ABSTRACT

This paper presents an experimental investigation of the flexural and shear bond characteristics of thin layer polymer cement mortared concrete masonry. It is well known that the bond characteristics of masonry depend upon the mortar type, the techniques of dispersion of mortar and the surface texture of concrete blocks; there exists an abundance of literature on the conventional 10 mm thick cement mortared masonry bond; however, 1 mm-4 mm thick polymer cement mortared masonry bond is not yet well researched. This paper reports a study on the examination of the effect of mortar compositions, dispersion methods and unit surface textures to the flexural and shear bond characteristics of thin layer mortared concrete masonry. A non-contact digital image correlation method was adopted for the measurement of strains at the unit–mortar interface in this research. All mortar joints have been carefully prepared to ensure achievement of the desired thin layer mortar thickness on average. The results exhibit that the bond strength of thin mortar layered concrete masonry with polymer cement mortar is higher than that of the conventional masonry; moreover the unit surface texture and the mortar dispersion methods are found to have significant influence on the flexural and shear bond characteristics. From the experimental results, a correlation between the flexural and the shear bond strengths has been determined and is presented in this paper.

Keywords: Thin layer mortared concrete masonry, Flexural bond strength, Shear bond strength, Polymer cement mortar, Digital image correlation, Concrete block
1.0 INTRODUCTION

Thin polymer cement mortar layered concrete masonry structural walls can offer significant productivity gains to the masonry industry through the development of a masonry construction technology suitable for onsite construction that does not require highly skilled masons and hence could address the severe problem of skills shortage. Thinner layer of mortar cannot be achieved without stringent control of the height of the concrete blocks. Currently blocks are available with height tolerance of ±2mm; however for thin layer mortared masonry, much tighter tolerance would be required, which could only be achieved through a process of grinding the moulded and cured blocks. Grinding will alter the surface condition of the units – this variable was, therefore, included in this investigation.

For the development of the thin layer mortared concrete masonry construction, a fundamental understanding of its basic bond characteristics is essential. To date the bond development in thin mortar layered masonry is not well understood; therefore, an extensive series of bond tests were carried out with particular focus on the shear and flexural bond strengths of thin mortar layered concrete masonry by considering the block surface roughness, mortar application methods and the polymer content in the mortar as variables.

The results show that the bond strength of thin layer mortared masonry is affected by the surface texture of blocks; the smoother the surfaces the better the bond. A regression analysis shows that the shear bond strength of thin layer mortared masonry is approximately equal to its flexural bond strength.

2.0 REVIEW OF MASONRY BOND

Bond strength is essential for appropriate structural performance of masonry walls, especially those under the lateral loading, including wind and earthquake. In the conventional masonry, the bond between the units and the cementitious mortar is derived from the penetration of the cement hydration products, such as the calcium silicate hydrates in the mortar, into the units through the surface voids and pores.

Major factors that influence the bond between the mortar joints and masonry units, both in the conventional and thin mortar layered masonry are (1) the type of mortars (mix design, workability, water retention, setting characteristics and air content), (2) the type of masonry
unit (absorption characteristics and the surface texture/roughness) and (3) workmanship (quality of filling the valleys of the unit surface, degree of pressure applied to masonry unit and the type of tooling used and productivity achieved).

To maintain uniform thin joint thickness, special tools are often used to control the rate of discharge of mortar. Although these tools might control the volume of mortar discharged over a short period of time, depending on the unit surface roughness (depth of valleys) and the pressure applied to fill the mortar into these valleys (thereby avoiding entrapped air), the response of the bond to flexure and shear will vary. Since the thin mortar layered masonry is relatively new, only few studies have been carried out on the bond behaviour of this form of masonry. Among the few studies that have been carried out so far on this form of masonry, it has been found that the characteristics of thin polymer cement mortar layered mortar and those of the unit constituents enhance the bond strength and in many instances exceed the modulus of rupture of unit (Marrocchino et al., 2009). Marrocchino et al., 2009, Nicholas et al., 2008, and Kanyeto and Fried 2011 conducted flexural tests on thin mortar layered dense concrete masonry with polymer modified mortar and have independently concluded that the flexural strength of thin mortar layered masonry is two to three times higher than those specified in the British code of practice (BS 5628, 1992) compared to conventional mortars.

