Rheology of penetrations tests I: theory and finite element simulations

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Abstract

Measurement of highly visco-elastic medium such as cement during hardening and setting is difficult to access with standard viscometers or rheometers. That is why the rheological properties of cement based materials are currently measured with standardised penetration tools such as Vicat needles, ball indentation, penetrometers and Hilti nail guns. These are non conventional rheometers since results depend on the measuring device and only give information in arbitrary units.

Presently, no existing theory links these tests one to another. Despite this, empirical correlations have been reported between the Vicat, the Proctor or the Hilti nail gun measurements and more classical rheology.

In this article, an overview of these tests is given in which similarities and differences are pointed out. It is emphasized that they share a number of common issues and that resolving them for one should shed light onto how to better interpret all of them. This is done for penetrometers with support of finite element modelling which demonstrates that this particular test solicits the material in shear and gives a result related to the material yield stress.

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1 Introduction

Various empirical tests are used to follow the setting of cementitious materials. These are some times defined as consistency or setting time measurements. They include the Vicat needle, penetrometers and the Proctometer also known as the Proctor needle, as well as the Hilti nail gun.

Some of these techniques measure the penetration resistance under an imposed speed, while others measure the penetration depth for an imposed load. They are typically carried out following a series of standardised procedures as summarised in Table 1.

Table 1: Characteristics of penetration tests.

Test	Measurement type	Setting time	Remarks	Norm
Vicat	Measurement of penetration depth for an imposed load.	Penetration of 25 mm	Not continuous, but multiple measurements at different points (possibly automated).	C 191 C 807-99
Penetrometer	Measurement of a force to maintain a given speed.		Continuous at the same location (automated).	D 3441-79 D 1558-84
Proctor needle	Measurement of the force needed for the needle to reach a depth of 25mm.	3.5 MPa	Not continuous, but multiple measurements at different points (manual).	C403 C1117/89
Hilti needle	Measurement of the depth reached by a nail shot (fixed initial kinetic energy).	Material too hard for nail to enter	Not continuous, but multiple measurements at different points (manual).	Not known

Although these techniques are widely used, there is only scarce literature dealing with the quantification of a material property that they might measure. Consequently, there are also few studies convincingly showing how to relate these tests among each other.

The main reason for this probably lies in the fact that up to recently it was not possible to follow the evolution of a quantifiable mechanical property of cement paste during setting. Consequently, these penetration tests have remained empirical, delivering strictly comparative values. The recent development of ultrasound spectroscopy makes it possible follow the evolution of both shear and bulk modulus during the setting of cement paste. Based on this new technique, we demonstrate the existence of a relation between shear yield stress and the force measured by penetrometers [1]. Finite element simulations are used in this and confirm main parametric dependences expected from a simple scaling that is also proposed.

2 Description of the penetration tests

2.1 Vicat needle

The Vicat needle test consists in letting a loaded needle (300g, 1mm in diameter) penetrate a hydrating sample and measuring the depth of penetration. Repeated tests can be performed at different positions until the sample is too hard for the needle to penetrate it (Figure 1). The start and end of setting are defined by standards for specified penetration depths. These values are arbitrary and can only be used on a comparative basis. They are not appropriate for concrete because of the large aggregates [2,3].

