequate levels of strength were obtained with all three cement types

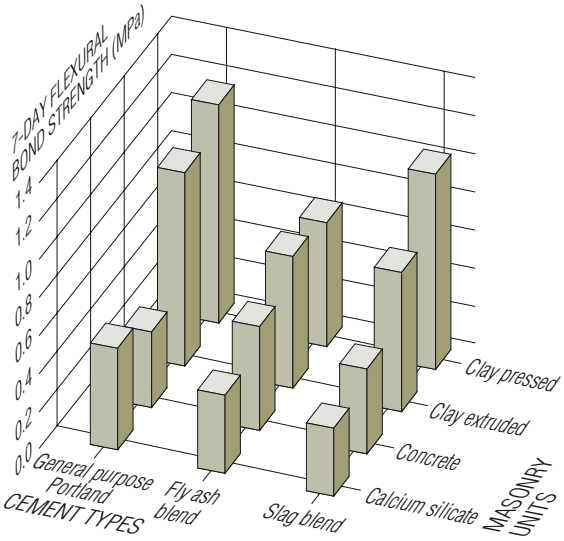

Figure 3: Cement and masonry unit effect on 7-day flexural bond strength

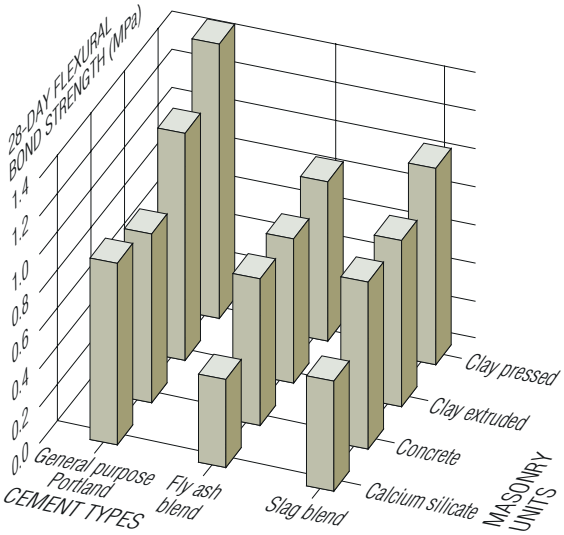

Figure 4: Cement and masonry unit effect on 28-day flexural bond strength

tested and the cement effect is no more significant than the brick effect or the mix effect.

An example of results is presented in **Figure 5** which shows the average strengths for two mixes and three cements in combination, when used with clay bricks and tested at an age of 7 days. The two mixes are 1:1:6 and 1:1/4:3, while the three cements are FAB, (Type GB containing fly ash), GP (general purpose portland) and SB (Type GB containing blast furnace slag). Again, this figure shows that the mix effect is more significant than the difference between the cements. It should be noted that even at the 1:1:6 proportions, the blended cement mortar passes the 0.2 MPa required for bond strength in AS 3700. Therefore, there is scope for a re-examination of whether there is a necessity to differentiate mortars made with blended cements.