Commonly thin mortar layered masonry mortars contain polymers; depending on the proportion of polymers in the mortar, the process of gaining bond strength differs. Polymer mortars undergo polymerisation in the presence of water. Dry curing is said to improve polymerisation and the strength of mortar (Colville et al., 1997); because, the film produced due to polymerisation can block the pores and seal the moisture into the young mortar and avoid escaping to the atmosphere; the initial water added is thereby retained and is available for the hydration of the cement in the mortar. In other words, unlike the non-polymer/cementitious mortars that cure well under moist condition, polymer mortars will not require additional moisture for curing, which is an advantage for its sustainability. Due to these fundamental differences between the polymer based and the conventional mortars in masonry applications, it appears prudent to characterise the flexural and shear bond strengths of the thin mortar layered concrete masonry. The research reported in this paper is part of an ongoing investigation into the complex mechanisms of the thin mortar layered masonry bond.
Since the flexural and shear bond strengths are important parameters for the design of masonry, especially for the in-plane and out-of-plane flexure and shear of masonry walls, in the past many attempts have been made to understand the bond characteristics in conventional masonry. Various test set-ups have been used for the characterisation of tensile and shear bond behaviour of the unit-mortar interface. These include (1) uniaxial tensile test on couplets (2) four-point beam tests and (3) bond wrench pier tests. For the evaluation of the flexural bond response of masonry, four-point beam test and bond wrench pier tests are commonly practiced. Obtaining the pure shear condition in the joint is more challenging. Van der Pluijm (1993) proposed a test set-up which minimises bending stresses at mortar-unit interface, however this set-up is quite complex and is not used in this research. Couplet and triplet tests are widely used to determine the shear bond strength of masonry.

The parameters influencing the bond strength are the consistency of mortar, additives in mortar and treatments of the unit surfaces were examined by Sarangapani et al., 2005. They’ve showed that it is important to use either a high-cement mortar or a mortar with plasticising additives to produce better bonding in the conventional masonry. They also concluded that the surface texture of the units affects the bond strength.

Reddy and Gupta (2006) showed that smooth surface (with many finer pores) on the surface of the units lead to increase in bond strength. This is because surfaces with many finer pores (smoother surface) can be uniformly ‘coated’ with mortar relatively easier than the surfaces containing fewer - however larger pores (rough surface) – given the pressure of application the same. A similar finding was also noted from the studies on dental plaster bond reported by Ariyaratnam et al., 1999 and Leong et al., 2006 where the bond strength was shown significantly influenced by the surface characteristics – with the smoother surfaces exhibiting higher bond strength.

Many other conventional masonry bond studies are also reported in the literature (Rao et al., 1996; Lim and Lissel 2011; Almeida et al., 2002; Khalaf 2005; Lawrence et al., 2005; Azeredo and Morel 2009; Reddy et al., 2007; Reddy and Gupta 2006; Reddy and Vyas 2008; Walker 1999), where each author has used different bricks/blocks and mortar types in their examination of various parameters that affect the bond strength of the conventional masonry containing 10mm cement –lime mortar. Similar studies on thin mortar layered masonry are fewer, if any and hence this study. In the present study, an attempt is made to
characterise the bond strength of thin mortar layered concrete masonry using various combinations of blocks and polymers; all work has been carried out in various laboratories of the Queensland University of Technology, Australia.

### 3.0 EXPERIMENTAL PROGRAM

The primary purpose of this investigation is to determine the flexural and shear bond characteristics of thin polymer cement mortar layered concrete masonry, with due consideration to the parameters influencing the bonding between the surfaces of concrete unit and mortar. The flexural bond strength was determined using four point bending (beam) test using the provisions for the conventional masonry in ASTM E513 (2003) and AS 3700 (2001). To determine the shear bond strength; the triplet test for the conventional masonry provided in BS EN 1052-3 (2002) has been adopted.

The effects of the surface textures of the concrete unit, polymer mortar types and mortar application methods to the thin mortar layered masonry bond have particularly been examined.

#### 3.1 Surface textures

Solid concrete blocks (390 mm× 90 mm× 90 mm) were cut into 45 mm×90 mm× 90 mm slices using a diamond saw cutter of blade thickness approximately 2 mm. The characteristics of the cut surfaces of the concrete unit were altered as follows:

1. **Ground (smoother) surface**: The 220 abrasive silicon carbide powder was used on a grinding machine to grind the blocks (each side of the surface was ground for 2 minutes to maintain consistency of the surface).
2. **Sand blast (rougher) surface**: The Garnet (30-50 mesh) was used in sand blasting with 500 kPa pressure (each unit surface was sand blasted for 15 seconds).

