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Use of Hand-Spray Plaster as a Coating for Soil Bulk Volume Measurement

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ABSTRACT

This paper presents a new coating material [hand-spray plaster (HSP)] used to measure the bulk volume of soil specimens having irregular shapes. The new method has been validated against two benchmark methods, namely, the wax and plastic bag methods, by conducting swelling and shrinkage tests on intact Maryland clay. The results show that the new method yields similar values of volume but with much reduced data scattering. The HSP method is also far easier to use than the other two methods. Finally, the stiffness of the coating has been measured and its restraining effect has been found to be negligible. Some of the benefits of using the HSP method are: (1) limited fluid retention by the specimen post-immersion for volume measurement, (2) reduced water-intake rate with elimination of cracking upon swelling caused by high-suction gradients, (3) absence of the restraining effect on specimens upon swelling, and (4) accurate determination of the swelling and shrinkage curves with only one specimen per curve.

Keywords

expansive soil, bulk volume, shrinkage, swelling, coating, cracking

Introduction

Over the past decades, different facets of soil shrinkage have been investigated through a range experimental methods (see [Fleureau et al. 1993](#); [Tariq and Durnford 1993](#); [Braudeau et al. 1999](#); [Boivin et al. 2004](#); [Krisdani et al. 2008](#)). Most authors agree that accurate volume measurement is a critical requirement to ensure accurate estimation of saturation degree or void ratio. Bulk volume can be inferred via specimen dimensions measured by a vernier caliper ([Krisdani et al. 2008](#)), automated three-dimensional laser scanning ([Rossi et al. 2008](#)), digital camera imaging ([Tang et al. 2011](#)), or environmental scanning electron microscopy coupled with a digital image analysis

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(Montes-H et al. 2003). Gauging physical dimensions can, however, prove problematic in the case of excessive shape distortion upon shrinkage. A simpler and more reliable solution is to immerse the specimen in a fluid. Use of a coating (e.g., paraffin, latex membrane, saran resin, MEK saran, or Elmer's craft glue) (Krosley et al. 2003; Cornelis et al. 2006) is required in case of wetting fluids to prevent adsorption by the specimen. However, most of these coatings are relatively stiff, tend to rupture at small strains, and do not allow much moisture transfer. Consequently, it is not possible for the coated specimen to lose or gain moisture, meaning that the coating has to be removed or several specimens have to be used in parallel (Pellissier 1991). Recently, Elmer's glue has been proposed as an alternative to hazardous coating materials, such as MEK saran (Krosley et al. 2003). However, the mass of glue evolves in time and testing was conducted on the drying path only. It is unsure whether the product can also be used for swelling. A successful alternative to the coating approaches is the so called "plastic bag method" developed by Boivin et al. (1991), which allows rapid non-destructive measurement of the soil bulk volume at any water content. However, this method requires application of vacuum, which translates into an effective stress that can deform the soil specimens.

In this study, a new and efficient coating material has been tested. It consists of sprayable band-aid, or hand-spray plaster (HSP), commercialized by Elastoplast. Such a product permits the short immersion of a coated specimen with limited fluid retention, while allowing slow water evaporation or adsorption. The hand-spray plaster offers a number of advantages: it is easy to apply, stretchable, non-toxic, relatively long lasting, inexpensive, and available from most pharmacists. The new method has been validated by comparing measurements of bulk volume along drying and wetting paths to the wax method (ASTM D 4943-02) and the plastic bag method (Boivin et al. 1991).

Experimental Methods and Materials

TESTING PROGRAM AND METHODS

To investigate the properties of the new coating material, free shrinkage tests, also called clod tests, and free swelling tests were performed on coated and uncoated soil specimens. Swelling tests took place in a fog room, where a humidity of 100 % is achieved by means of a water-mist system. For each test, two specimens were used in parallel to assess the repeatability.

