1. ABSTRACT

The effect of grout and reinforcement on the load bearing capacity of concrete masonry was investigated in this paper by test and analysis. Proposals for the prediction of the capacity of grouted concrete masonry and reinforced concrete masonry are given. The modulus of elasticity and stress-strain curve of grouted concrete masonry and reinforced concrete masonry were determined and compared to hollow concrete masonry.

2. INTRODUCTION

Compressive strength is the most important property of masonry. Two methods determining the compressive strength of masonry have been recommended in the North American Codes and Standards (such as CAN3-S304-M84 and ACI 530-88/ASCE5-88) : (1) Using a table of masonry strengths based on block strengths and mortar types; and (2) testing concrete masonry prisms laid in stack bond, with a aspect ratio of 2 to 5, and made of the constituent materials used in actual construction. The British Masonry Code BS 5628 (1978, 1992) proposes a procedure for the direct determination of the characteristic compressive strength of brick masonry by testing prisms made with varying numbers of bricks and built with different brick orientations, some with concrete infill. There is, however, no provision in BS 5628 regarding the construction and testing of blockwork prisms to determine characteristic compressive. BS 5628 gives values of characteristic for blockwork masonry in tables and graphs. These relate the compressive strength of grouted concrete block masonry to the strength of the unit block and the type of mortar. Chinese Design Code for Masonry Structures (GBJ3-88) (1988) also gives the values of compressive strength for masonry in tables, and proposals for compressive strength of masonry.

The grout increases cross-sectional area and load bearing capacity of masonry. Hamid and Drysdale (1979) have developed a mathematical model to predict the prism strength depending on the

Key words: Concrete Masonry; Load Bearing Capacity; Stress-Strain Curve; Modulus of Elasticity.
mechanical properties of prism components. Cheema and Klingner (1986) have developed an analytical model for masonry prism considering the constituents as linear elastic materials. They accounted for material nonlinearity by using the secant modulus of elasticity. Boult (1979) and Hamid and Chukwunenye (1986) have shown that a three-course prism model can practically be considered representative for masonry strength investigation. Previous work by Drysdale and Hamid (1979) on concrete block masonry prisms have shown that, using values of the compressive strength of the masonry, based on block strength and mortar type, was not appropriate for grouted concrete block masonry. This is because the mortar joint has a negligible effect on the compressive strength of the prism. They suggested that matching the deformation characteristics of the grout and the block would be more effective than increasing the grout strength in increasing the masonry strength. They also suggested that testing a 3-course-high prism gives a more accurate representation of strength of concrete block masonry, since it exhibits a failure mode similar to that for wall.

Tests on hollow concrete masonry, grouted concrete masonry and reinforced concrete masonry were conducted under axial compression in this investigation. The effect of the grout and reinforcement on bearing capacity of concrete masonry specimens was investigated. Proposals for the prediction of the compressive strength of grouted and reinforced concrete masonry are given. The effect of vertical reinforcement, instead of horizontal reinforcement and lateral ties, on bearing capacity of concrete masonry was considered in this investigation. The modulus of elasticity and the stress-strain curves of grouted and reinforced concrete masonry were determined and compared to hollow concrete masonry.

3. BEARING CAPACITY OF CONCRETE MASONRY

At present, there are many different empirical formulas to predict the compressive strength of hollow concrete masonry based on the compressive strength of unit and mortar, and formulas predicting the compressive strength of grouted and reinforced masonry are mainly concentrated on reinforced concrete masonry and often based on the masonry prism strength (Colville and Wolde-Tinie 1991 and Khalaf, Hendry and Fairbairn 1993). Experiments have shown that the strain of vertical reinforcements were only half of the yield strain. Therefore, only 50% of the yield strength of reinforcement is considered in the formula proposed by Khalaf, etc., (1993).

3.1 Unreinforced Masonry

The formula to predict the compressive strength of unreinforced masonry is given in Chinese Design Code for Masonry Structures (GBJ3-88) as follows:

\[
f_m = k_1 \cdot f_1^u \cdot (1 + 0.07f_2) \cdot k_2
\]  

(1.1)

The formula is only suitable for the masonry with lower strength mortar and block.