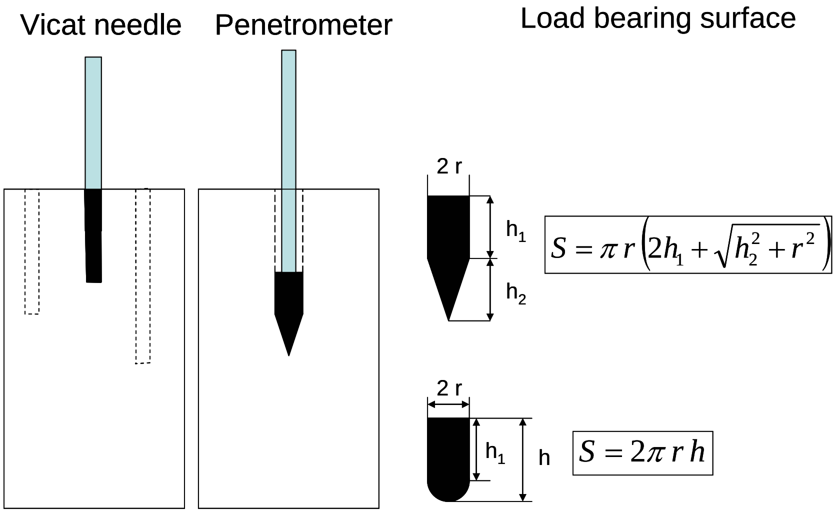

Figure 1. Schematic illustration of the difference between Vicat needle and penetrometer tests. The Vicat needle is used in different locations and the bearing surface decreases as the material stiffens (left). The penetrometer drives into the sample a needle of which the load bearing surface is constant over time (center). The expressions for those load bearing surfaces are given above for two needle geometries (right).

From a rheological point of view, yield stress is what stops the needle penetration. Furthermore, as the needle enters the surface supporting the applied load is increased and the shear stress at its surface decreases. The needle should immobilise itself once that stress is resisted by the material yield stress [4]. In terms of setting time, the fact of fixing a given penetration depth corresponds to fixing the yield stress. This is clearly a mechanical definition and the link to hydration degree is therefore only indirect.

2.2 Penetrometer

Penetrometers are instruments on which mounted needles are continuously driven into samples at a given speed and the force required to do so is measured over time. An important aspect is that the needle tip is wider than the rod on which it is mounted (Figure 1). Consequently, samples with a yield stress above a minimum value (not defined here) do not close up the gap above the tip and the load bearing surface *S* is constant during the experiment. A change in force over time can therefore be attributed not to a deeper penetration of the needle but to a change of the material measured. Results tend to be reported after dividing the applied load in Newtons by a calibration constant of 500 to give pressures in MPa. Using this convention, the initial and final setting times are determined when the stress reaches 3.5 MPa and 27.6 MPa respectively.

The penetrometer operates at a very slow speed (1μm/s), making the measurement quasi-static, which simplifies analysis. In comparison, measurements done with the Proctometer described below apply a much faster initial speed.

2.3 Proctometer

The proctor is a needle mounted spring which gives a digital display of the force applied while the needle is manually pushed into the sample. The needle is straight (Vicat type rather than penetrometer type, see Figure 1). The speed at which this needle is driven in depends on the operator and the material stiffness at the time the measurement is performed. Jolin *et al* [5] have shown that the evolution of stress with the penetration depth is constant after a certain penetration depth (15 mm in the case of a needle of a diameter of 9 mm). This means that there we can neglect, until a certain value, the effect of the side of the needle.

2.4 Hilti needle gun

The Hilti needle test consists in shooting a nail into a material and measuring the penetration depth [6]. From a rheological point of view, we may consider that when the test starts, the nail has received a given kinetic energy from the nail gun. Therefore, the nail should immobilise itself once that energy is lost by deforming the material.

It is reported that the compressive strength C_S is a decreasing exponential function of the penetration depth P measured with this test [7], with an empirical relation of the type:

$$C_S = C_{S_0} + C_{S_1} \exp\left(-\frac{P}{P_0}\right) \qquad \text{Eq. (1)}$$

In the case of Bracher's table we have $C_{S_0} = 5\,10^3\ Pa$, $C_{S_1} = 6\,10^7\ Pa$ and $P_0 = 25.7\ mm$.

3 General considerations

Let us try to consider the ensemble of these tests from the similar perspective of deformation energy. In the case of the Hilti needle, we have stated that the nail has given an initial kinetic energy and that it reaches its final position, once that energy has been consumed by deforming the material. The situation is rather similar in the case of the Vicat needle, except that the initial energy is a potential energy due to gravity. In this case, that energy has to be expressed in terms of the final position.
In the case of the penetrometer, the material is constantly deformed as the needle advances. The derivative of that energy with respect to position is the force applied for that displacement to proceed at constant speed.

