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# Static penetration test for historical masonry mortar

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## HIGHLIGHTS

- A static penetration test for historical masonry mortar is presented.
- The test provides the penetration load as a function of the penetration depth.
- Experiments were performed on five historical buildings with decayed mortar.
- Penetration tests are compared with direct shear and percussion penetration tests.

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## ABSTRACT

The penetration test for historical masonry mortar presented in this study is based on the principle of "static" penetration. A pin is driven at constant velocity by a stepper motor controlled by a computer. The test result is the penetration load as a function of the penetration depth. The penetrometer has been tested on masonry walls consisting of decayed mortar. The objective of the test is to provide information about the mechanical characteristics of mortar (friction coefficient, cohesion). To this end, the results are compared with those from direct shear tests on mortar samples and with those from a previous percussion penetration test.



## 1. Introduction

The response of masonry constructions is noticeably affected by mortar quality, as shown, for instance, by recent seismic events [1–4]. The mechanisms can be either out-of-plane [5,6] or in-plane [7,8]. When masonry walls are properly constrained by horizontal structures and toothed with orthogonal walls, out-of-plane mechanisms are usually prevented and in-plane mechanisms can develop, which depend on the mechanical properties of masonry [9–11].

In the assessment of existing buildings, due to the size of the units, there is no practical way of performing destructive tests on a representative volume of masonry. We might be able to circumvent this problem by determining the mechanical characteristics of the masonry components (units, mortar and unit-mortar interface) and using them to calculate the equivalent characteristics at the macro-scale, according to either the Mann and Müller equation [12] or micro-mechanic modelling [13].

A number of *in situ* tests have been devised to determine the mechanical characteristics of the mortar and the unit-mortar interface [14].

The shove test [15,16] measures the shear strength of the horizontal unit-mortar interface. Upon isolating laterally an individual unit from the rest of the wall, a jack inserted into the masonry gets this unit to slide along the horizontal direction. The shear strength depends on the vertical compression, which can be assessed, or controlled, through flat jacks.

The flexural bond strength, normal to bed joints, can be evaluated through the bond wrench test [17].

Both the shove test and the bond wrench can only be used on masonry with regular units.

A method to determine the hardness of jointing and pointing mortar, as a measure of overall quality, is based on a modified Schimdt pendulum hammer [18,19]. Pointing hardness is assessed through the median of nine recoil values of a pendulum hammer.

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Another method (helix test) involves inserting a helix into a pilot hole in the masonry joint, and measuring the pull-out load [20]. The method can be used to assess the mortar strength, provided that a suitable calibration curve is available.

A penetration test, thanks to its moderate destructiveness, can also provide useful information. Penetration tests were originally introduced in geotechnical engineering around 1930 and were standardized by Mohr [21]. The procedure involves inserting a metal drill into the soil and measuring the corresponding resistance to penetration. The penetrometers can be either static (pressure drills) or dynamic (percussion drills). The static penetration test, known as Cone Penetration Test (CPT), involves inserting a conic drill into the soil at controlled speed, usually 20 mm/s [22]. The dynamic penetration test, or Standard Penetration Test (SPT), uses a sampler tube, with an external diameter of 50 mm, internal diameter of 35 mm and a length of approximately 650 mm [23,24]. For the history and applications of SPT, see [25].

In structural engineering, one of the most common tests for the *in situ* determination of the compressive strength of concrete is the Windsor probe. A metal probe is driven at high speed into concrete by a calibrated explosive charge. The penetration depth is generally below 10 mm. The test result is the mean value of penetration over three blows. Given the resistance to penetration and the Mohs' hardness of the aggregate, the test estimates the compressive strength of concrete through empiric relations [26,27].

A penetration test specifically devised for masonry mortars is the PNT-G, which measures the energy used to make a hole with a normalized rotating drill [28,29]. Experimental investigations show that the penetration energy is correlated with the compressive strength, for sand mortars with a compressive strength of less than or equal to 4 MPa. For this test, the penetration depth is about 5 mm. A comparison of the PNT-G test with the helix test can be found in [30].

A penetration test for mortar strength evaluation using an adapted Schmidt rebound hammer is presented in [31]. The difference between the penetration depths after the tenth and the first impact is correlated with the mortar load capacity.