The mass and water content of the specimens were measured using a high-precision balance (down to 1/10 000 of a gram). The initial gravimetric water content was determined using broken-off pieces of soil specimen (of about 20 g) and following Australian Standard AS1289.2.1.1. At any point in time,

the water content was assessed from the previous water content and the loss/gain of specimen mass measured using the precision balance. The specific gravity was determined using an automated gas pycnometer (Micromeritics Accupyc II 1340, accuracy of 0.05 %). The bulk volume of the specimen was determined by immersion in de-aired silicone oil (SO) using a high-precision balance (1/10 000 of a gram) and a specifically designed hanger and basket (Fig. 1). The specimen basket was initially tared while being immersed in the SO. Then the specimen was carefully placed into the basket and submerged in the SO. After about 30 s of equilibration, the digital reading of the balance (m_{oil}), which equals the difference between the mass of the soil sample in the air and that in the oil, was recorded. The bulk volume of the specimen can be calculated as:

$$(1) \quad V = \frac{m_{oil}}{\rho_{oil}}$$

where:

m_{oil} = mass of SO displaced by the specimen and recorded by the scale, and

ρ_{oil} = density of de-aired SO measured to be $0.9575 \pm 0.0054 \text{ g/cm}^3$.

The round bar the basket hangs from (Fig. 1) ensures that the basket always sits at the lowest point, thus improving the repeatability of measurements.

After immersion, the specimen was delicately cleaned using adsorbent papers and cotton balls and its mass was measured again. Cleaning was deemed sufficient when the amount of oil retained on the specimen was less than 0.5 % of its dry mass. This was usually achieved in less than 3 min, thus limiting water evaporation before the mass check.

The results obtained using the HSP method were compared to those achieved by the plastic bag method, described in Boivin et al. (1991), and the wax method (ASTM D 4943-02). For these two methods, parallel specimens were employed, as the methods are not prone to continuous testing. Indeed, removing the wax without damaging the specimen is not trivial, and the plastic bag method requires handling the specimen in and out of the bag a number of times, which can smear or deform the specimen.

FIG. 1 Experimental setup for bulk volume measurement.

CHARACTERISTICS OF THE NEW COATING PRODUCT AND COATING PROCEDURE

Medical spray plaster is made of acrylic copolymer solutions, the exact composition of which depends on the manufacturer. It was developed to waterproof wounds while allowing them to “breathe.” When applied to a soil specimen, it enables slow adsorption or loss of water while preventing fluid adsorption/retention when the soil specimen is immersed in a fluid for a short time. In addition, it is easy to apply, non-toxic, easily available, highly stretchable, and long lasting. These properties make it a perfect coating product for continuous shrinking or swelling tests with regular measurement of bulk volume. The HSP was sprayed on specimens placed on three pins to avoid the coating sticking to a flat support. During the 2 h required for the HSP to set, a small container was placed over the specimen to limit evaporation. Testing showed that the coating can last about 3 weeks under air-drying conditions and more than 1 month in case of swelling in a fog room. The decision to re-coat the specimen was taken if, despite meticulous cleaning, the mass of oil retained by the specimen after immersion in SO exceeded 0.5 % of the dry mass of soil. A correction was applied to account for the volume of HSP covering the specimen after volume measurements. This can be done by assessing the mass change before and after coating and using a density of HSP of 0.77 g/cm^3 .