Using this simplistic view a number of common issues can be identified as pertinent for the better interpretation of all these tests. These involve determining:

1) The role of the elasto-plastic behaviour of the cementitious materials at the time such tests are performed.
2) The type of local deformation associated with such a needle penetration (shear or compression).
3) The stress field around the needle.
4) The energy required to deform a cementitious material and allow penetration of a needle shaped object.

In order to address these questions, we have undertaken finite element simulation of the penetrometer test as described below.

4 Finite element simulations conditions

Finite element simulations of a penetrometer tip embedded in a large cylindrical body were been done with the following conditions:

1) The geometry, load and material of the structure exhibit axial symmetry. Therefore a simplified axi-symmetric finite element

model has been used in this study.

2) The needle tip taken as a hemisphere of either 5 or 10 mm in diameter (Figure 3). This tip is considered to be perfectly rigid and undeformable.
3) The tested material is defined either as purely elastic or ideally elasto-plastic (Figure 2). J2 plasticity model with Von-Mises yielding function has been used. In such a material, hydrostatic stress in the material does not influence yielding. However, hydrostatic stress is assumed to remain small in the model since the cement sample is still in a soft state.
4) Shear modulus and bulk modulus are varied separately to determine which deformation mode is most important in the overall resulting force.
5) The contact surface between the tip and the cementitious material was considered either frictionless or with a friction coefficient of 0.13 (range of values used for metals, a probably reasonable upper bound).

The simulations were carried out with the FEM Code Abaqus 6.6.1 by Simulia (Providence, USA).

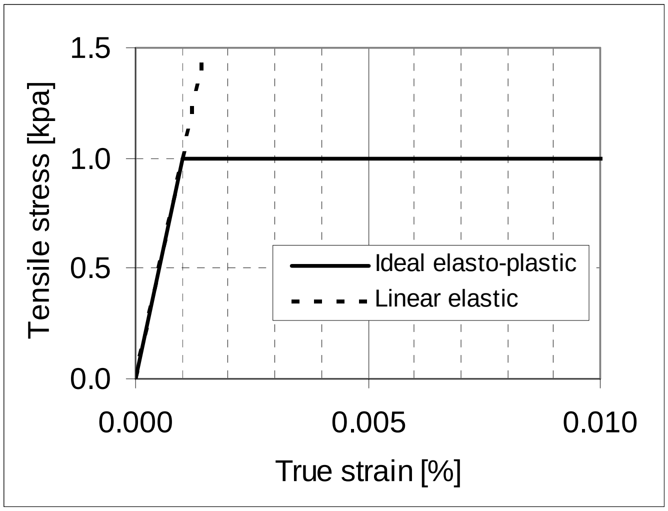

Figure 2. Uniaxial tensile stress-strain curves of the two behaviours assumed (elastic and ideal elasto-plastic).

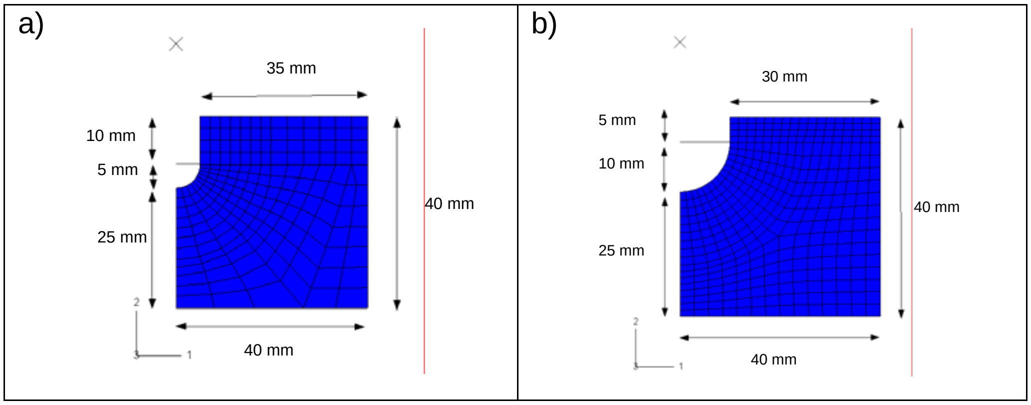

Figure 3. Representation of the different tips used in the simulations and the associated mesh of the cementitious material. Cases a) and b) are for the hemisphere only.

