DETERMINATION IN SITU OF MORTAR LOAD CAPACITY
BY A DRILLING TECHNIQUE.

Natale Gucci and Riccardo Barsotti

1. ABSTRACT

The indirect technique developed at the Istituto di Scienza delle Costruzioni of the University of Pisa evaluates the compressive strength of sand mortar by measuring the amount of energy spent in drilling a small cylindrical hole in a mortar layer (drilling work). The apparatus, designed and built just for this purpose, has been tested to relate the geometric parameters (i.e., the diameter and the depth of the cavity) and the drilling work to the compressive strength of sand mortar. The role played by both the geometric parameters and the sand grain size distribution is illustrated in the paper. The experimental results are reported and discussed.

2. INTRODUCTION

At present there is no reliable and practical method to determine in situ the strength of masonry mortar layers. Chemical-physical methods such as petrographic sections, x-ray diffraction, thermogravimetric analysis and others give inaccurate evaluation of the mortar strength. Mechanical methods such as the flat-jack test or even the loading test of large portions of masonry walls in laboratory are more reliable but expensive and not always convenient [1].

Keywords: Mortar strength determination, Experimental technique, Masonry diagnosis.

1 Prof. Ing., Istituto di Scienza delle Costruzioni, The University of Pisa, Italy
2 Dr. Ing., Istituto di Scienza delle Costruzioni, The University of Pisa, Italy
More recently, tests based on drilling techniques were developed [2], [3]. This paper deals with one of these methods, developed by the Authors, based on the measurement of the amount of energy required to drill a small cavity in a mortar layer (PNT-G). The results of the experimental study performed on sand mortars, reported below, show that the drilling work is related to the mortar compressive strength and that such relation is the same for all mortar having sand aggregate and compressive strength less than 4 MPa.

3. INSTRUMENTATION SET DESCRIPTION AND CALIBRATION

The instrumentation consists in a battery hand drill with an ordinary cutting edge in tungsten carbide connected with an electronic circuit which measures the drilling work so as to avoid the influence of the drill electromechanical efficiency. The apparatus, showed in figures 1 and 2, is very light and easy to use.

To calibrate the PNT-G and to choose the most suitable values of the geometric parameters (i.e., diameter and depth of the cavity) there were drilled a total number of 750 cavities on the mortar layers of twelve small walls (100x50x65 centimeters) each built with a different sand mortar type.

The mortars were prepared using a highly hydraulic lime (characteristic compressive strength equal to 3 MPa) and a Portland 325 cement. The mortar composition and compressive strength, the latter evaluated by loading test on cubical specimens, are reported in table 1. It is worth pointing out that two different sand grain size distributions (a single-valued one and an ordinary one, see figure 3) were used to verify the influence of such parameter.

Fifteen cavities were drilled close to each measurement point. A statistical elaboration of the unrefined values was performed following the analogous criteria yet developed for the Schmidt hammer [4]. Four series of tests were done changing the drill diameter (4; 5 and 6 millimeters) and the cavity depth (5 millimeters and 1 centimeter). The average and the standard deviation of the experimental values of the drilling work are reported in table 1. The respective diagrams are plotted in figures 4 and 5, with the straight lines which fit them obtained with the minimum $\chi^2$ technique. As one can see, the two diagrams plotted in figure 4 (relative to the standard measurement parameters, as will be shown later) are quite close, regardless of the different sand grain size distribution, for mortar compressive strength lower than 4 MPa.
4. INTERPRETATION OF THE RESULTS

4.1 Choice of the geometric parameters

The drill diameter should be small compared to the mortar layer thickness, otherwise the drill will break the weak bond between the mortar and the adjacent bricks, thus affecting the measurement. On the other hand, the cavity dimensions should be big enough compared to the maximum sand grain radius. Since the 4 millimeters drill diameter (the smaller ordinary wall bit) show a high meter sensitivity (about 130 units per MPa) and satisfy the above requirements, such value was adopted for the drill diameter.

The cavity depth should be the minimum allowing a suitable sensitivity so as to minimize the errors due to the possible variation of the mortar mechanical properties and to the influence of the friction between the drill and the cavity lateral surface. Therefore a 5 millimeters depth was chosen.