Therefore, along with the freshly cut surface, three surface textures were used in the experimental investigation.

To quantify surface texture variation of the concrete units, the roughness of the three prepared surfaces were measured using a Talysurf stylus machine (Figure 1) which is widely used for metal tribological applications (Caliskan, et al., 2002; Abu-Tair et al. 2000). The
functional procedure of Talysurf stylus machine is as follows: a sharp stylus is tracked slowly across the surface and the up and down movement of stylus is recorded.

The term roughness average ($R_a$) is used to describe the irregularities of the surface texture, which is the measure of the arithmetic mean of the deviation between the measured vertical profile and the average profile. The typical unit surface roughness profiles obtained from the block surface measurements are presented in Figure 2.

![Figure 1: The view of Talysurf stylus surface measurement machine](image)

Six random blocks surfaces were selected from each type (Cut, Ground, and Sand blasted) of the prepared unit surfaces and roughness was measured in two perpendicular directions on each specimen. Therefore 12 roughness measurements were made for each unit surface type to obtain the average roughness value. Table 1 presents the average roughness values of three prepared surface. It can be seen from the table, the sand blasted surface has the highest roughness value and ground unit surface has the lowest roughness value. Therefore, surface treatment methods have altered the unit surface textures.

<table>
<thead>
<tr>
<th>Type of concrete unit surface</th>
<th>Number of measurements</th>
<th>Average Roughness $(\mu m)$</th>
<th>COV(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground with silicon carbide powder</td>
<td>12</td>
<td>2.74</td>
<td>13.7</td>
</tr>
<tr>
<td>Diamond cut</td>
<td>12</td>
<td>4.57</td>
<td>11.5</td>
</tr>
<tr>
<td>Sand blasted</td>
<td>12</td>
<td>6.13</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Table 1: Average Roughness values of three prepared concrete unit surfaces
Figure 2: A Typical unit surface roughness profiles (a) Cut (b) Ground (c) Sand Blasted

3.2 Mortar mix

Polymer cement mortars were supplied by Rockcote Australia. These mortars were supplied as dry powder in air-tight containers with specified blend of all ingredients; only water was required to be added at site. Three types of polymer cement mortars, each with 2%, 3% or 4% polymer content by volume were chosen. Although better to be consumed once opened, as long as the air-tight lid is well locked immediately after retrieval of the required quantity of mortar mix, it was found that the mortar can be reused with good workability and consistency; mortars were kept for up to 90 days.
The polymer mortar mixes (with 2%/ 3%/ 4% polymer content each) were tested for compressive and flexural strength as per BS EN 196-1:2005. Both the compressive and the flexural strengths were found to increase with the increase in polymer content. The mean compressive strength (coefficient of variation in parenthesis) of the mortar mixes containing 2%, 3% and 4% polymer content was determined as 5.26 MPa (6.0%), 5.42 MPa (11.0%) and 5.75% (7.0%) respectively. The mean flexural strength (coefficient of variation in parenthesis) of the mortar mixes containing 2%, 3% and 4% polymer content was determined as 2.76 MPa (18.0%), 2.87 MPa (14.0%) and 2.98% (14.0%) respectively. It is remarkable to note that (1) the mean flexural tensile strength of the polymer mortar is more than 50% of its mean compressive strength (in conventional mortars flexural tensile strength is in the order of 10% of its compressive strength) and (2) almost linear trend with the increase in these two strengths for the increase in polymer content.

3.3 Method of application of mortar

To examine the influence of the method of application/ usage of tooling, four techniques of mortar dispersion were adopted: (1) brushing (2) roller discharging (3) dipping of units into the mortar bucket and (4) traditional trawelling.

3.4 Masonry Specimen Preparation

The mortar was mixed with a ratio of 250 ml of water to 1 kg of dry mortar mix. This amount of water was finalised after several trials of mortar mixing from the perspective of consistency of mix and workability. All three polymer modified mortars (2%/ 3%/ 4%) were mixed to a workable condition and appropriate consistency commensurate to proper application. The data provided in section 3.2 on the mean compressive and flexural tensile strengths of these mortars correspond to this water – polymer mortar ratio.