A method based on the continuous measurement of the penetration load applied to a pin is presented in [32]. The pin has both rotation and translation movements, at controlled speed. When the method is applied to a mortar, the resistance to penetration provides information on the design mix (sand/cement).

Another test aimed at estimating the compressive strength of mortar is based on the measurement of the penetration depth increment of a steel probe for each hammer blow [33].

A similar penetration test, i.e. based on the penetration of a metal pin driven by multiple blows, is aimed at estimating the friction coefficient of historical masonry mortar, which is often in a state of decay and has poor cohesion [34,35]. The penetration depth can be up to 40–50 mm. The test provides the average number of blows required to drive the pin one millimetre. This test overcomes the drawbacks of many foregoing penetrometers, i.e. the high energy of the Windsor penetrometer, which is unsuited to decayed mortars, and the shallow penetration depth of the PNT-G, which only provides information on a limited depth. Through empirical relations, the test provides the friction coefficient of the mortar, given the joint thickness and the compressive stress along the vertical direction. An experimental database of over one hundred buildings has been collected in recent years by means of this test.

A new version of the penetration test, based on the principle of "static" penetration, is presented in this study. A pin is driven at constant velocity into the mortar, and the test gives the applied load as a function of the penetration depth. The penetrometer has been tested on decayed lime-based mortar joints of five historical buildings, providing preliminary information on their quality. The results are compared to those obtained from direct shear tests on mortar samples. Finally, the new penetration test is compared to the previous percussion test.

## 2. Static penetrometer

The penetrometer is based on driving a metal pin into mortar at controlled speed, and continuously acquiring the applied load. The result of the test is the diagram of the load as a function of the penetration depth. The penetration depth can reach 70 mm, so as to overcome the shallow layer, which is mostly decayed because of exposition to atmospheric agents, or may have been replaced through repointing and might not be representative of most of the wall cross section.

The equipment consists of:

1) penetrometer;
2) control unit;
3) lock plate.

The penetrometer consists of: pin, drum, cylinder, worm screw, gearmotor, stepper motor, load cell, encoder, connecting cable (Fig. 1). The pin is made of steel, has a diameter of 3 mm and a conic tip at an angle of 27.5°. It is lodged into the drum, which slides inside the cylinder. The drum is driven, through the worm, by the gearmotor, which in turn is operated by the stepper motor. The cylinder head guarantees the correct alignment of the pin and makes it possible to clamp the penetrometer to the lock plate, which in turn is anchored to the wall to be tested. The load is measured by a button load cell located between the end of the worm screw and the drum. The displacement of the pin is measured by the encoder. During the test, the penetrometer is linked to the control unit by a connecting cable.

The control unit consists of: computer, battery, multifunction plug (Fig. 2). The control unit, featuring a touch screen, allows us to specify the settings of the test (speed, acquisition step, initial and final displacements, maximum load), acquires the data during the test (displacement and applied load), pulls back the pin to the home position at the end of the test, records the data on a flash Universal Serial Bus unit, and enables us to operate the pin manually, either at high or low speed, both configurable. During the test, the control unit displays in real-time the displacement of the pin and the applied load. The battery allows us to execute the test without resorting to an alternating current supply. The battery is charged by means of a cable connected to a multifunction plug.

The lock plate (Fig. 3) is made of stainless steel and is anchored to the masonry through expansion screws. The penetrometer is bolted to the plate. The penetrometer can be mounted on the plate

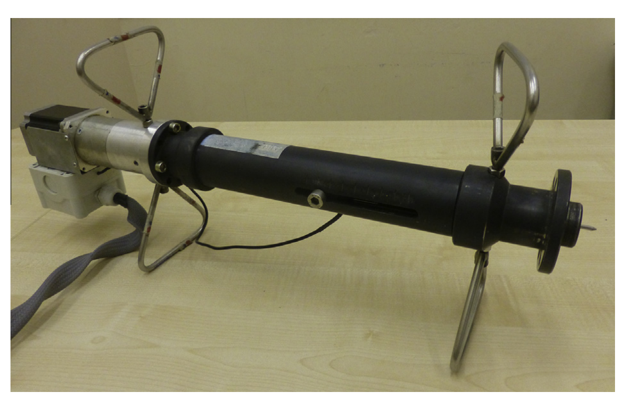

**Fig. 1.** Penetrometer.