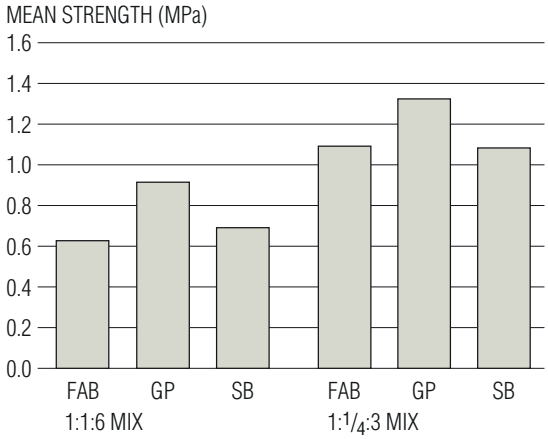

Figure 5: Mortar mix and cement effects at 7 days age for clay bricks

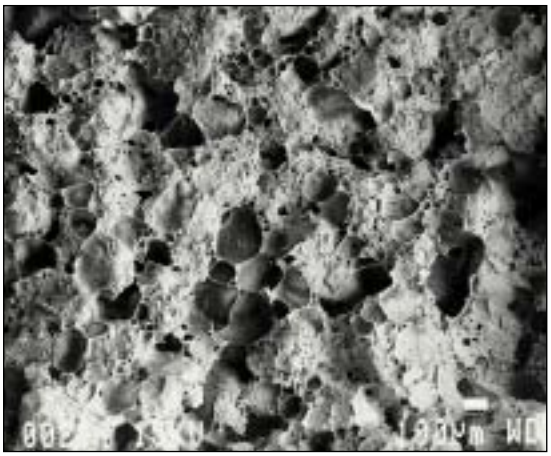

Figure 6: Electron micrograph of mortar overdosed with air entrainer

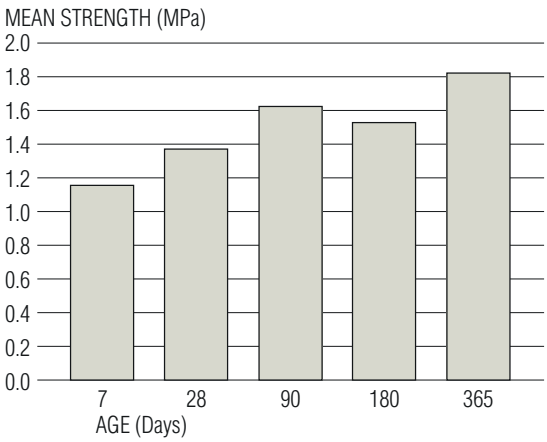

Figure 7: Example of the variation of bond strength with age (clay bricks and GP cement)

Admixtures

The surveys undertaken as part of the research asked respondents to indicate whether additives were used to enhance workability and, if so, which type is the most common. The results showed that the use of air entrainer is widespread and that detergent is the next most common workability enhancer, despite the fact that AS 3700 prohibits it. It is well known that when air entrainer is used it is common to overdose it because of the extreme workability enhancement that can be produced. However, this overdosing produces severe reductions in bond strength. An example of the effect of overdosing air entrainer is shown in **Figure 6**, which shows an electron micrograph of a mortar with a high level of entrained air. The figure clearly shows how the air bubbles consume the cementitious paste in the formation of shells, leaving less of the paste to form the interlocking layer at the surface of the brick, leading to reduced bond strength.

For at least the last 20 years, the use of water thickener to enhance bond strength with concrete and calcium silicate units has been recommended. These water thickeners are modified methylcellulose products specifically manufactured for masonry mortar. Some tests have also shown that these products can enhance bond strength with clay units where particular types of sand are used. The survey asked whether these additives are commonly used for clay, concrete and calcium silicate units.

The survey revealed that no water thickener is used in South Australia, Tasmania and Victoria and enquiries reveal that the type of product is virtually unknown in those States. Very little is used in Western Australia. In the ACT, New South Wales and Queensland, water thickener is used to some extent for calcium silicate units, but very little is used for concrete units. It seems common for builders to use an identical mortar mix for laying both clay and concrete units, despite the clear evidence that tailoring the mix to the specific type of unit enhances bond strength.

Age and curing

The research showed that, in general, bond strength increased with age. In some cases a decrease in bond occurred between 90 and 180 days followed by a further increase. **Figure 7** shows an example of the variation for clay bricks and GP cement, under laboratory curing conditions. The reasons for this strength variation are not clear, but are possibly the result of the interacting effects of increasing strength due to cement hydration and decreasing strength caused by shrinkage-induced micro-cracking in the mortar and at the brick-mortar interface, combined with progressive

carbonation of the mortar. Research is continuing into these aspects.