The average mortar joint thickness achieved in the constructed specimens was determined by subtracting the specimen lengths from the stack length of seven blocks (for beams) and three blocks (for triplet); the stack lengths of seven blocks (for beams) and three blocks (for triplets) were determined prior to mortar application. It was found that the mortar joint thickness was achieved with an accuracy of ±0.2 mm, which is attributed to the method and the skills adopted.
To construct the specimen without misalignment of units, L shaped rig boards as shown in Figure 3(a) were prepared and the specimens were constructed on the edges of the board. The specimens were weighed and then were fully covered with plastic sheets to prevent moisture loss and cured until were ready for testing see Figure 3(b).

![Beam specimens](image1.png) ![Triplet specimens](image2.png)

**Figure 3: Specimens left for curing**

With three surface textures, three mortar types and four methods of application, there were 36 combinations available. For the flexural bond study all possible combinations were examined, which resulted in 108 beams (3 beams for each of the 36 combinations). For the shear bond tests, only the two types of application methods were considered based on the results of the flexural bond studies, which reduced the number of combinations to 18. Allowing three triplets for each combination, a total of 54 triplets were prepared and tested. Whilst more replicates for each combination would be desirable, the rather large number of combinations restricted the number of replicates to just three in this investigation; authors carry out separate study on the effect of number of specimens and variability of the bond performance of thin mortar layered masonry. The dimensions of beam and triplet specimens are illustrated in Figure 4. Each specimen (beam or triplet) was provided with a unique name as presented in Table 2.

**Table 2: Naming convention of Specimens**

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Trowel(T)</th>
<th>Brushing(B)</th>
<th>Dipping(D)</th>
<th>Roller(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground (G)</td>
<td>2% 3% 4%</td>
<td>2% 3% 4%</td>
<td>2% 3% 4%</td>
<td>2% 3% 4%</td>
</tr>
<tr>
<td>Cut (C)</td>
<td>CT2 CT3 CT4</td>
<td>CB2 CB3 CB4</td>
<td>CD2 CD3 CD4</td>
<td>CR2 CR3 CR4</td>
</tr>
<tr>
<td>Sand Blasted (S)</td>
<td>ST2 ST3 ST4</td>
<td>SB2 SB3 SB4</td>
<td>SD2 SD3 SD4</td>
<td>SR2 SR3 SR4</td>
</tr>
</tbody>
</table>
Moreover to avoid steel platen contact on to the masonry specimen, which can cause premature bearing failure, timber pieces were inserted between the specimen and the support/loading steel plates. Testing of all specimens was carried out within 7-10 days after construction. All tests were performed in a 50 kN Instron machine and the loading was recorded with 0.0001 kN precision using the displacement speed of 0.3 mm/min.

![Figure 4: Test setups](image)

(a) Beam specimen  
(b) Triplet specimen

Figure 4: Test setups

![Figure 5: Typical Test set-up.](image)

The deformation of the specimens was monitored through digital imaging. A digital SLR camera (EOS 1000D) was used for the purpose; the camera was attached to a tripod at a distance to provide clear coverage of the specimens, especially the unit – mortar interface. Once the shear triplet was placed under the testing rig and properly aligned, the digital camera was set up approximately parallel to the specimen on a tripod in such a manner it provides good coverage of the test specimen (Figure 5).
The camera was connected to a computer that controlled the shutter through special purpose software specific to the camera. Each test took approximately 2-3 minutes; digital images were taken at 5 seconds interval. A total of 30-40 images were obtained from each test and used in the deformation analysis.

4.0 RESULTS AND DISCUSSION

4.1 Failure modes of beam and shear specimens

All specimens failed through mortar unit interface as shown in Figure 6.

![Figure 6: Typical failure pattern.](image)

Since mortar thickness is thin (2 mm), it was difficult to ascertain whether the failures occurred through mortar or through the interface. For low polymer content, sudden failure through the interface was noticed. However, as the polymer content increased to 4%, the specimens failed in a more not sudden manner with the specimens exhibiting capability of holding the maximum load for reasonable period of time.

4.2 Flexural Bond strength

The characterisation of flexural bond strength in thin mortar layered concrete masonry was studied through the beam test for different combinations of polymer mortars, unit surface textures and mortar application methods. The average flexural bond strengths and the corresponding coefficient of variations determined from each group of test specimens are given in Table 3.
Table 3: Flexural bond strength.

