THE EFFECTS OF MOISTURE ON COMPRESSION STRENGTH AND MODULUS OF BRICK MASONRY

A. M. Amde¹, J. V. Martin² and J. Colville³

Abstract

The effects of moisture on the compressive strength and modulus of elasticity of brick masonry are investigated. Eight prisms per mortar type were constructed, and after an extended period of dry curing, four of the eight prisms were placed in a moist room under a rotating sprinkler system, for the last 48 hours of the curing cycle. The testing involved four different mortar types: Type S masonry cement; Type S Portland cement; and two polymer modified Type S masonry cement mortars. The chord modulus was used to determine the modulus of elasticity. ASTM Standards were followed for the determination of both compressive strength and elastic modulus. The test results showed that the wet/dry ratio for compressive strength had an average value of 0.81 and the corresponding ratio for elastic modulus was 0.88.

Key Words

Modulus, compressive strength, brick masonry, moisture.

1 Introduction

A considerable amount of work has been done in the area of brick masonry compressive strength and modulus of elasticity. Almost all the work, however, has been performed on dry brick specimens, and as a result, very little is documented on the effect of moisture on compressive strength and modulus of elasticity. The current study deals only with brick masonry. A notable early work in the area of compressive strength includes investigations by Fattal and Cattaneo (1976) at the National Bureau of Standards. The study suggested that prisms were good predictors of masonry wall behaviour. Other investigations include, McNary and Abrams (1985), Hilsdorf, H.K.

¹ (Formerly Amde M. Wolde-Tinsae), Professor, Dept. of Civil & Environmental Engineering, University of Maryland, College Park, MD 20742, USA, amde@umd.edu
² Design Engineer, T.Y. Lin International, Alexandria, Virginia, USA.
³ Emeritus Professor, Dept. of Civil & Env. Engineering, University of Maryland.
Houston and Grimm (1972) investigated the influence of prism height (h) to thickness (t) ratio on compressive strength. The current study used the maximum allowable prism h/t of 5. Only one study on the effect of moisture on compressive strength was found. Baker (1909) determined that the wet/dry ratio for compressive strength of brick masonry is about 0.85. Grimm (1999) suggested that poor workmanship coupled with a soaking rain could reduce the factor of safety of clay masonry.

The modulus of elasticity of masonry has also been the subject of much research but none of the previous studies have addressed the effect of moisture on modulus of elasticity of masonry. Prior to 1988, US codes utilized the expression, \( E_m = 1000 f_m' \), to determine the modulus of elasticity of masonry elements, an expression based on concrete codes between 1941 and 1960 (Amde et al, 1993). Since then, a more thorough investigation of that expression has been undertaken, resulting in the current US MSJC Code (2002) of \( E_m = 700 f_m' \). In an extensive study involving published and unpublished data from the US and Canada, Amde, Atkinson, and Hamid (1993) determined that when using compressive strength of brick masonry prisms, the ratio \( E_m/f_m' \) should be about 500, however, when the unit strength method is to be employed, then the ratio of \( E_m/f_m' \) should, in fact, be about 700. This is because the \( f_m' \) values in the MSJC Specifications (2002) are conservative and require a larger multiplier to obtain corresponding modulus values.

This study uses four different types of mortar mixes in masonry prisms and investigates how moisture affects prism compressive strength and modulus of elasticity. The results will show the differences between prisms constructed using Type S masonry cement mortar and Type S Portland cement/lime mortar. The results will also attempt to show whether the adding of the various admixtures actually improves compressive strength and modulus of elasticity under dry and wet conditions.

2 Materials

All the bricks used in this study came from the same cube. Individual units were selected as per ASTM C67 (1998). Mortars were proportioned as per ASTM C 270 (1998). The Type S masonry cement mortar was mixed in a proportion of 1-part masonry cement to 2-parts sand. The Portland cement/lime Type S mortar was proportioned 1-part Portland cement Type I, 2 1/4-parts sand, and 1/2-part lime. The natural mason’s sand used in the mix was first oven-dried and analyzed. In the case of the Polymer Modified Mortars, Type S masonry cement was used, and the two mixes were designated SR67 and SR1044. In this nomenclature, the S represents the type of masonry cement used, the R represents the superplasticizer used, and the final numeric extension identifies the polymer used. The admixtures, all in liquid form, were first diluted in a portion of the mix water before being added to the dry mix. A listing of the admixtures used is shown in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Product</th>
<th>Generic Name</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>Airbond CP-67</td>
<td>Acrylic Emulsion</td>
<td>Air Products</td>
</tr>
<tr>
<td>Polymer</td>
<td>Neocryl A-1044</td>
<td>Acrylic Emulsion</td>
<td>ICI Resins</td>
</tr>
<tr>
<td>Defoaming Agent</td>
<td>Nopco NXZ</td>
<td>Liquid Defoaming Agent</td>
<td>Henkel Products</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>Rheobuild 1000</td>
<td>Naphthalene</td>
<td>Master Builders</td>
</tr>
</tbody>
</table>
3 Specimen Preparation and Testing