4.2 Influence of the sand grain size distribution

For weak mortars (compressive strength lower than 4 MPa for the sand mortars tested) the sand grain size distribution has little influence on the measurement because the drill does not break the grains of sand and the cracks pass through the cement only. This can be seen by observing the mortar broken up by the drill (figures 6 and 7).

For stronger mortars ($f_m$ greater than 4 MPa, see figure 4) the sand grain size distribution has a greater effect and the PNT-G shows a higher meter sensitivity in the case of single valued grain size distribution. In this case, in fact, the drill breaks the grains of sand and the cracks pass through both the cement and the sand (figures 8 and 9). Therefore the sand’s petrologic characteristics and grain size distribution affect the PNT-G.

The higher amount of energy spent in drilling in the case of single valued grain size distribution is due to the higher amount of cement broken by the drill. Since the mortar load capacity depends on that of its cement or lime, in case of high strength aggregate [5, 6] it follows that for single valued grain size distribution the meter sensitivity will be higher because the percentage of voids is higher than in ordinary sand.

4.3 Theoretical interpretation

The cracks produced by the drill will pass through the binder only or will break also the grains of sand whether the ratio binder strength/sand strength is smaller or greater than a limiting value.
Neglecting long distance effects between the grains of aggregate (see figure 10) a first expression for such limiting value is [7], [8]

\[
\frac{f_b}{f_s} = \frac{8\nu(1-\nu)(d-a)}{d(3-4\nu)}
\]  

(1)

where \(d\) = distance between the crack tip and the grain, \(a\) = grain radius, \(\nu\) = binder Poisson’s ratio. When \(f_b/f_s\) exceed such value the grain of sand will be passed through by the crack while on the contrary it will be disjoint from the binder.

The correlation between the drilling work and the mortar load capacity can be interpreted as a first approximation by reducing the dynamic actions of the drill to a couple of forces acting in a quasi-static regime (see figure 11), by using the Coulomb failure criterion for the mortar and by using the Griffith energy criterion to evaluate the shearing stress at the crack onset. Under such assumptions the drilling work can be expressed as [8]:

\[
E_d = \pi\beta K_{II,c}hd^2(sin\Phi_m + kcos2\Phi_m) \\
2a_i(1+k^2)(1-cos2\Phi_m)
\]  

(2)

where \(a_i\) is the medium length of the initial flaws, \(\beta = \beta(a/d)\) is a dimensionless coefficient, greater or equal to unity, which takes into account scale effects, since \(a\) is the medium grain radius; \(d\) is the drill diameter, \(h\) is the cavity depth, \(K_{II,c}\) is the critical intensity factor for pure shear, \(\Phi_m\) is the angle between the crack and the direction of cutting and \(k\) is the mortar internal friction. It is worth pointing out that the linear relation between \(E_d\) and \(h\) does not hold for big cavity depths. This is due to the greater influence of the friction between the drill and the cavity lateral surface. This latter aspect is not covered in equation (2) because of the cavity depth was taken to be small.

Let’s give to the parameters in (2) their values relative to the cement mortar (mortar type number 9 in table 1): \(d = 4mm, h = 5mm, k\) is deduced from the mortar tensile and compressive strength [10] [11] and is set equal to 1, \(\beta = 1\) (no sensible scale effects were observed), \(a_i = 0.1mm\) [9] and \(K_{II,c}\) is obtained by making the mean of the values of \(K_{II,c}\) for cement mortars reported in [9] and is set equal to \(4 \times 10^5 Nm^{-3/2}\). By making the power spent a minimum [8]

\[
\Phi_m = \frac{1}{2}(arctg(1/k) - \delta + \gamma_m)
\]

(3)

in which \(\gamma_m\) is the angle of resultant rake and is 0 for the kind of drill used, \(\delta\) is the angle of rolling friction between the broken up mortar and the cutting edge and is set equal to \(5^\circ\). In this case the value given by equation (2) is 1423 units (1 unit = \(6 \times 10^3\) joule) and the experimental mean value of the drilling for the cement mortar (see table 1) is 1515 units and so the (2) is in good agreement with the results of the test.