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>TROWEL</th>
<th>BRUSHING</th>
<th>ROLLER</th>
<th>DIPPING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT2</td>
<td>GT2</td>
<td>ST2</td>
<td>CB2</td>
</tr>
<tr>
<td>Average(MPa)</td>
<td>1.1</td>
<td>1.15</td>
<td>0.67</td>
<td>1.07</td>
</tr>
<tr>
<td>COV/(%)</td>
<td>9.09</td>
<td>7.09</td>
<td>35.4</td>
<td>17.66</td>
</tr>
<tr>
<td>Combination</td>
<td>CT3</td>
<td>GT3</td>
<td>ST3</td>
<td>CB3</td>
</tr>
<tr>
<td>Average(MPa)</td>
<td>1.18</td>
<td>1.2</td>
<td>0.71</td>
<td>1.33</td>
</tr>
<tr>
<td>COV/(%)</td>
<td>17.49</td>
<td>15.36</td>
<td>52.01</td>
<td>23.78</td>
</tr>
<tr>
<td>Combination</td>
<td>CT4</td>
<td>GT4</td>
<td>ST4</td>
<td>CB4</td>
</tr>
<tr>
<td>Average(MPa)</td>
<td>1.21</td>
<td>1.23</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>COV/(%)</td>
<td>12.55</td>
<td>30.72</td>
<td>10.26</td>
<td>8.54</td>
</tr>
<tr>
<td>TEXTURE</td>
<td>As Cut</td>
<td>Ground</td>
<td>Sand</td>
<td>As Cut</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>blasted</td>
<td></td>
</tr>
</tbody>
</table>
The results clearly reveal that the flexural bond strength of thin mortar layered concrete masonry is higher compared to conventional masonry. The average flexural bond strength of thin mortar layered concrete masonry varies between 0.42 MPa to 1.37 MPa in this investigation. From Lawrence et al (2005) and Masia et al., (2012) and other data generated in this research, it can be stated that the thin mortar layered masonry flexural bond strength is approximately twice that of the conventional masonry bond strength. The higher ratio of the flexural to compressive strength of the polymer mortar reported in Section 3.2 could have contributed to this increase in bond strength observed – this matter is of further ongoing research.

It can be seen that the rougher (sand blasted) surfaced specimens consistently show substantially lower bond strength. Smooth (Ground) surfaced specimens have achieved the highest bond strength irrespective of the method of application and also have shown less sensitivity to the polymer content. This finding is consistent with the studies from dental plaster bond by Ariyaratnam et al., 1999 and Leong et al., 2006 The ‘valleys’ at the rough surface interface might create stress concentration during the loading lead to those specimens failing in lower bond strength levels. Reddy and Gupta (2006) concluded similarly for soil-cement block masonry. Therefore it is clear that the method of application (workmanship) and the surface textures are more important than the polymer content in the mortar itself.

Thin mortar layered concrete masonry requires tightly controlled dimensions (especially heights) of the concrete units; in order to achieve the desired tolerance of height, units must be ground. This process will add cost to the unit manufactures, however from the results shown above it can be concluded that the ground units would improve the bond strength with proper application method.

4.3 Shear Bond strength

Since four application methods have been tried in the flexural bond strength study (resulting in 108 specimens) and two of the methods that either outperformed the others or resulted poor in flexural bond strength. Therefore for shear bond strength studies only brushing (highest flexural bond strength) and dipping (lowest flexural bond strength) methods were considered.
Table 4 provide shear bond strength results obtained from different block-mortar combinations and application methods. It can be seen from the table that the shear bond strength remains higher in thin mortar layered concrete masonry construction containing polymer mortar relative to the conventional masonry.