3.1 Mortars
The adequacy of the mortar was determined by testing the freshly mixed mortar for initial flow and air content. The initial flow test is used to determine whether the mortar possesses a desirable consistency. This test was performed in accordance with ASTM C 230 (1998), and according to this standard, an initial flow of 115% ± 5% was targeted. While these percentages are targeted in the laboratory, the ASTM C 270 (1998) appendices make it quite clear that construction mortars made in the field could possess flow values in the range of 130-150%. The air content of the mix was determined using the pressure method as per ASTM C 231 (1998). This test gives some measure of the workability of the mortar and to a certain extent, its durability. Air content ranged from 5.75 % for Type S masonry cement mortar to 16.7 % for the polymer modified mortar mix.

3.2 Prisms
Eight prisms were built for each mortar type corresponding to ASTM C1314 (1998). The height to thickness (h/t) ratio used for all the prisms was approximately 5. Also, each prism was numbered 1 thru 4 depending on the order in which it was built, with the batch number, 1 or 2, noted. The prisms were constructed out of cored brick and were seven courses high. Concave 3/8 inch bed joints were used between units. Two separate batches were used to build the eight prisms required per mortar type. This minimized the length of time the mortar was left standing after first being mixed. According to ASTM C 270 (1998) specifications, after 2 1/2 hrs of initial mixing, mortar should be discarded as retempering at that point is considered harmful (ASTM C 270, 1998). Immediately after being built, the prisms remained undisturbed at the site of construction for a minimum of 48 hours, after which time they were placed in a designated area and allowed to air-cure. All prisms were cured for a period between 90 and 97 days. During the last 48 hours of the curing period, four out of eight prisms for each mortar-type were placed in a moist room under a rotating sprinkler system. Capping of the prisms was done at least 14 days into the curing cycle. High strength gypsum cement was used in accordance with ASTM C 1314 (1998).

Prisms were tested for modulus of elasticity and compressive strength. A Universal Testing Machine was used to load the specimens while Linear Variable Differential Transformers (LVDT’s) attached to the prisms were used to determine deformations. Modulus of elasticity was determined using the chord method between the points pertaining to 0.05f_m’ and 0.33f_m’. The average of two readings from two LVDT’s attached to each of the two wide faces of the prisms was used for strain readings. Two calibration cycles were performed for each LVDT to ensure an accurate and reliable relationship between voltage and displacement. Immediately before subjecting the prisms to loading, the LVDT’s were attached to the prisms using miniature L-shaped brackets maintaining a gage length of 16.5 inches.

3.3 Testing
The modulus of elasticity was determined following the ASTM E 111 (1998) specification. The chord modulus was used and it was taken between the points 0.05f_m’ and 0.33f_m’ as defined in the US MSJC Code (2002). Two loading cycles were run to ensure that consistent results were obtained. In the first loading cycle, the load is kept under the elastic range. Two loading rates were used for measuring the modulus. For loads 0-22,241 N (0-5000 lbs), a loading rate of 4,448 N/min (1000 lb/min) was used with LVDT readings taken at 4,448 N (1000 lb) increments. The second loading rate
was 22,241 N/min (5000 l b/min) and it was effective from 22,241 (5000) to the highest applied load. Depending on which mortar mix was being tested, the high load ranged from 155,688 N (35000 lbs) to 289,134 N (65000 lbs). At the 22,241 N/min (5000 lb/min) loading rate, readings were taken every 22,241 N (5000 lbs). After reaching the predetermined high load, the prisms were unloaded, and then the identical loading sequence was repeated, subjecting each prism to a total of two loading cycles. To determine compressive strength, the LVDT’s were detached after the second cycle and the specimens were loaded to failure as per ASTM E 447 (1998).

