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

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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.

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(1969) and Atkinson, Noland and Abrams (1985). 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 1 Admixture List

Type	Product	Generic Name	Manufacturer
Polymer	Airbond CP-67	Acrylic Emulsion	Air Products
Polymer	Neocryl A-1044	Acrylic Emulsion	ICI Resins
Defoaming Agent	Nopco NXZ	Liquid Defoaming Agent	Henkel Products
Superplasticizer	Rheobuild 1000	Naphthalene	Master Builders

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% $\pm$ 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 (5000l 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 $0.05f_m$' and $0.22f_m$' 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

Project Unit Strength MPa (psi)	98.06 (14222)			
f_m' MPa (psi) [from MSJC Code]	27.58 (4000)			
f_m' MPa (psi) [from Regression Analysis]	29.74 (4313)			
Properties	**Prism Mortar Types**			
	MC	**PCL**	**SR67**	**SR1044**
f_m' [dry] MPa (psi)	37.83 (5486)	44.53 (6459)	47.13 (6836)	38.81 (5629)
f_m' [wet] MPa (psi)	32.37 (4694)	35.32 (5156)	35.73 (5182)	32.32 (4688)
f_m' [wet/dry] ratio	0.86	0.80	0.76	0.83
% Red. = $\frac{\text{Dry - Wet}}{\text{Dry}} \times 100$	14	20	24	17
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 (2.89.06)	15,996 (2.32E+06)	18,065 (2.62E+06)
E_m [wet/dry] ratio	0.86	0.92	0.78	0.96
% Red. = $\frac{\text{Dry - Wet}}{\text{Dry}} \times 100$	14	8	22	4
E_m / f_m' (dry) [fm', assemblage strength]	520	486	434	483
E_m / f_m' (dry) [fm', unit str. from MSJC Code]	713	785	743	680
E_m / f_m' (dry) [fm', from regression analysis]	661	728	689	631
E_m / f_m' (wet) [fm', assemblage strength]	522	560	448	559
E_m / f_m' (wet) [fm', unit str. from MSJC Code]	613	723	580	655
E_m / f_m' (wet) [f_m', from regression analysis]	568	670	538	607

f_m' of 27.58 MPa (4,000 psi) from Table 1 of the MSJC Specifications, and f_m' of 29.74 MPa (4,313 psi) from the regression equation discussed earlier. The resulting values for E_m/f_m' are 742 for dry and 579 for wet, based on the 4,000 psi value listed in the code, and 689 and 537 for dry and wet, respectively, based on the regression equation. See Table 2 for summary of results.

4.4 SR1044 Polymer Modified Mortar

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 of 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 was12765 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.

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