EXPANSIVE SOIL TESTED

A residual expansive clay coming from Maryland, New South Wales, was used for this study. It contains about 50 % of smectite and is characterized by a specific gravity of 2.65, a remolded shrink swell index (proposed by Fityus et al. 2005) of 5.5 %, a liquid limit of 69.8 %, and a plasticity index of 45.7 %. Its grading curve determined using a Micromeritics x-ray particle size system (Sedigraph5120) is presented in Fig. 2. It can be noticed that the clay fraction (particle diameter less than $2 \mu\text{m}$) is about 71.8 %. For an expansive clay with 50 % of smectite, a similar liquid limit (around 70 %) was obtained on Canadian Regina clay, which contains similar percentage of smectite (around 50 %), as presented by Fredlund (1976). The possible reason for having relatively low liquid limit is that both natural clays likely contain some poorly crystalline mixed-layer clays such as interstratified smectite-illite, which can reduce the liquid limit compared to pure smectite. More information on Maryland clay can be found in Fityus and Smith (2004). Intact blocks of structured Maryland clay (mass of about 30 to 50 g) taken from the site have been used for the current study. The water content of each specimen to be tested was measured using an offcut. Depending on the test to be conducted, i.e., swelling or shrinkage, the soil specimens were initially air dried or saturated in a fog room. Then the saturated specimens were left to air dry and the dry specimens were left to swell in a fog room. Note that the specimens were placed on the bristles of an upturned bristle brush to

FIG. 2 Grading curve of Maryland clay.

allow moisture exchange by all faces and to permit deformation of the specimen at the contact with the support. The drying process happened in two phases: initial drying took place in an air-conditioned room ($20^\circ\text{C} \pm 2^\circ\text{C}$, $56\% \pm 5\%$ relative humidity) followed by drying in a desiccator with silica gel for a better control of relative humidity. Because of the small size of the specimens (1 to 3 cm^3) and the low rate of moisture change due to the coating (see next sections), the specimens were not left to equilibrate before measurement of their volume. The water content distribution within the specimens was considered close to uniform. However, for specimens of bigger size, it is recommended to leave the coated specimens in a sealed jar for an equilibration period before each measurement.

Results and Discussion

VALIDATION OF THE NEW METHOD

The swelling and shrinkage curves obtained on intact Maryland clay with coating are shown in Fig. 3. The quality of the curves shows that using the HSP allows a close monitoring of the volumetric deformation of a specimen. This proves critical when trying to determine the air entry value and the shrinkage limit. In the next step, it is important to compare the new method to benchmarks method. This is shown in Fig. 4, which presents the results obtained with HSP and those obtained with the wax and plastic bag methods. Note that the comparison was performed along a drying path (Fig. 4(a)) and a wetting path (Fig. 4(b)). The results clearly show that, for both paths, the results of the HSP method fall within the cloud of points associated with the wax and plastic bag methods. Note that the continuous line in Fig. 4 is not a best fit but the line that joins all the data points obtained with the HSP. Figure 4 not only validates the HSP

FIG. 3

Comparisons of shrinkage and swelling behavior of intact Maryland clay with coating: (a) saturation degree versus water content, and (b) void ratio versus water content. D and W correspond to the drying and wetting path, respectively. Only one specimen was used per curve.

method but also clearly highlights the reduction of data scattering associated with the new HSP method.

EFFECT OF THE HSP ON THE VOLUMETRIC DEFORMATION OF SPECIMENS

As the coating can be left on the specimen during testing, its restraining effect on volumetric deformation, especially during swelling, has to be assessed. This was achieved by (1) conducting a series of tensile tests on the coating, (2) by computing the restraining pressure exerted by the coating for different volumetric deformations, (3) by comparing the evolution of volumetric deformation upon swelling of coated and uncoated specimens, and (4) by comparing the unconfined compressive strength of coated and uncoated specimens.

Inspired by ASTM D882-10, the tensile tests were conducted by spraying a thin HSP film (thickness of 0.01 mm as per soil coating) on a thin latex membrane of known mechanical response. The tensile modulus of elasticity of the coating can be estimated to be about 11 MPa on the basis of the experimental results presented in Fig. 5(a).

To assess the actual restraining pressure P exerted by the coating upon soil swelling, the HSP was considered as a thin

spherical membrane subjected to an internal pressure P for which we have:

$$(2) \quad \sigma_{\theta} = \frac{P \cdot r}{2t}$$

where:

P = internal pressure,

t = membrane thickness (0.01 mm),

r = inside radius of the sphere, and

σ_{θ} = hoop stress within the membrane.