4 Results

4.1 Type S Portland Cement/Lime Prisms
The PCL prisms were stronger than the MC prisms as expected. The average compressive strength for the dry PCL prisms was 44.53 MPa (6,459 psi), while the average for the wet prisms was 35.32 MPa (5,156 psi). The modulus values ranged from 15,790 MPa to 23,512 MPa (2.29 x 10^6 psi to 3.41 x 10^6 psi) for the dry prisms, cycles 1 and 2, and from 15,376 MPa to 22,685 MPa (2.23 x 10^6 psi to 3.29 x 10^6 psi) for the wet prisms. The average wet and dry moduli were 19,927 MPa (2.89 x 10^6 psi) and 21,650 MPa (3.14 x 10^6 psi), respectively. These results give a wet/dry ratio for compressive strength of 0.80 and a wet/dry ratio for modulus of 0.92, which translates to a 20 % reduction for compressive strength and an 8 % reduction for modulus. The average $E_m/f_m'$ ratio, based on prism compressive strength, was 486 for dry and 560 for wet. When based on the unit strength method of $f_m'$ based on the US MSJC Code, the $E_m/f_m'$ ratios are 785 for dry and 721 for wet. In the MSJC specifications (2002), the maximum value given for $f_m'$ is 27.58 MPa (4,000 psi), corresponding to a unit strength of 91.01 MPa (13,200 psi). The unit strength of the brick used in this study was 98.06 MPa (14,222 psi). A regression analysis on the values in Table 1 of the MSJC Specification (2002) gives a power equation of the form $Y = 5.2064 X^{0.7027}$. This equation provides an $f_m'$ equal to 29.74 MPa (4,313 psi) for a unit strength of 98.06 MPa (14,222 psi) resulting in $E_m/f_m'$ ratio of 728 for dry and 670 for wet. The results are summarized in Table 2.

4.2 Type S Masonry Cement Prisms
The average dry and wet compressive strengths are 37.83 MPa and 32.37 MPa (5,486 psi and 4,694 psi), respectively, while the dry and wet modulus are 2.85 x 10^6 psi and 2.45 x 10^6 psi, respectively. The wet/dry ratio for compressive strength is 0.86, i.e., a 14 % reduction. The wet/dry ratio for modulus was also found to be value 0.86, however, the modulus values for this case were obtained based on a chord modulus between 0.05$f_m'$ and 0.22$f_m'$ because the compressive strength was underestimated.

4.3 SR67 Polymer Modified Mortar
The SR67 polymer mortar showed relatively high compressive strength, however, the modulus seemed to have been more seriously affected by the exposure to moisture. The average dry and wet compressive strengths were 47.13 MPa and 35.73 MPa (6,836 psi and 5,182 psi), respectively. A wet/dry ratio of 0.76 was obtained for compressive strength. For the modulus, the average for the wet was 15,996 MPa (2.32 x 10^6 psi) and for the dry 20,478 MPa (2.97 x 10^6 psi), giving a wet/dry ratio of 0.78. The $E_m/f_m'$ values based on the prism compressive strength are 434 for dry and 447 for wet. In terms of unit strength, two sets of values are given and they pertain to
**Table 2 Summary of Test Results**

<table>
<thead>
<tr>
<th>Project Unit Strength MPa (psi)</th>
<th>98.06 (14222)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_m)' MPa (psi) [from MSJC Code]</td>
<td>27.58 (4000)</td>
</tr>
<tr>
<td>(f_m)' MPa (psi) [from Regression Analysis]</td>
<td>29.74 (4313)</td>
</tr>
</tbody>
</table>

**Properties**

<table>
<thead>
<tr>
<th>Prism Mortar Types</th>
<th>MC</th>
<th>PCL</th>
<th>SR67</th>
<th>SR1044</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_m)' [dry] MPa (psi)</td>
<td>37.83 (5486)</td>
<td>44.53 (6459)</td>
<td>47.13 (6836)</td>
<td>38.81 (5629)</td>
</tr>
<tr>
<td>(f_m)' [wet] MPa (psi)</td>
<td>32.37 (4694)</td>
<td>35.32 (5156)</td>
<td>35.73 (5182)</td>
<td>32.32 (4688)</td>
</tr>
<tr>
<td>(f_m)' [wet/dry] ratio</td>
<td>0.86</td>
<td>0.80</td>
<td>0.76</td>
<td>0.83</td>
</tr>
<tr>
<td>% Red. = (\frac{\text{Dry} - \text{Wet}}{\text{Dry}}) x 100</td>
<td>14</td>
<td>20</td>
<td>24</td>
<td>17</td>
</tr>
</tbody>
</table>