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5. CONCLUSION

The PNT-G evaluates the mortar compressive strength in situ by drilling a small cavity in a mortar layer and by measuring the amount of energy spent. The calibration performed on sand mortars showed that the instrumentation has got a high resolution, about 130 units per MPa, and a good precision (standard deviation less than 10%) when the mortar compressive strength is lower than 4 MPa. For such mortars, the sand grain size distribution has little influence on the measurement and so the PNT-G can be considered a useful aid for the determination of the load capacity of low strengthened masonry (such as ancient buildings). For stronger mortars, only the order of the mortar strength can be estimated, since the drilling work depends on the mechanical properties of the aggregate. Such information is always enough, because for stronger mortars the masonry load capacity depends much on that of its bricks (or stone) and so the exact value of the mortar load capacity is not needed. An extension of the calibration to several aggregate class may allow estimation by analogy. Further studies are needed to assess the reliability of the PNT-G when the mortars' aggregate is different from the sand and, more generally, when other materials, showing analogous relation between the load capacity and the drilling work, are employed.

6. REFERENCES

4. "Recommendation for testing concrete by hardness methods", RILEM, Mat. & Str. vol. 16 n. 95, 1983.
Figure 1: The instrumentation set.

Figure 2: Execution of test.

Figure 3: Grain size distribution of the two types of sand.
DRILLING WORK (1 unit = 0.006 joule)

Table 1

<table>
<thead>
<tr>
<th>Mortar Type</th>
<th>Composition</th>
<th>Cavity depth = 5mm</th>
<th>Cavity depth = 10mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement/Sand</td>
<td>Media s. q. m.</td>
<td>Media s. q. m.</td>
</tr>
<tr>
<td>1</td>
<td>0/1/1/3</td>
<td>28 5</td>
<td>121 21</td>
</tr>
<tr>
<td>2</td>
<td>0/1/2</td>
<td>117 10</td>
<td>232 29</td>
</tr>
<tr>
<td>3</td>
<td>0/1/3</td>
<td>19 4</td>
<td>37 5</td>
</tr>
<tr>
<td>4</td>
<td>1/2/9</td>
<td>373 41</td>
<td>640 79</td>
</tr>
<tr>
<td>5</td>
<td>0.5/2/9</td>
<td>183 34</td>
<td>170 39</td>
</tr>
<tr>
<td>6</td>
<td>0.2/2/9</td>
<td>100 13</td>
<td>104 14</td>
</tr>
<tr>
<td>7</td>
<td>1/1/5</td>
<td>803 41</td>
<td>1362 246</td>
</tr>
<tr>
<td>8</td>
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<td>854 70</td>
<td>1300 146</td>
</tr>
<tr>
<td>9</td>
<td>1/0/3</td>
<td>1515 200</td>
<td>2280 228</td>
</tr>
<tr>
<td>10</td>
<td>0/1/3</td>
<td>130 24</td>
<td>135 25</td>
</tr>
<tr>
<td>11</td>
<td>1/1/5</td>
<td>1310 245</td>
<td>2149 518</td>
</tr>
<tr>
<td>12</td>
<td>1/0.5/4</td>
<td>2081 240</td>
<td>2973 305</td>
</tr>
</tbody>
</table>

Drilling work *

\( P_G = 117f_m^3 \)
\( r = 0.98 \)

\( P_G = 53f_m + 267 \)
\( r = 0.99 \)

* 1 unit = 0.006 joule

Figure 4
Drilling work

- $d=5\text{ mm}$
- $h=5\text{ mm}$

- Ordinary sand, $c=5\text{ mm}$
- Single-valued grain size distribution sand, $c=10\text{ mm}$
- Single-valued grain size distribution sand, $c=20\text{ mm}$

Compressive strength

- $f_m (\text{MPa})$

* 1 unit = 0.006 joule

Figure 5
Figure 6: Mortar type number 2, $f_m = 1.11$ MPa (16x).

Figure 7: Mortar type number 10, $f_m = 1.08$ MPa (16x), single-valued grain size distribution (16x).

Figure 8: Mortar type number 9, $f_m = 22.40$ MPa (16x).

Figure 9: Mortar type number 12, $f_m = 16.13$ MPa, single-valued grain size distribution (6x).
Figure 10

Elastic half plane under a compressive force acting homogenoulsly in the surface.

Figure 11

Forces acting on the drill

Scheme of the drill