The volumetric deformation of the sphere ε_v can be related to the radius r and change in radius Δr as per:

$$(3) \quad \varepsilon_v = \frac{\Delta V}{V} = \frac{(r + \Delta r)^3}{r^3} - 1$$

and the hoop strain ε_{θ} is equal to:

$$(4) \quad \varepsilon_{\theta} = \frac{\Delta r}{r}$$

In the elastic domain, the hoop stress σ_{θ} and hoop strain ε_{θ} are related by the tensile modulus of elasticity. Considering the

FIG. 4

Comparison of results obtained via the new HSP method, the wax method and the plastic bag method. (a) Evolution of void ratio with water content during shrinkage. (b) Evolution of void ratio with water content during swelling. All tests were performed on intact Maryland clay clods.

FIG. 5

(a) Results of tensile tests on the coating material (thickness of 0.01 mm). (b) Theoretical evolution of the restraining pressure exerted by the coating as a function of volumetric deformation. (c) Experimental evolution of volumetric deformation versus water content upon wetting for intact Maryland clay without coating, with coating and with segmented coating. (d) Stress–strain relationships for compacted Maryland clay with and without coating during unconfined compression.

isotropic stress state on a small element of the thin spherical membrane subjected to an internal pressure P , it yields:

$$(5) \quad \sigma_{\theta} = \varepsilon_{\theta} \frac{E}{1 - \nu}$$

where:

E = tensile modulus of elasticity determined by the 1D tensile test.

By combining Eqs 2 to 5, the restraining pressure of the HSP can be calculated. **Figure 5(b)** shows the relationship between restraining pressure and volumetric deformation. This was calculated for an initial volume of 6 cm³, a modulus of 11 MPa, and a Poisson's ratio of 0.5 (conservative).

The swelling test presented in **Fig. 5(c)** shows no noticeable difference up to about 30 % of water content between a coated and uncoated specimen. Afterward, the two curves slightly diverge. However, as indicated by the error bars plotted for the last two data points of the uncoated specimens, this divergence can reasonably be imputed to measurement errors rather than to a physical restraining effect.

This is confirmed by the results of a third swelling test (repeated once for the sake of consistency) where the soil specimen was coated before each volume measurement but the coating was delicately cut with a scalpel after measurement to prevent any restraining effect. Note that the coating was not

peeled off, so that no error pertaining to removal of soil particles was introduced. This test is referred to as “segmented coating” in **Fig. 5(c)**.

Finally, the possible restraining effect by HSP was also evaluated by performing a series of unconfined compression tests on coated and uncoated specimens according to [ASTM D2166-2](#). Six specimens (38 mm in diameter and 76 mm in height) of the Maryland clay at a water content of 21.7 % were prepared by static compaction, among which three specimens were coated with HSP. A low dry density of 1.2 g/cm³ of the specimens, corresponding to a high initial void ratio of 1.21, was chosen to obtain a low unconfined compressive strength and evidence a possible restraining effect. The axial stress–strain relationships from these tests are presented in **Fig. 5(d)**. It can be noticed that the unconfined compression behavior of the coated specimens is quite close to that of the uncoated ones. The difference of average peak compressive strength is just 1.6 kPa with a higher value for the coated specimens, which can be considered negligible considering the variability of the unconfined compressive strength of compacted specimens. The results confirm again that no significant restraining effect can be induced by the HSP on the clay tested.

In addition, the range of variation of gravimetric moisture content for Maryland clay in situ has been estimated to 15 % to 42 % ([Fityus et al. 2004](#)). Considering that the evolution in

FIG. 6

(a) Evolution of absolute errors of saturation degree (S_r) as a function of the water content during shrinkage and swelling test on coated Maryland clay. (b) Evolution of water content in time during a swelling test for coated and uncoated specimens.