For concrete and calcium silicate units where the specimens were cured under plastic until testing, the strength increase from 7 days to 28 days averaged 93%, and for concrete and calcium silicate specimens cured under plastic for the first 7 days and then exposed to laboratory air, the average increase was 84%. The increase in strength from 7 days to 28 days for specimens exposed to outside conditions averaged 50%.

For clay bricks where the specimens were cured under plastic until testing, the strength increase from 7 days to 28 days averaged 21%, and for clay brick specimens cured under plastic for the first 7 days and then exposed to laboratory air, the average increase was 9%. The increase in strength from 7 days to 28 days for specimens exposed to outside conditions averaged 30%. These results are less marked than those for concrete and calcium silicate units but nonetheless show a consistent increase from 7 days to 28 days.

In relation to design practice, Type GP and Type GB cement mortars showed levels of bond at an age of 7 days consistent with the assumptions in AS 3700, exceeding a target mean value of 0.34 MPa (corresponding to an assumed characteristic value of 0.20 MPa). The increase in strength beyond 7 days is a bonus because AS 3700 uses the 7-day strength for design and testing, but the masonry is not likely to be fully loaded before an age of 28 days. At least for higher values of bond strength (as would be specified for Special Masonry), the current code assumption that the 7-day flexural tensile strength corresponds to the final strength appears to be overly conservative and there are grounds for the review of this assumption in the light of this data.

Using various bricks, mortars and cements, the research showed that in all cases there was a significant difference in bond strength for the inside and outside curing history. In most cases (but not always), the bond strengths for outside conditions were less than their inside counterparts, although the trends varied considerably with both brick and mortar type. The results discussed above highlight the beneficial effect of curing, which retains moisture in the masonry to facilitate hydration of the cement. In a building, the surrounding mass of masonry and other construction, will limit moisture loss while further benefit could be obtained from an increase in the humidity of the environment. However, excessive wetting of new masonry construction can lead to problems with shrinkage and efflorescence and is not recommended.

For clay bricks, the average ratio of bond strengths for outside and inside curing conditions was 0.79 at 7 days and 0.94 at 28 days. For concrete and calcium silicate units, the average ratio of bond strengths for outside and inside curing conditions was 0.84 at 7 days age and 0.68 at 28 days. Despite these reductions for outside curing conditions, the observed bond strengths, with a few exceptions, were still at acceptable levels for ordinary masonry.

Workmanship

The surveys carried out in this research indicated that there is widespread misunderstanding about the appropriate mortar mixes to use with particular masonry units. There is also widespread abuse of admixtures including air entraining such as detergent. The adverse effects of these practices were discussed above.

The survey also asked respondents about batching methods and the overwhelming majority nominated shovel batching as the usual method. Only some of the larger contractors attempt to use volume batching, giving greater assurance that the mix composition achieved matches that specified. Very few indicated that they use the good practice of adding a measured volume of cement to a mixer of known volume to ensure that the proportion is correct.

Wetting of the masonry units before laying was also indicated by many respondents to the survey as common practice. This is a particularly bad practice with concrete and calcium silicate units, where it promotes shrinkage and efflorescence and probably does little to enhance bond strength. In some of the cases where wetting was indicated, no water thickener was being used in the mortar mix. A much better alternative is to control the high suction of these units by using a water thickener in the mortar mix.

It was also surprising that so many respondents indicated that clay units are commonly wetted, especially amongst the bricklayers in New South Wales. Wetting of the units affects the delicate balance between transport of moisture and fines to the interface and subsequent hydration of the cement to form a strong bond. It is much better to match the mortar to the suction of the units, by means such as the addition of lime to the mix, rather than to wet the units before laying.