<table>
<thead>
<tr>
<th>Combination</th>
<th>CB2</th>
<th>GB2</th>
<th>SB2</th>
<th>CD2</th>
<th>GD2</th>
<th>SD2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average(MPa)</td>
<td>1.14</td>
<td>1.05</td>
<td>0.72</td>
<td>0.6</td>
<td>0.82</td>
<td>0.5</td>
</tr>
<tr>
<td>COV(%)</td>
<td>6.56</td>
<td>12.26</td>
<td>5.91</td>
<td>5.9</td>
<td>31.44</td>
<td>5.62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combination</th>
<th>CB3</th>
<th>GB3</th>
<th>SB3</th>
<th>CD3</th>
<th>GD3</th>
<th>SD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average(MPa)</td>
<td>0.99</td>
<td>1.07</td>
<td>0.71</td>
<td>0.88</td>
<td>0.98</td>
<td>0.66</td>
</tr>
<tr>
<td>COV(%)</td>
<td>40.59</td>
<td>10.65</td>
<td>6.61</td>
<td>22.98</td>
<td>22.14</td>
<td>7.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combination</th>
<th>CB4</th>
<th>GB4</th>
<th>SB4</th>
<th>CD4</th>
<th>GD4</th>
<th>SD4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average(MPa)</td>
<td>1.23</td>
<td>1.29</td>
<td>0.79</td>
<td>0.91</td>
<td>1.06</td>
<td>0.69</td>
</tr>
<tr>
<td>COV(%)</td>
<td>1.82</td>
<td>7.05</td>
<td>4.65</td>
<td>24.34</td>
<td>13.69</td>
<td>5.35</td>
</tr>
</tbody>
</table>

The average shear bond strength of the triplets has varied between 0.5 MPa to 1.29 MPa in this study. Similarly to the flexural bond strength, it can be stated that the thin mortar layered masonry shear bond strength is approximately twice that of the conventional masonry bond strength. It can be seen that the higher the polymers content in mortar, the higher is the shear bond strength; this is analogous to flexural bond strength characteristics. The increase in shear bond strength is prominent for ground unit texture specimens. On the other hand, cut and sand blasted (rounder surfaced) unit specimens did not depict noticeable increase in shear bond strength as the polymer content increases.

From the three surface textures examined in this shear bond strength study, sand blasted surface texture unit combinations gave the lowest bond strength and ground unit surface gave the highest shear bond strength. This has to be ascribed that the use of rough surface units with the polymer mortar did not lead to a complete adhesion of the mortar layered joints contrary to the use of smooth unit surface with the polymer mortar, thus aligning with the findings of other researchers.
5.0 RELATIONSHIP BETWEEN SHEAR AND FLEXURAL BOND STRENGTH

Fig 7: Relationship between flexural and shear bond strength

In the present study, a regression analysis from the experimental data is made to establish a linear relationship between the flexural and shear bond strength of thin polymer cement mortar layered concrete masonry. Given the complexity of bond formation in masonry and materials used, some level (30% COV) of spread in bond strength results is acceptable. To avoid the bias prediction of a relationship, the highly scattered data from shear and flexural bond strength are omitted in the analysis. Furthermore the mean shear and flexural bond strength values are used in this analysis to derive the correlation (Figure 7). The regression equation obtained from the analysis is as follows:

\[ f_{ms} = 1.0955f_{mt} - 0.0032 \]  

Where \( f_{ms} \) and \( f_{mt} \) are the mean shear and flexural bond strength respectively. The adequacy of the regression analysis has been verified through checking the coefficient of multiple determination \( R^2 = 0.8956 \), which is acceptable for bond studies. This relationship can be taken in design of thin polymer cement mortar layered concrete masonry walls using polymer based mortars, when only one of the bond strengths is known. However, other parameters which affect the bond strength such as mortars workability, water retention, setting characteristics, air content and masonry unit absorption characteristics are to be investigated.
to validate this relationship to finally derive a correlation between shear and flexural bond strength for thin polymer cement mortar layered concrete masonry.

The Australian masonry standard AS 3700 provides a correlation between shear bond strength and flexural bond strength for design purpose for conventional masonry, which is $f'_{ms} = 1.25f'_{mt}$ where $f'_{ms}$ and $f'_{mt}$ are the design characteristic shear bond strength and design characteristic flexural bond strength respectively. However, for thin polymer cement mortar layered masonry there is no relationship between shear and flexural bond strength is provided in the code. Recently Masia et al., (2012) checked existing Australian standard correlation between shear bond and flexural bond strength with different mortars and units, and reported large scatter for shear bond strength and flexural bond strength in conventional masonry and in some cases shear bond strength is well below the flexural bond strength.

Also from the present study for thin polymer cement mortar layered concrete masonry, the relationship between shear bond and flexural bond does not match with AS3700 guidelines. Therefore the general practice of taking shear bond strength is 25% higher than flexural bond strength for design in Australian masonry design standard (AS3700) should be relooked.