Fig. 5(c) is almost linear, 27 % of moisture content change roughly corresponds to a volumetric deformation of about 35 % (Fig. 5(c)). Stretching the HSP to that point would require a confining pressure of about 3.5 kPa (Fig. 5(b)), which can be considered negligible. Note that soil with lower swelling potential would expand less and experience much less restraining effect.

ADVANTAGES OF USING THE HSP OVER CONVENTIONAL COATING MATERIALS

Unlike many coatings, the HSP stays on the specimen during the full drying or wetting path, allowing a close monitoring of the soil response as per Fig. 3. Using some wax, or similar product, requires using several specimens in parallel as the coating is non-trivial to remove and impedes any moisture transfer. In theory, the plastic bag method (Boivin et al. 1991) could be employed with only one specimen rather than parallel specimens. In practice, handling the specimens in and out of the plastic bag is not very practical and can damage them.

In addition, the HSP overcomes few inherent drawbacks of the plastic bag method:

- The plastic bag method is not ideal for saturated specimens, which is often the condition of interest in geomechanics (especially when determining the air entry value).
- With the HSP, there is no need of a vacuum pump during measurement and there is no modification of the stress state because of a vacuum.
- With the HSP, there is no risk of entrapped air affecting the volume measurement.
- With the HSP, there is no specimen handling in and out of the bag with a risk of losing pieces (crumbs) of material. Indeed, the coating remains throughout the test.

In fact, one of the last statements in Boivin et al. (1991) is that the plastic bag method could be improved with a more supple and stretchable coating, which is what the HSP is.

In terms of accuracy of measurement, the plastic bag method yields about 4 % of error in the measurement of volume for large pieces of soils (Boivin et al. 1991). Here, the absolute

errors in the water content and of the saturation degree were calculated using a law of error propagation (Drosg 2006). According to the principle of error propagation, the absolute error in the water content (not shown here) increases during the test (i.e., with the number of measurements). The error in the water content affects the absolute error of the saturation degree differently in drying or wetting (as seen in Fig. 6(a)). The increase of water content during wetting compensates for the error propagation and the error of the saturation degree remains roughly constant. On the contrary, the diminution of water content during drying exacerbates the error of the saturation degree. In any case, the magnitude of error of the saturation degree is very low: 2 % maximum, which is comparable to the 4 % obtained with the plastic bag method.

Finally, the HSP avoids two issues, namely that the surface smearing effect associated with handling wet materials (operation required by the plastic bag method) and the cracking upon wetting caused by excessive suction gradient. This problem is illustrated in Fig. 6(b) that clearly demonstrates that coating the specimen significantly reduces the adsorption rate. One consequence is that, unlike the uncoated specimen, the coated one did not experience any cracking after twice the time in the fog room. Note that cracking was observed for the slowest transfer mechanism through vapor. Wetting by placing the specimen on wet sand is typically faster and makes the use of HSP even more critical.

It has to be specified that, although the results presented here were obtained on relatively small specimens, the method can perfectly be adopted on larger structured soil clods as macro cracks can be sealed off with the coating. This, however, proves quite time consuming.

Concluding Remarks

In this study, a new coating product has been tested on soil specimens with the objective to improve the ease and accuracy of volume measurement, void ratio, and saturation degree. The

coating product, referred to as hand-spray plaster (HSP), is a medical sprayable plaster developed to waterproof wounds while letting them “breathe.” In addition, it is highly stretchable, non-toxic, relatively long lasting, and easily available from most pharmacists. The HSP has been combined with immersion in silicone oil for bulk volume measurement and it has been found that the swelling and shrinkage curves can be closely followed with only one specimen per curve. A relatively large amount of data points have been obtained with low error. The HSP method has been compared against two benchmark methods with a good agreement. The tests performed in the study also showed that the coating reduces fluid retention by the specimen, the rate of water adsorption, and the likelihood of cracking upon swelling. Finally, the coating does not have any restraining effect on the specimens upon swelling. The HSP proved a superior alternative to any coating material considered previously.

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