3.2 Grouted Masonry

In order to determine bearing capacity of grouted masonry, the following assumptions are made: (1) the concrete block are fully grouted, (2) concrete block and grout are bonded together. The load-bearing capacity is given by:

\[
N_{gm} = N_m + N_g = \varepsilon \cdot E_m \cdot A_{net} + \varepsilon \cdot E_c \cdot A_c = f_{m,n} \cdot A_{net} \cdot (1 + \frac{E_c}{E_m} \cdot \frac{A_c}{A_{net}})
\]  

(2)

The compressive strength of grouted concrete masonry based on the gross area is given by:

\[
f_{gm} = f_m \cdot (1 + \frac{E_c}{E_m} \cdot \frac{A_c}{A_{net}})
\]  

(3)

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For practical application, it might be more convenient to express the compressive strength of grouted masonry by the compressive strength of hollow masonry and grout than by deformation characteristics as in Eq. (3). As observed in the tests, the stress of grout reaches about 60%～80% of its compressive strength at the failure of masonry, it is consistent with some literature (Colville and Wolde-Tinae 1991 and Khalaf and Hendry 1993). 70% of compressive strength is taken in this paper. Hence the bearing capacity of grouted concrete masonry can be given by:

\[ N_{gm} = N_m + N_g = f_m \cdot A_{gross} + 0.7 \cdot f_c \cdot A_c \]  
\[ f_{gm} = f_m + 0.7 \cdot f_c \cdot \frac{A_s}{A_{gross}} \]

3.3 Vertically Reinforced Concrete Masonry
The compressive strength of vertically reinforced and grouted concrete masonry should be predicted in the same way as for grouted masonry, assuming that steel, grout and units are bonded together. Based on the gross area of masonry, the compressive strength of vertically reinforced and grouted concrete masonry is given as follow:

\[ f_{vm} = f_m \cdot \left(1 + \frac{E_c}{E_m} \cdot \frac{A_c}{A_{gross}} + \frac{E_s}{E_m} \cdot \frac{A_s}{A_{gross}} \right) \]

The compressive strength of vertically reinforced and grouted concrete masonry can also be expressed by the compressive strength of hollow concrete masonry and grout. The stress of reinforcement reaches only about 50%～70% of yield strength, 60% of yield strength is taken in this paper

\[ f_{vm} = f_m \cdot \left(1 + 0.7 \cdot \frac{f_y}{f_m} \cdot \frac{A_s}{A_{gross}} + 0.6 \cdot \frac{f_y}{f_m} \cdot \frac{A_s}{A_{gross}} \right) \]

As can be seen in Eq.(6) and (7), the contribution of vertical reinforcement to the bearing capacity of masonry is comparative low due to little reinforcements in concrete masonry for practical engineering.

4. TEST PROCEDURE
4.1 Material Properties
Concrete Block The dimensions of the concrete block are depicted in Fig.1. The thickness of face shell and web changes along the height of the concrete block. The compressive strength of the concrete block was 18.12Mpa.

Fig.1 Configuration and dimensions of concrete block
Mortar  Mortar type had been shown have relatively little influence on grouted masonry (Boult 1979). The compressive strength of the mortar was 31.88 MPa based on tests on six 70.7 mm cubes.

Grout  Grout was used in the investigation: 4.36 : 1 : 6.97 : 4.84 : 1.71 cement : fly ash : aggregate : sand : water by weight. The compressive strength of the grout was 35.11 MPa based on tests on six 150 mm cubes.

Steel bar  The diameters of the deformed steel bar for tests were 12 mm and 16 mm. The tensile yield strengths of the steel bars were 406.72 MPa and 386.21 MPa, respectively.

4.2 Test Specimen and Test Procedure
Test specimens are 3-course-high concrete masonry prisms, as shown in Fig. 2. The dimensions and shape of the concrete masonry prism are illustrated in Fig. 2.

![Fig.2 Design details of prism specimen](image)

The prisms tested were divided into three series: Series No. 1 are hollow concrete masonry prism specimens, series No. 2 are grouted concrete masonry prisms specimens and series No. 3 are vertically reinforced and grouted concrete masonry prism specimens. The vertical steel bars were placed in each core of concrete block. Three test series and the material properties are shown in Table 1 and Table 2, respectively.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Number of tests</th>
<th>Prism type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>Hollow concrete prism</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Grouted concrete prism</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Vertical reinforced and grouted concrete prism</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Material properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prism type</td>
<td>Specimen</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3BP1</td>
</tr>
<tr>
<td></td>
<td>3BP2</td>
</tr>
<tr>
<td></td>
<td>3BP3</td>
</tr>
<tr>
<td>2</td>
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<td></td>
<td>BPG3</td>
</tr>
<tr>
<td>3</td>
<td>BPGV1</td>
</tr>
<tr>
<td></td>
<td>BPGV2</td>
</tr>
<tr>
<td></td>
<td>BPGV3</td>
</tr>
</tbody>
</table>
4.3 Test Results

All specimens failed in brittle mode. When about 60% of ultimate load was reached, vertical cracks occurred on the specimens. With increasing load, for hollow concrete masonry prisms, an extensive spalling of the external shells of the blocks occurred, for the grouted concrete masonry prisms, a longitudinal vertical crack along the core occurred, for the reinforced concrete masonry prisms, the spalling was limited to only small parts of the specimen. The failure modes of the specimens are shown in Fig.3 to Fig.5.