6.0 DEFORMATION CHARACTERISTICS

The deformation measurements were performed at the unit-mortar interfaces using digital image correlation (DIC) method. As illustrated previously in section 3.4, the shear strains at unit-mortar interface have been measured for the triplet specimens and the average strains are plotted against the relevant stress values.

6.1 Method of deformation measurement

In recent years non-contact deformation measurement methods have become popular in many engineering applications; DIC is one such method. A special class of DIC, known as Particle Image Velocimetry (PIV), was developed for measuring velocity of fluids at Cambridge university, UK (Adrian 1991); this technique was modified by White et al, (2003) for natural sand particle deformation. Later Thusyanthan et al, (2007) used this technique to measure the strains in clay beam. Fundamentally, this technique predicts strains accurately, provided
‘particles’ (of specific texture and colour) are identified clearly by the algorithm, which depends upon the quality of the digital image recorded during the experiment. More details of the image analysis of deformation can be found in Bandula-Heva & Dhanasekar (2011). Since the specimens sizes are small (reduced block sizes), this method of measuring deformation is much easier than the conventional types of deformation measuring method in this investigation.

The basic principle of DIC analysis is tracking of the same points (or pixels) between two images recorded before and after deformation as schematically illustrated in Figure 8. The coordinates of mid points of each patch of each successive image are determined by the algorithm through calibration of the distance between the pixels to a standard distance measure. The initial distance between the selected two points is first determined from the reference image. The distance between the two points during the deformation of the specimen is obtained from the successive deformed images.

![Figure 8: Schematic illustration of basic principle in DIC analysis.](image)

In the DIC analysis, the digital image is divided into a grid of patches as shown Figure 9. The size of the patch and the distance between patches were decided depending on the purpose of measurement. A set of coordinates of the patch centre locations for each of the successive images is first generated. The displacement vector in the centre of each patch during the interval between successive images is found by locating the peak of autocorrelation image.
function of each patch. The peak in the autocorrelation function indicates that two images of each particle captured in the images exactly overly on each other. Therefore the correlation offset is equal to the displacement vector. The surface strain field is thus determined from Equations (1) – (3).

\[ \varepsilon_{xx} = \frac{\partial u_x}{\partial x} = \frac{(a_i - a_0') - (a_i - a_0)}{(a_i - a_0)} \]  
\[ \varepsilon_{yy} = \frac{\partial u_y}{\partial y} = \frac{(b_i' - b_0') - (b_i - b_0)}{(b_i - b_0)} \]  
\[ \gamma_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} = \frac{(a_i - a_0) - (a_i - a_0)}{(b_i - b_0)} + \frac{(b_i' - b_0') - (b_i - b_0)}{(a_i - a_0)} \]  

6.2 Deformation plots of beam and triplet Specimens
Digital images taken at 5 second intervals from start to the end of each test (as described in Section 3.4) resulted in a total of 30-40 images for each test. These images were analysed to obtain strain information. The procedure of analysing the digital images is illustrated through typical example shown in Figure-9 for triplet shear specimens.

Mid points of two patches \(P_i\) and \(Q_i\), were selected (refer to Figure 9) to analyse the shear strain at unit-mortar interface of triplets. In order to calculate the shear strain, the vertical
coordinate differences between the points \( P_1-Q_1 \) and the horizontal coordinate differences between \( P_1-Q_1 \) (in every successive image from initial undeformed image) were considered and the shear strains were calculated using equation (3). A zone of 45mm \( \times \) 80mm was chosen for the analysis for both beam and triplet specimens. For triplet the zone was divided into 11 \( \times \) 11 patches, with the size of a typical patch as 50\( \times \)50 pixel.

Almost all the combinations exhibit similar deformation behaviour, which is around 2500-3000\( \mu \) ultimate shear strain. The evaluation of the shear stress versus the shear strain at the unit mortar interface with different specimen combinations are presented in Figure 10 from digital image analysis technique. Only the deformation plots of CB, GB and SB specimens with different polymer contents are presented in this paper. One should note that the post-peak deformation behaviour could not be captured from the image deformation analysis, because the shear triplets failed suddenly once cracked in the unit-mortar interface.
Figure 10: Shear stress vs. Shear strain at unit-mortar interface.