| \(E_m\) [dry] MPa (psi) | 19,651 (2.85E+06) | 21,650 (3.14E+06) | 20,478 (2.97E+06) | 18,754 (2.72E+06) |
| \(E_m\) [wet] MPa (psi) | 16,893 (2.45E+06) | 19,927 (2.89E+06) | 15,996 (2.32E+06) | 18,065 (2.62E+06) |
| \(E_m\) [wet/dry] ratio | 0.86 | 0.92 | 0.78 | 0.96 |
| % Red. = \(\frac{\text{Dry} - \text{Wet}}{\text{Dry}}\) x 100 | 14 | 8 | 22 | 4 |

| \(E_m / f_m\)' (dry) | [\(f_m\)', assemblage strength] | 520 | 486 | 434 | 483 |
| \(E_m / f_m\)' (dry) | [\(f_m\)', unit str. from MSJC Code] | 713 | 785 | 743 | 680 |
| \(E_m / f_m\)' (dry) | [\(f_m\)', from regression analysis] | 661 | 728 | 689 | 631 |

| \(E_m / f_m\)' (wet) | [\(f_m\)', assemblage strength] | 522 | 560 | 448 | 559 |
| \(E_m / f_m\)' (wet) | [\(f_m\)', unit str. from MSJC Code] | 613 | 723 | 580 | 655 |
| \(E_m / f_m\)' (wet) | [\(f_m\)', from regression analysis] | 568 | 670 | 538 | 607 |
The results show that the average compressive strengths for the dry and wet prisms were 5,629 psi and 4,688 psi, respectively, giving a wet to dry ratio of 0.83. There was very little difference between the wet and dry modulus, which gave a very high wet to dry ratio of 0.96. The $E_m/f_m'$ values based on the Unit strength were found to be 654 for the wet, and 681 for the dry using the 4,000 psi maximum value from the MSJC code. Wet and dry $E_m/f_m'$ values of 608 and 631, respectively, were calculated using the $f_m'$ from the regression equation. Using $f_m'$ of the assemblage gave $E_m/f_m'$ values of 558 for wet and 483 for dry.

4.5 Polymer Mortars and Type S PCL Mortar

The results show that the two polymer modified mixes used in this project were of similar compressive strength and stiffness compared to the PCL mortar. In fact, a closer look at the results shows that the SR67 prisms were of almost identical compressive strength and stiffness to that of the PCL prisms, for both dry and wet cases. The SR1044 prisms, on the other hand, gave lower values for both compressive strength and modulus of elasticity of the wet and dry prisms.

4.6 Moisture Effects on Masonry Components

Tests on the individual masonry components showed that the average unit strength for five wetted half brick was 12,765 psi. This marked a 10% reduction in unit strength. In addition, the four mortar mixes used in the prism construction were duplicated and tested under dry and wet conditions. With the exception of the PCL mortar, which underwent a 10% reduction, the reductions in strength were very large, especially for the polymer modified mortars, which experienced reductions of 48% (SR67) and 46% (SR1044). The results for the polymers were somewhat surprising since the presence of the polymers was expected to serve as a sealant against water penetration. The failure to prevent water penetration could be partly explained by the high air content of the mortar mixes. Previous research has shown that the physical properties that are most affected by the addition of polymer admixtures to mortar are the cohesive and adhesive bond properties of the mortar (Amde et al 1995, Amde et al 2003, Colville et al 1995, Colville et al 1999).

5 Conclusions

PCL mortar prisms proved to be very strong in compression, however there is a 20% reduction in compressive strength, and an 8% reduction in elastic modulus due to saturation with moisture. Similar reductions were observed for the prisms with polymer modified mortars. For both the PCL and MC mortars, the results obtained from testing the unit and mortar separately, seem to suggest that the compressive strength reduction in the prism assemblage, due to moisture, is as a result of strength losses in both the mortar (10% PCL and 26% MC) and the unit (10 %). The results indicate that the presence of moisture significantly reduces the compressive strength and modulus of elasticity of masonry. The effect of this reduction on factor of safety should be considered on masonry elements that will be subjected to moisture for an extended period. Also this study concurs with the recommendation that, when $f_m'$ from prism tests is to be used in determining the modulus of elasticity, the relationship put forward by
Amde et al (1993) of $E_m = 500\ f_m'$ gives the best results. When the unit strength method of the US MSJC Specifications is used to determine $f_m'$, then the ratio of $E_m/f_m'$ comes out to be about 700 which is the value specified in the MSJC Specifications. $f_m'$ values based on the unit strength method in the MSJC Specifications (2002) are conservative and require a larger multiplier to obtain corresponding modulus values.

1 References

ACI 530-02/ASCE 5-02/TMS 402-02, 2002, Building Code Requirements for Masonry Structures, Masonry Standards Joint Committee, Detroit, MI/New York, NY/Boulder, CO.

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