5 Results

5.1 Friction

The first result we examine is the role of friction at the interface between the needle tip and the sample. As indicated in Figure 7, it turns out that including friction does not lead to significant changes in the force displacement curves. This is true both for the elastic and the ideal elastoplastic case.

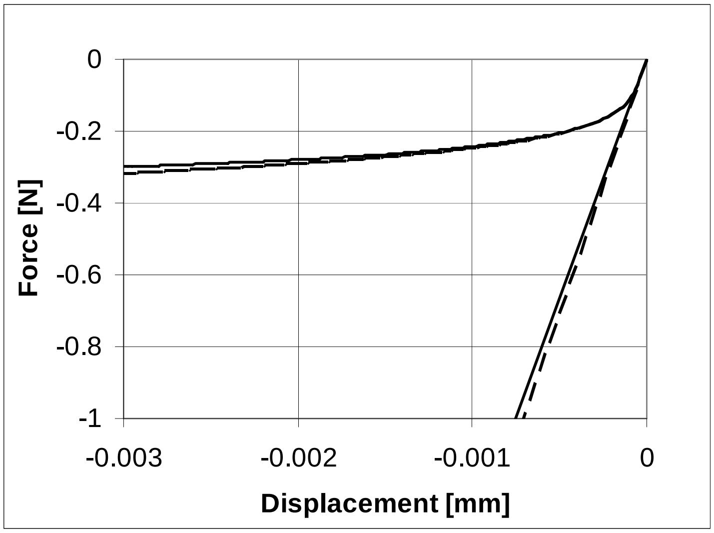

Figure 4. Force displacement relations. A) Penetrometer tip with a hemisphere 5mm in radius and cylinder 10mm high. Data shows the force on the needle as a function of the displacement. The continuous lines are the frictionless case and the discontinuous ones those with a friction coefficient of 0.13. The straight lines are the elastic case, while the curved ones show the ideal elasto-plastic situation.

5.2 Elastic versus elasto-plastic case

In Figure 4, simulations show a clear difference between the elastic and ideal elasto-plastic case for displacements larger than about 0.2 μm. In the first case, the force increases linearly with displacement as expected. On the other hand, the force reaches a plateau in the elasto-plastic case. This plateau is reached after about 3 μm displacement, but is already close after 1 μm. This corresponds respectively to 3s and 1s, so that the time to reach that plateau value can be considered as instantaneous for all practical means.

5.3 Shear yield stress, modulus and critical deformation

In Figure 5 we see that when the critical strain is decreased by a factor two, the plateau force is decreased in the same proportion. This point to the fact that the plateau force measured by the penetrometer is related to shear yield stress, which is consistent [4, 8]. The fact that the critical strain in cementitious materials is more or less constant during hydration [9], means that the force measured by penetrometers should generally scale with shear modulus although it is really a yield stress measurement.

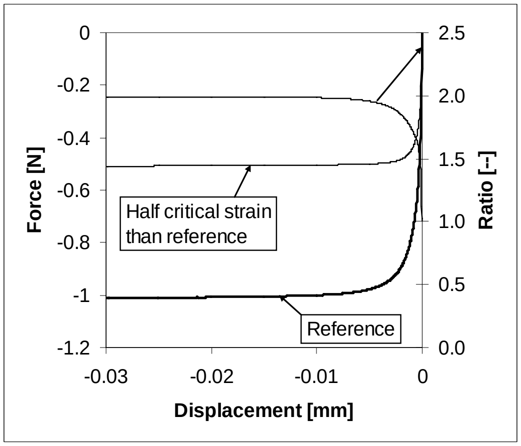

Figure 5. Effect of changing the critical strain. The graph shows a reference sample and one for which the elastic modulus is maintained constant but the critical strain is reduced by half, causing a similar reduction in the force.