The hollow concrete masonry almost behaved elastic, which failed without any signs due to splitting of block (face shells or webs) at the joints, and splitting of the webs was observed prior to face shells splitting. Grouted concrete masonry and reinforced concrete masonry exhibited slightly nonlinear behavior, which gradually failed by vertical splitting through the block shell, starting at the bed joint. Neither grout nor mortar suffered much damage. Grout and mortar which had Poisson ratios greater than those of block at large strain, expanded near the bed joints under axial compression and split the block shell at the bed joints. Axial bearing capacities of the grouted concrete masonry and reinforced concrete masonry depended on the splitting resistance of the shell and the crushing resistance of the grout. The test results are given in Table 3.

<table>
<thead>
<tr>
<th>Prism type</th>
<th>Specimen</th>
<th>Modulus elasticity (Mpa $\times 10^5$)</th>
<th>Ultimate load (KN)</th>
<th>Compressive strength (Mpa)</th>
<th>Mean value (Mpa)</th>
<th>Maximum strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3BP1</td>
<td>2.08</td>
<td>673</td>
<td>9.55</td>
<td>9.14</td>
<td>0.00125</td>
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<tr>
<td></td>
<td>3BP2</td>
<td>1.9335</td>
<td>622</td>
<td>8.82</td>
<td>8.635</td>
<td>0.00092</td>
</tr>
<tr>
<td></td>
<td>3BP3</td>
<td>2.2127</td>
<td>637</td>
<td>9.04</td>
<td>8.97</td>
<td>0.00096</td>
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<tr>
<td>2</td>
<td>BPG1</td>
<td>2.2812</td>
<td>1540</td>
<td>21.84</td>
<td>21.03</td>
<td>0.00316</td>
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<tr>
<td></td>
<td>BPG2</td>
<td>1.9597</td>
<td>1610</td>
<td>22.84</td>
<td>22.10</td>
<td>0.00143</td>
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<tr>
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<td>BPG3</td>
<td>2.2535</td>
<td>1510</td>
<td>21.42</td>
<td>21.18</td>
<td>0.00119</td>
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<td>0.00315</td>
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<tr>
<td></td>
<td>BPGV2</td>
<td>2.6677</td>
<td>1645</td>
<td>23.33</td>
<td>23.04</td>
<td>0.00179</td>
</tr>
<tr>
<td></td>
<td>BPGV3</td>
<td>2.2279</td>
<td>1710</td>
<td>24.26</td>
<td>23.52</td>
<td>0.00178</td>
</tr>
</tbody>
</table>

5. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL COMpressive STRENGTH

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The load bearing capacities of the grouted concrete masonry and reinforced concrete masonry are determined by Eq.(5) and Eq.(7), respectively. The experimental and predicted values are given in Table 4.

Gross cross-sectional area of masonry: \( A_{\text{gross}} = 70500 \text{mm}^2 \)
Net cross-sectional area of masonry: \( A_{\text{net}} = 33800 \text{mm}^2 \)
Gross cross-sectional area of grout \( A_G = 36700 \text{mm}^2 \)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Mortar ( f_m ) (Mpa)</th>
<th>Grout ( f_G ) (Mpa)</th>
<th>Steel bar ( f_y ) (Mpa)</th>
<th>Hollow masonry ( f_m ) (Mpa)</th>
<th>Predicted (Mpa)</th>
<th>Experimental (Mpa)</th>
<th>Ratio Predict./Exper.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPG1</td>
<td>31.88</td>
<td>35.11</td>
<td>9.14</td>
<td>21.92</td>
<td>21.84</td>
<td>21.84</td>
<td>1.0037</td>
</tr>
<tr>
<td>BPG2</td>
<td>31.88</td>
<td>35.11</td>
<td>9.14</td>
<td>21.92</td>
<td>22.84</td>
<td>0.9597</td>
<td></td>
</tr>
<tr>
<td>BPG3</td>
<td>31.88</td>
<td>35.11</td>
<td>9.14</td>
<td>21.92</td>
<td>21.42</td>
<td>1.0233</td>
<td></td>
</tr>
<tr>
<td>BPGV1</td>
<td>31.88</td>
<td>35.11</td>
<td>405.03</td>
<td>9.14</td>
<td>22.41</td>
<td>22.98</td>
<td>0.9752</td>
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<tr>
<td>BPGV2</td>
<td>31.88</td>
<td>35.11</td>
<td>386.21</td>
<td>9.14</td>
<td>22.52</td>
<td>23.33</td>
<td>0.9653</td>
</tr>
<tr>
<td>BPGV3</td>
<td>31.88</td>
<td>35.11</td>
<td>406.33</td>
<td>9.14</td>
<td>22.91</td>
<td>24.26</td>
<td>0.9444</td>
</tr>
</tbody>
</table>

As can be seen in Table 4, good agreement between the load bearing capacity by experiments and that by proposed formulas can be obtained. The grout and steel bar can increase the capacity of masonry.