The secant shear modulus was calculated at one third of the peak shear stress (Figure. 10) and is presented in Table 5. It can be seen, as depicted in shear bond strength the shear modulus also varied in similar analogy. The cut and ground block (smoother surfaced) specimens showed higher shear modulus than the sand blasted (routher surfaced) specimens. This can be attributed to the lower bond strength showed the way to lower modulus and higher bond strength lead to higher shear modulus. The results show generally the higher bond strength specimens demonstrate higher shear modulus.
Table 5: Average secant shear modulus of specimens

<table>
<thead>
<tr>
<th>Application</th>
<th>Brushing</th>
<th>Dipping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination</td>
<td>CB2</td>
<td>GB2</td>
</tr>
<tr>
<td>Secant shear modulus (MPa)</td>
<td>333.3</td>
<td>363.6</td>
</tr>
<tr>
<td>COV(%)</td>
<td>28.7</td>
<td>14.3</td>
</tr>
<tr>
<td>Combination</td>
<td>CB3</td>
<td>GB3</td>
</tr>
<tr>
<td>Secant shear modulus (MPa)</td>
<td>340</td>
<td>388.9</td>
</tr>
<tr>
<td>COV(%)</td>
<td>35.2</td>
<td>11.4</td>
</tr>
<tr>
<td>Combination</td>
<td>CB4</td>
<td>GB4</td>
</tr>
<tr>
<td>Secant shear modulus (MPa)</td>
<td>378.8</td>
<td>463</td>
</tr>
<tr>
<td>COV(%)</td>
<td>15.7</td>
<td>19.4</td>
</tr>
<tr>
<td>Texture</td>
<td>As Cut</td>
<td>Smooth</td>
</tr>
</tbody>
</table>

7.0 CONCLUSIONS

In an attempt to characterise the bond strength of thin polymer cement mortar layered concrete masonry, a total of 108 beam and 54 triplet specimens were tested to determine the flexural and shear bond strength respectively. Various combinations of polymer mortar types, unit surface textures and mortar application techniques were used in preparing the specimens.

The beam specimens were tested under four-point bending in an Instron machine under displacement control and the triplets were tested as per BS EN 1052-3. In addition, this investigation adapted a method of surface roughness measurement of concrete units. Furthermore a method of non-contact deformation measuring technique through digital image analysis called PIV was tried in this investigation to better understand the thin polymer cement mortar layered concrete masonry bond behaviour.

The following conclusions were made:

(1) Polymer mortars can be used in thin polymer cement mortar layered concrete masonry to improve the bond strength in masonry. Polymer mortars exhibit flexural tensile strength as high as 50% or more of its compressive strength; even 2% polymer in mortar mix is found to be quite effective.
(2) The flexural and shear bond strength of thin polymer cement mortar layered masonry containing polymer mortar is consistently higher than conventional masonry. As the polymer content increases, the bond strength has increased.

(3) Where the polymer content increases in the mortar, the failure was more less brittle than the conventional masonry in flexural failure. Therefore observation of improve in deformation characteristics is encouraging in thin polymer cement mortar layered concrete masonry flexural bond behaviour.

(4) Smooth surface textured units have exhibited higher bond strength (both in flexure and in shear) compared to the rough surfaces. The ability of filling the valley in rough surfaces without entrapped air pocket is limited in the methods of applications investigated; the methods work better and provide well mortared surface in smooth textured units and hence the increase.

(5) Digital image correlation technique can be used to measure the deformation of the triplets masonry specimens.

(6) A regression analysis has shown that the shear and the flexural bond strengths were found approximately equal to each other. The scatter in the bond strength data is common in masonry studies. This relationship should be further examined as it contradicts the AS3700 (2011) provision of the shear bond strength being 25% larger than the flexural bond strength.

The bond between the mortar and the masonry units is one of the most important properties of masonry construction perhaps the most essential factor. The present study is helpful to better understand bond formation in thin mortar layered concrete masonry systems, where it can lead ultimately to develop robust thin mortar layered concrete masonry construction systems.
ACKNOWLEDGMENT

The authors thank the Australian Research Council for the financial support to this project (LP0990514) and Queensland University of Technology provided technical support. The support from the industry partners Adbri Masonry and Rockcote for providing the required concrete blocks and the cement mortar are gratefully acknowledged.

REFERENCES


European Standard. 2002. *BS EN 1052-3 Methods of test for Masonry*