The nature of the material property most directly measured by a penetrometer can be further inferred from Figure 6. There, the doubling of the shear modulus doubles the force.

On the other hand the bulk modulus measures the response in pressure due to changes in relative volume. The bulk modulus is therefore a direct measure of changes in hydrostatic stress which cannot be observed with a J2 plasticity Model. In that case, nothing can be deduced from FEM about the influence of the bulk modulus on the yield stress. However general considerations from fluid and continuum mechanics show the yield stress to be independent on the bulk modulus in the case of cement paste.

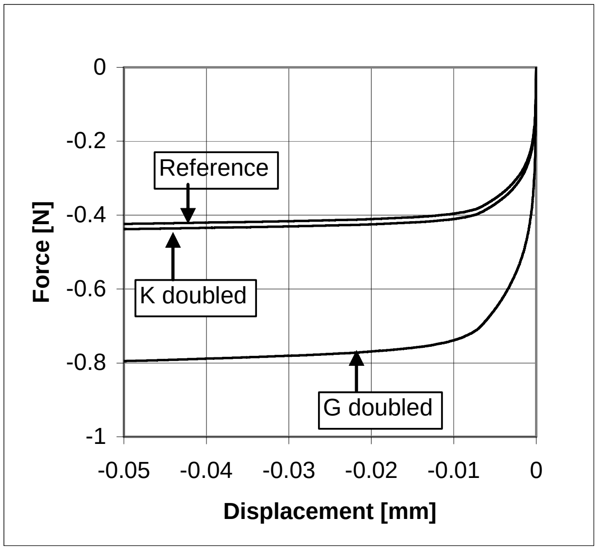

Figure 6. Effect of changing shear and bulk modulus independently. The force displacement curve shows a reference curve and ones for which the shear modulus (G) and bulk modulus (K) are varied independently. The shear modulus is seen to control the global response.

5.4 Role of tip radius

The dependence of the steady state force on the radius tip is seen in Figure 7a, where data show the difference obtained with tip radius of 5mm and 10mm respectively. In the elastic case the ratio between both forces is constant and equal to 2. In the ideal elasto-plastic case the ratio of the plateau force is slightly below 3 (Figure 7b). Our experimental results reported in a separate paper indicate that the ratio is rather 4 [1]. Without developing the reasons for this discrepancy here, we may state the the elasto-plastic case is certainly closer to reality than the purely elastic situation.

6 Discussion

The FEA results indicate clearly that cementitous materials are solicitated in shear mode when penetrometer tests are run. Furthermore, it was shown that the force measured is proportional to the material yield stress. In fact we find that if the yield stress for our model material, which is 1000 Pa, is multiplied by the surface of the hemisphere, we get steady state forces of respectively 0.16N and 0.63N for the tips with 5 and 10mm radius. This suggests that the surface bearing the load is larger than the tip surface.

Indeed, the result showing that friction does not affect the results indicates that the boundary between the portion of the material deformed plastically and the zone deformed elastically is not locallised directly at the tip surface.