6. STRESS-STRAIN CURVES OF CONCRETE MASONRY

The \( \sigma - \varepsilon \) curves were determined by experiments. The descending branch of the \( \sigma - \varepsilon \) curves were not measured. The \( \sigma - \varepsilon \) curves can only be specified up to the strain at maximum load. So the ultimate strain was not determined. The ratio of maximum strain corresponding to ultimate load to ultimate strain \( \varepsilon_{\text{max}} / \varepsilon_u \) is about 1.2. That means that the maximum strain is nearly equal to the ultimate strain.

The \( \sigma - \varepsilon \) curves of concrete masonry under axial compression are nonlinear, so the modulus of elasticity is not constant. The modulus of elasticity was taken as secant modulus between a point on stress-strain curves at zero stress and 0.43 maximum stress. The experimental results (compressive strength \( f_m \), maximum strain \( \varepsilon_{\text{max}} \), modulus of elasticity \( E \)) are given in Table 5.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>( f_m ) (Mpa)</th>
<th>( \varepsilon_{\text{max}} ) ( \times 10^{-3} )</th>
<th>( E ) (Mpa ( \times 10^4 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.14</td>
<td>1.0433</td>
<td>2.0754</td>
</tr>
<tr>
<td>2</td>
<td>22.03</td>
<td>1.6467</td>
<td>2.1648</td>
</tr>
<tr>
<td>3</td>
<td>23.52</td>
<td>1.8067</td>
<td>2.5571</td>
</tr>
</tbody>
</table>

As can be seen in Table 5, The modulus of elasticity and maximum strain of the grouted and reinforced masonry increase slightly, compared to hollow masonry.

The \( \sigma - \varepsilon \) curves of concrete masonry are shown in Fig.6 to Fig.8. The \( \sigma - \varepsilon \) curves of hollow masonry exhibited a linear behavior up to the point of failure, corresponding to an axial strain of about 0.001. The \( \sigma - \varepsilon \) curves of grouted masonry and reinforced masonry exhibited slightly nonlinear behavior, the maximum strain of grouted masonry increased to 0.0016, the reinforced masonry 0.0018.
7. CONCLUSIONS

1. Good agreement was observed between the load bearing capacity of the grouted concrete masonry by tests and that by proposed formulas.
2. The grout and steel bar can increase load bearing capacity of masonry.
3. The stress-strain curves of hollow masonry exhibited almost linear behavior up to the point of failure. The stress-strain curves of grouted masonry and reinforced masonry exhibited slightly nonlinear behavior. Maximum strain of the grouted and reinforced masonry increase slightly, compared to hollow masonry. But it is obviously below the usually assumed failure strain of similar concrete.
4. The modulus of elasticity of the grouted and reinforced masonry increase slightly, compared to hollow masonry.

REFERENCES


**NOTATION**

\[ A_o = \text{cross-sectional area of the grout (mm}^2) \]
\[ A_{gross} = \text{gross cross-sectional area of the concrete masonry (mm}^2) \]
\[ A_{net} = \text{net cross-sectional area of the concrete masonry (mm}^2) \]
\[ A_y = \text{cross-sectional area of the steel bar (mm}^2) \]
\[ E_c = \text{modulus of elasticity of the grout (Mpa)} \]
\[ E_m = \text{modulus of elasticity of the mortar (Mpa)} \]
\[ E_s = \text{modulus of elasticity of the steel bar (Mpa)} \]
\[ f_b = \text{compressive strength of the block (Mpa)} \]
\[ f_{cu} = \text{cube compressive strength of the grout (Mpa)} \]
\[ f_c = \text{prism compressive strength of the block (Mpa)} \]
\[ f_{gm} = \text{compressive strength of the grouted masonry (Mpa)} \]
\[ f_{m} = \text{compressive strength of masonry (determined in tests or according to Eq. (1)) (Mpa)} \]
\[ f_{m,un} = \text{compressive strength of unreinforced masonry based on the net area (Mpa)} \]
\[ f_{mo} = \text{compressive strength of the mortar (Mpa)} \]
\[ f_{m,rm} = \text{compressive strength of the reinforced masonry (Mpa)} \]
\[ k_1 = \text{coefficient related to block type and construction method} \]
\[ k_2 = \text{correction coefficient for lower or greater mortar strength} \]
\[ N_g = \text{load bearing capacity of the grout (KN)} \]
\[ N_m = \text{load bearing capacity of the hollow masonry (KN)} \]
\[ N_{gm} = \text{load bearing capacity of the grouted masonry (KN)} \]
\[ \alpha = \text{coefficient related to height of the block} \]

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