SUMMARY

The research has shown that:

- The mix proportions given in AS 3700 Table 10.1 for the generic types of masonry units will achieve the implicit bond strength of 0.20 MPa in that standard.
- Using the same mix proportions, adequate levels of bond strength were obtained with the portland and blended cements tested.
- There is a significant increase in bond strength with age and that the assumption of the 7-day flexural strength as the final strength may be unduly conservative.
- Increasing the cement content of the mortar mix produced higher bond strength.
- Increasing the cement content and matching the mix composition with the masonry unit may enable the use of a significantly higher value of bond strength provided special class masonry is specified.
- Water thickener admixtures as specified in AS 3700 should be specified and used
- Overdosing of mortar with air entraining agents reduces bond strength.
- The use of mixes incorporating lime is beneficial.
- Sands for masonry mortar should be clean and free of clay content. The sand should be well graded with a difference between the percentage retained on successive sieves of not more than 50% except for the 150-µm and 300-µm sieves where the difference should be 25%. The fine fraction should not exceed 10%. The coarse fraction (percentage retained on the 4.75-mm and 2.36-mm sieves) should not exceed 1%.

PRACTICAL CONSIDERATIONS

Recommended practices for mixing mortar and constructing masonry to achieve good bond strength include:

- Bricklayers should ensure that the mortar composition matches the masonry unit. Factors to be considered include type and suction characteristics of the masonry unit, sand grading, inclusion of lime and use of admixtures.
- Water thickening admixtures should be used where appropriate, eg in mortar for concrete units.
- Air entraining admixtures, if used, should be in accordance with the manufacturer's recommendations. Overdosing of mortar with air entraining agents reduces bond strength.
- Use of detergents, drinks, sugars and the like must not be allowed. They destroy bond strength. AS 3700 specifically bans these substances as admixtures.
- Lime contributes to the volume of fines in the mortar which enhances workability and cohesion and promotes adhesion at the interface.
- Only clean, sharp sand free of clay content should be used. Clay (fire clay) should not be added to the sand or to the mortar mix. This reduces the bond strength.
- One of the most significant sources of problems with bond strength is poor construction techniques. Bad practices such as incomplete filling of joints and laying pressed bricks with the frog down adversely affect bond strength. Also, stringing out too much mortar in a course before placing the bricks on it allows the loss of too much moisture to the lower course and consequently weakens the bond to the upper course. Dampening or wetting the unit prior to laying reduces the suction of the unit which leads to poor bond. It is better to proportion the mortar to match the suction characteristics of the units.
- Movement of the units after initial contact with the mortar is a common problem leading to inadequate bond strength. This has the effect of causing a rounding of the upper surface of the mortar bed, because of the stiffening from moisture being sucked into the lower course of units. This rounding will prejudice the formation of bond at the interface adjacent to one or both faces of the unit, and these areas are the most critical under out-of-plane bending forces. Any disturbance of units more than a few seconds after placement should be avoided.
- The simplest way of batching mortar is to use a mixer with a known volume and add to it known volumes of cement and lime such as a full or part bag. The mixer can then be filled with sand and a suitable quantity of water to produce a mix of the correct volumetric proportions. The correct quantity of water is best left to the bricklayer because the research indicates that bond strength is enhanced by the presence of water, up to the limit of workability of the mortar.

  A minimum mixing time of six minutes is recommended because shorter times can produce strength and colour variations in the mortar. While there is no recommended maximum, it is particularly important that mortars with air-entraining admixtures should not be over-mixed. Extended mixing of these mortars will entrain too much air and lead to very low bond strength.
- The most effective method of quality control is regular site inspections to ensure that good practices have been followed. Tests are required for masonry that is nominated as Special Masonry with bond strength higher than the AS 3700

implied value of 0.2 MPa. In this case, the bond wrench is used for testing, as described in AS 3700 Appendix D.

- In addition to specifying that mortar must comply with AS 3700, designers and specifiers must also ensure that the required performance will be achieved with the materials specified. A high value for design bond strength should not be assumed without matching the units and the mix composition of the mortar with which the masonry work is to be constructed.

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