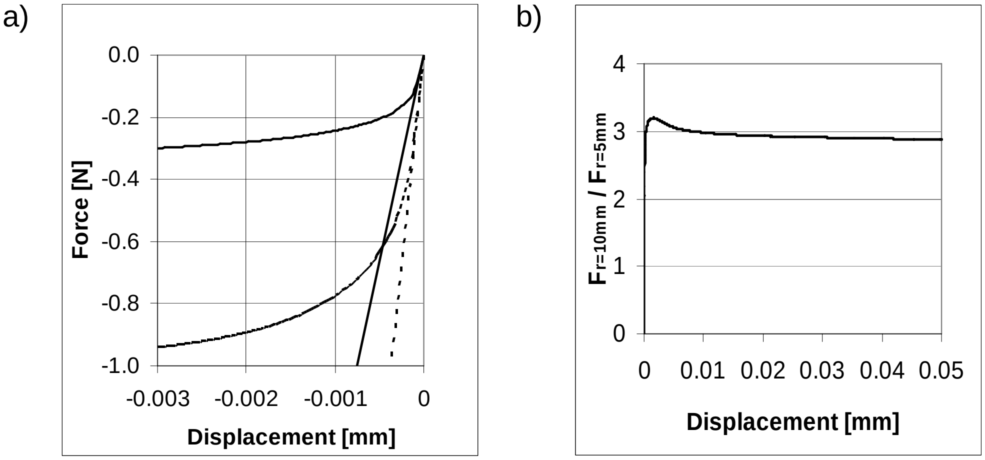

Figure 7. Force displacement relations. a) Penetrometer tip with a hemisphere of 5mm (continuous lines) and 10mm (discontinuous lines) radius. The straight lines are the elastic case, while the curved ones show the ideal elasto-plastic situations. b) Ratio between the forces obtained both in the ideal elasto-plastic case. In the elastic case this ratio is very close to 2 over the range of displacements represented.

Estimating what that surface is not trivial. One approach consists in adopting the approach of Roussel [10]. In this case we assume that the materials is well described by a Bingham fluid, such that its apparent viscosity, μ_a, is approximated by

$$\mu_a \cong \frac{\tau}{\dot{\gamma}} = \frac{\tau_0}{\dot{\gamma}} + \mu_B \qquad \text{Eq. (2)}$$

where τ is the shear stress, τ_0 is the shear yield stress, $\dot{\gamma}$ is the shear rate and μ_B is the plastic viscosity.

The shear rate around an object may be approximated by:

$$\dot{\gamma} = k\frac{V_s}{d} \qquad \text{Eq. (3)}$$

where k is a constant that depends on the tip geometry (close to unity for spheres), V_S is the velocity of the tip and d its diameter.

Roussel's argument is that Stokes' law, although derived for a sphere in a Newtonian fluid, may be used for a non Newtonian fluid provided the Newtonian viscosity μ is replaced by the apparent viscosity μ_a. Thus we would get:

$$F = 3\pi\,\mu\,dV_S \cong 3\pi\,d^2\,\tau_0 \qquad \text{Eq. (4)}$$

where we have neglected μ_B in Eq. (2) because the tip is moving extremely slowly (1μm/min), and also assumed k to be unity.

For our simulations with a yield stress of 1000 Pa and the tips of diameter 10 and 20 mm, this would correspond to forces of 0.9 and 3.8 N respectively. These are less close to the former results and in contrast to those the overestimated rather than underestimate the steady state forces. The reality must therefore lie in between both these assumptions. In the later case, we must emphasize that we are using Stokes law for a sphere without any corrections for the fact that simulations are done with a hemisphere.

In any case, it remains that both expressions predict a scaling of the force with the second power of the tip radius. This is consistent with the experimental results presented elsewhere but contrasts with the simulations presented here. The reasons for this discrepancy still need to be investigated.

7 Conclusions

Penetration tests are widely used to follow cementitious materials during setting. Despite limited quantification of the physical properties probed by these tests practical experience shows their usefulness. In this paper we have inferred that these tests share a number of similarities and that a detail investigation on one of them should shed light onto the others.

By using finite element analysis to examine the case of a penetrometer, we demonstrated that the plateau force scales with yield stress. However, since the critical strain in cementitious materials is constant, this force also scales directly with shear modulus, but not with the compressive modulus. Owing to the practical importance of yield stress it is not surprise that these *apparently empirical* are widely used.

Another implication of these results is that other properties may be related to penetration tests in as much as they relate to yield stress or shear modulus. This may be the case for rebound [5, 7] but it is more questionable that it would be the case for compressive strength although such arguments can be found [11].

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